Striking the Right Balance: Examining Optimum Insulation Levels Based on Lifecycle Cost, Emissions, and Societal Impacts

Mohamed Abdelsalam, David Pudleiner, and Urvi Shah, ICF
Amy Schmidt, Nest Solutions

ABSTRACT

Everyone agrees that buildings need insulation, but how much is enough? With energy codes beginning to consider the inclusion of embodied carbon, this adds an additional dimension across which the merits of building materials for efficiency should be assessed. In this paper, we examine the impact of exterior wall and roof insulation across 6 climate zones and 3 building types: single family homes, small offices, and strip malls. Using the EnergyPlus prototypical models developed by PNNL for IECC-2021/ASHRAE 90.1-2019 and an optimization framework built on JEPlus software, this study analyzes the optimum level of insulation from three perspectives. First, the building owner cost optimum level is evaluated utilizing life cycle cost analysis, the primary metric utilized by DOE in calculating code cost-effectiveness. Secondly, the carbon optimum level is examined balancing embodied carbon and lifetime emissions during building operation. Finally, the societal global optimum considering both carbon and energy costs is calculated by monetizing carbon emissions impacts utilizing the social cost of carbon estimates and energy costs using avoided energy supply costs. The results show that embodied carbon need not be a limiting assumption for determining the appropriate code insulation requirements for the building types examined. In all 18 cases examined, the building owner cost-optimum insulation levels are generally lower than the IECC 2021 and ASHRAE 90.1-2019 requirements. Furthermore, for the parameters examined in this study, the societal cost optimum insulation level aligns with the lifecycle cost optimum.

Introduction

In 2021, buildings accounted for 30% of global energy consumption and 27% of total energy sector emissions (IEA 2021). Buildings in the US consume 75% of the electricity and 40% of the total energy, resulting in 36% of all carbon dioxide emissions (EIA 2023). In buildings, the thermal envelope plays a pivotal role, accounting for approximately 50-60% of the total heat exchange occurring between the interior space and the exterior environment (Kumar et al. 2020). The thermal envelope encompasses insulation materials that act to reduce the heating and cooling demands, thereby reducing energy costs and improving indoor thermal comfort. In addition, proper design and selection of insulation materials serve to provide condensation control, reduce air leakage, and attenuate the noise level transmitted to the occupied space.

Building energy codes provide a cost-effective means of reducing energy consumption and greenhouse gas emissions from buildings. These codes offer guidance for building construction to meet minimum energy requirements. In the US, the two main building energy code systems are developed by ASHRAE, and the International Code Council (ICC). The ASHRAE 90.1 standard is recognized as the national model energy code for commercial facilities and multifamily mid- and high-rise residential buildings (i.e., greater than three stories).

Similarly, the IECC is recognized as the national model energy code for energy efficient low-rise residential buildings (Bartlett et al. 2003).

The US Department of Energy (DOE) issues a determination to evaluate whether the newly added efficiency measures in the latest release of the energy code or standard improves energy efficiency compared to the preceding energy code or standard. Once a determination is published, states are required to review the provisions of their commercial and residential building codes regarding energy efficiency and decide whether to update their codes to meet or exceed the updated edition of ASHRAE and IECC (Xie et al. 2023). Furthermore, Pacific Northwest National Laboratory (PNNL) are directed by the DOE to conduct cost-effectiveness analysis to evaluate the energy and economic impacts associated with the updated IECC and ASHRAE 90.1 standard. (Salcido et al. 2021; Tyler et al. 2021) The process of examining the cost effectiveness of the code changes involves four main steps: (1) identification of the building components affected by the updates to the prescriptive and mandatory provisions of the code or standard that directly affect energy use, (2) assessment of construction costs associated with these updates, (3) analysis of energy and cost impacts associated with these updates, and (4) cost-effectiveness analysis of the updates, combining the incremental costs of these updates with the associated energy impact. Life-Cycle Cost (LCC) is the primary metric used by DOE for determining the cost effectiveness of an overall or individual code or standard change.

The progression of building envelope upgrades in the ASHRAE 90.1 standard and IECC is characterized by evolving requirements aimed at improving energy efficiency in buildings. For example, between the 2006 and 2021 editions of the IECC, the maximum assembly U-factor for wood-frame exterior wall dropped by 21-45% depending on the climate zone. Similarly, between the 2004 and 2019 editions of the ASHRAE 90.1 standard, the maximum assembly U-factor for steel-frame exterior wall dropped by 32-48% depending on the climate zone.

There is a large body of literature on the optimization of insulation material and thickness for various building types using different objective functions, with primary emphasis on energy, environmental, and economic impacts of building's insulation level. Most studies focused on a single optimization criterion, whereas only a few studies considered combining different objective functions in pursuit of near-global optimization (Rad and Fallahi 2019). In their comprehensive literature review, Kumar et al. (2020) uncovered the prevalence of insulation optimization studies that only considered LCC as the sole objective function, which is limited to the consideration of economic benefits. Very few investigations were reported to consider cost, energy, emission, and thermal comfort as the optimization criteria. Furthermore, studies that explored the effect of various optimization criteria realized that the optimum insulation thickness calculated using one criterion is different from that calculated using a different criterion.

The majority of the insulation optimization studies followed a case-study approach, focusing on certain building types in specific climate zones, with notable prevalence of use of simplified degree-day method rather than dynamic building energy modeling. Despite its simplicity and ability to provide a means for analytical optimization solution, the degree-day method fails to accurately capture the dynamic behavior of the building during heating and cooling cycles.

Nyers et al. (2015) developed an energy-economic optimization framework to evaluate the optimum thickness of thermal insulation layer for exterior walls. A simplified thermal resistance model was developed to estimate the operational energy savings associated with the increased level of insulation to the wall. A simple payback period was used as the objective function for the optimization. The optimization model was then applied to a case in Serbia, where the considered wall was assumed to be made of brick and the insulation material was assumed to be polystyrene. The results showed that for the assumed price of electricity of €0.09 per kWh and total cost of insulation of approximately €40 per square meter of insulation, the optimum insulation thickness for minimized payback period was around 7 cm (2.75 in).

Annibaldi et al. (2019) conducted a study aiming at improving the energy efficiency of the envelopes of historical buildings. Their study commenced by evaluating the thermal resistance of the exterior wall assembly absent of insulation using in-situ testing versus values available in the literature. Then, a host of ten insulation materials were analyzed to identify optimum insulation thickness based on life-cycle costs. The analysis framework applied the heating degree day approach on a case study in the Province of L'Aquila in Italy. The results highlighted the sensitivity of the optimum insulation thickness to the baseline wall thermal resistance as well as the insulation material. Using thermal resistance values from the literature resulted in 2.5 – 4.75% over-estimation of the cost for the optimum thickness of various insulation materials, compared to using in-situ measurement values.

Axaopoulos et al. (2019) presented the optimum insulation thickness for exterior walls of different composition and orientation, for both the heating and the cooling period. Three different wall types and insulation materials were explored. The dynamic thermal behavior of the external walls' simulation was based on the heat conduction transfer functions method and using the hourly climatic data available for the city of Athens, Greece. The optimization methodology used a single objective function approach, combining the simulation of the thermal behavior of external walls with an optimization algorithm. The results indicated that the optimum insulation thickness varies from 11.2 to 23.4 cm and is different for each orientation, wall type, and insulation material. In addition, the annual operational CO_2 emissions per unit area of the wall were reduced by 63.2%–72.2%, depending on the insulation material and its position on the wall. It was noted that the optimum insulation thickness for the minimization of CO_2 emissions did not align with the lowest possible energy cost. As such, the authors suggested that if the building design requires the minimization of the overall cost, both the environmental and the economic parameters should be considered simultaneously.

Li and Tingley (2023) noted that the impact of variations of future climate conditions and the carbon intensity of the electricity grid are rarely studied. They found that ignoring future variations could lead to overestimation of the reduction potential of insulation on whole life energy consumption, and thus emissions reduction. The overestimation percentage for stock level whole life energy consumption reduction varied from 20.5% to 26.7%, and the overestimation percentage for stock level whole life carbon emissions reduction varied from 421.3% to 502%. In their study, the heating degree days were assumed to drop linearly with time up to 35% reduction by 2050. The study utilized the pareto frontier optimization method, looking at maximizing the whole life carbon emissions reduction, maximizing the whole life energy consumption reduction, and maximize both the whole life energy consumption reduction and whole life carbon emissions reduction.

Kumar et al. (2020) used EnergyPlus V9.2 to simulate a typical Australian residential building using the properties of 40 different insulation materials under different climate zones of Australia and calculated lifecycle carbon emission. The thickness was varied for each insulation material to calculate the optimum wall resistance against minimum lifecycle cost and carbon emission, calculated as the summation of carbon emission associated with embodied energy and operational energy. The results revealed that building walls with higher thermal resistance are more cost-effective in heating dominated regions, while walls with comparatively lower thermal resistance are more cost-effective for the cooling dominated region. The authors proposed an optimization framework that optimizes insulation based on four criteria: (1) energy, involving the trade-off between embodied energy and operational energy savings; (2) environment, involving a trade-off between the embodied carbon and the operational emission savings; (3) economy, involving a trade-off between insulation cost and energy bill savings; and (4) comfort, accounting for the impact of insulation on indoor thermal comfort and noise control.

Touloupaki and Theodosiou (2017) evaluated the optimal thickness of insulation that is cost effective to apply in urban multifamily domestic buildings in four climate zones of Greece. A national software tool called TEE-KENAK was used for energy analysis. A reference building was selected in order to perform calculations over ten scenarios of external insulation thickness for each climate zone. The operational energy savings for each insulation scenario were calculated and then the cost effectiveness of the measure was examined in financial and macroeconomic perspective for an economic life cycle of 30 years. The results of the study showed that buildings could save a very large amount of energy even with small thicknesses of insulating material. In each climate zone, the global cost of investment curve was found to shift upwards or downwards depending on the interest rates and future energy prices.

This study investigates the optimum insulation level in residential and commercial prototypes in six different climate zones in the US. Three different objective functions are explored: lifecycle cost, including the effect of insulation cost and bill savings; lifecycle emissions, including the effect of embodied carbon and operational emission savings; and lifecycle societal cost, including the combined effect of insulation cost, embodied carbon and emission costs, and generation cost. To the authors' knowledge, the societal cost is presented here for the first time as a means to provide the optimum insulation level from the perspective of societal impacts. This study considers the effect of both the exterior wall and the attic floor or roof insulation, as they are considered the largest contributors to the heat exchange with the outdoor environment. Unlike most previous studies, the current work optimizes the R-value of the envelope components rather than focusing on either the insulation thickness or material type. EnergyPlus hourly simulation tool is used to accurately capture the dynamic behavior of the modeled building under varying weather and operational conditions.

Methodology

The current investigation explores the optimal R-value for the exterior walls, attic floors, and roof assemblies of prototypical residential and commercial building models developed by PNNL for analyzing updates to building energy codes.[1] Specifically, the IECC 2021 single-family home model is selected to represent the residential sector, while the ASHRAE 90.1-2019 small office and strip mall prototypes are chosen to represent a range of commercial facility types in the United States. Table (1) summarizes the key characteristics of the selected prototypes. To account for varying weather conditions and corresponding building code requirements, building models for six climate zones (1-6A) are examined.

It is worth noting that the PNNL models for residential single-family homes comprise 16 prototypes per climate zone spanning four different foundation types (heated basement, unheated basement, crawlspace, and slab on grade) and four different heating systems (electric resistance, natural gas furnace, fuel oil furnace, and heat pump). The present study focused on six residential

[1] These models are made accessible by the office of Energy Efficiency & Renewable Energy (EERE) on https://www.energycodes.gov/prototype-building-models.

prototypes that constituted the majority (~86%)[2] of single-family homes in climate zones (1-6A): crawlspace/natural gas furnace, crawlspace/heat pump, slab on grade/natural gas furnace, slab on grade/heat pump, heated basement/natural gas furnace, and unheated basement/natural gas furnace.

Table 1. Summary of the key characteristics of the investigated prototypes

Building Characteristic	Residential	Commercial	
	Single-family Home	Small Office	Strip Mall
Conditioned Floor Area (ft^2)	2,377-3,565*	5,502	22,500
Exterior Wall Construction	Wood Frame	Wood Frame	Steel Frame
Exterior Wall Net Area (ft^2)	1,974	2,346	10,906
Attic Floor or Roof Construction	Wood Rafters (Vented Attic)	Wood Rafters (Vented Attic)	Metal-Deck Roof (Above-deck Insulation)
Attic Floor or Roof Area (ft^2)	1,188	6,113	22,500

*Conditioned floor area is 3,565 ft^2 for homes with heated basement and 2,377 ft^2 for homes with no basement.

JEPlus[3], an open-source parametric tool for EnergyPlus, is used to vary the R-value of exterior wall and attic floor or roof assemblies and run parallel simulations of the analyzed scenarios. Five R-values are chosen for the exterior wall assembly to cover the range from uninsulated wall to an R-value extending beyond the latest code. Similarly, five R-values are selected for the attic floor assembly in the cases of single-family home and small office and roof assembly in the case of the strip mall. The assembly R-value for a given envelope component is obtained from the reciprocal of the maximum assembly U-factor identified by the respective model energy code. It represents the effective R-value of all layers comprising the envelope component (i.e., the structural elements, the insulation and the finishing layers). The baseline R-values for the uninsulated cases are evaluated based on the balance of assembly R-values presented for the respective assembly types in ResCheck[4] and ComCheck[5] technical support documents. The baseline R-value represents the effective assembly R-value with no insulation. The other four R-values are chosen to align with the latest IECC and ASHRAE 90.1 standard requirements. Table (2) demonstrates the R-values for the exterior wall and the attic floor or roof assemblies of the prototypical buildings under study.

[2] Appendix B in “Energy savings analysis: 2021 IECC for residential buildings.” Salcido, V.R., Y. Chen, Y. Xie, and Z.T. Taylor. 2021. Pacific Northwest National Laboratory (PNNL): Richland, WA, USA.
[3] https://www.jeplus.org/wiki/doku.php
[4] https://www.energycodes.gov/rescheck
[5] https://www.energycodes.gov/comcheck

Table 2. Simulated R-values for exterior wall and attic floor or roof assemblies for the prototypical buildings

Prototype	Baseline Uninsulated Assembly (R0)		Insulated Assembly (R1-R4)	
	Exterior Wall Assembly	Attic Floor or Roof Assembly	Exterior Wall Assembly	Attic Floor or Roof Assembly
Single-family Home	3	2	12, 17, 22*, 25	29, 38, 42*, 45
Small Office	3	1	11, 16, 20*, 25	29, 37, 48*, 60
Strip Mall	2	1	12, 16, 20*, 25	21, 26, 31*, 35

* These values correspond to the IECC 2021 requirements for minimum assembly R-value.

For each prototype, 25 energy models are generated and simulated using EnergyPlus to capture the interactive effects of applying different insulation levels on the exterior wall and attic floor or roof assembly of the building. The results are aggregated to analyze the impact of insulation level combinations on building annual energy consumption in the six different climate zones. The operational energy savings are calculated as the difference between the energy consumption of baseline uninsulated case (i.e., with both the exterior wall and attic floor or roof assembly set to the uninsulated assembly R-values) and that of the insulated case.

This study examines three objective functions for insulation level optimization: lifecycle cost (LCC), lifecycle carbon emissions, and lifecycle societal cost.

Lifecycle Cost

Lifecycle cost is defined as the difference between the installed cost of the insulation and the present value of the energy bill savings over the lifetime of the insulation, assumed to be 50 years (Grazieschi, Asdrubali, and Thomas 2021). This metric provides the optimum insulation level from the perspective of building owner’s economics. In this study, mineral wool is selected for cavity insulation, whereas expanded polystyrene foam (EPS) is selected for continuous insulation. To simplify the analysis, the cavity insulation is assumed to fill the entire cavity and the remainder of the assembly R-value is assumed to be provided by the continuous insulation. Although, in practice, EPS foam boards are selected based on standard insulation thicknesses available in the market, the present study calculates the EPS insulation thickness required to exactly match the assembly R-value of interest with no regard to market availability. Such an assumption ensures consistency in results comparison. Table (3) summarizes the key properties of the insulation materials.

The energy bill savings are calculated by multiplying the annual operational energy savings by the energy retail rate. National average electricity and natural gas rates for residential and commercial applications are obtained from Annual Energy Outlook 2023 (EIA 2023). The installed costs of the insulation materials are obtained from 2024 RS Means cost database. Table (4) summarizes the key economic parameters used in the evaluation of the LCC.

Lifecycle Carbon Emission

Lifecycle carbon emission is defined as the difference between the embodied carbon in the insulation materials during the production and installation stage and the total operational emission savings over the lifetime of the insulation. This metric provides the optimum insulation level from the perspective of carbon footprint. In the past, it had been considered that embodied emissions constitute a small fraction of the operational emissions for the building sector. However, the improvement in energy design of the building envelope, heating and cooling equipment efficiencies, and the enhanced insulation and airtightness of the buildings have resulted in the reduction of operational emissions (Chen et al., 2001). Hence, the share of the embodied carbon to the total emissions is slowly but steadily increasing and several energy analysts are now taking it into account in order to reduce the total emissions. This study assumes the embodied carbon in mineral wool and EPS to be 0.68 and 2.10 kg CO_2e/kg of insulation material, respectively (Grazieschi, Asdrubali, and Thomas 2021).

To facilitate the calculation of the operational emissions, site-to-source conversion ratios are applied to site consumptions to evaluate the source consumptions. For electricity consumption the source-to-site ratio is taken as 2.95 and for natural gas the ratio is 1.09 (EIA 2021). To calculate the emissions the long run marginal emission rates (LRMER) are extracted from the 2022 Cambium database[6] for a Mid-case scenario, representing business-as-usual scenario, assuming no nascent technologies and production and investment tax credits are not phased out. Natural gas is assumed to have an emission rate of 5.3 kg CO_2e/therm[7]. The embodied carbon values for the insulation materials considered in the analysis are displayed in Table 3.

Lifecycle Societal Cost

Lifecycle societal cost involves the trade-off between the installed cost of insulation and the embodied carbon cost on one side, and the avoided generation and emissions cost on the other side. This metric provides the optimum insulation level from the perspective of the societal impacts.

The embodied carbon and avoided annual operational emission costs are calculated using social cost of carbon estimates presented in the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990 (IWG 2021). This analysis examines a medium estimate for social costs of carbon (ranging between $83 in 2020 to $125 in 2040 per metric ton of CO_2). It is worth noting that the IWG technical support document only provides cost estimates until 2040. As such, the cost data is linearly extrapolated to 2050, then the cost is maintained at a fixed value post-2050.

The avoided generation cost is extracted from 2022 Cambium database[6] which provides projections to 2050 for the total marginal cost induced by a change in end use load, including the effects of avoided energy generation, avoided capacity and operating reserves as well as avoided portfolio costs. Table 4 demonstrates the ranges for social cost of carbon and generation and capacity costs utilized in this analysis.

The present value of the lifecycle benefits is calculated and then subtracted from the total cost of insulation (including the cost of embodied carbon) to evaluate the lifecycle societal cost.

[6] https://www.nrel.gov/analysis/cambium.html
[7] Provided by the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Equivalencies Calculator (https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator)

Table 3. Summary of key properties of insulation materials

Insulation Material	Density (kg/m^3)	Thermal Conductivity (mW/m.°C)	Embodied Carbon (kg CO_2e/kg)*
Mineral Wool	120	36.5	0.68
EPS	34	35.0	2.10

* Source: Grazieschi, Asdrubali, and Thomas 2021

Table 4. Summary of key economic parameters (all in 2024 USD value)

Parameter	Value
Installed Cost of Insulation	Mineral Wool: 16.0 USD/m^3 EPS: 12.8 USD/m^3*
Energy Price (2024-2073)	Electricity: 4.0-4.3 ¢/kBtu Natural Gas: 1.1-1.3 ¢/kBtu
Social Cost of Carbon (2024-2073)	26.3-39.0 USD/MWh**
Generation and Capacity Cost (2024-2073)	41.4-45.0 USD/MWh
Real Discount Rate	Residential: 3% (Salcido et al. 2021) Commercial: 5% (NREL 2023)

* This analysis assumes a fixed cost per unit volume of insulation regardless of the thickness.
** Calculated using the product of social cost of carbon in USD/kg CO_2e and the LRMER in kg CO_2e/MWh.

Results and Discussion

This section presents the key outcomes from the parametric optimization of the exterior wall and attic floor or roof insulation levels using the three different objective functions: lifecycle cost, lifecycle emissions, and lifecycle societal cost. This study aims to serve two main purposes:

- Showing how the optimum insulation level compares with the code-level minimum insulation requirements. This highlights the key differences between the current approach and the one nominally based on traditional life cycle cost considering the tradeoff between installation cost and operational energy cost.
- Showing the effect of applying different objective functions on the optimum insulation level. This highlights the difference between optimum insulation levels from various perspectives: the building owner's economics, the environmental impact, and the societal impact. It also provides insights into the objective function that potentially offers a global optimum solution.

Single-family Home Prototype

Figures (1-3) show the effect of various combinations of exterior wall and attic floor insulation levels on lifecycle cost, lifecycle emissions, and lifecycle societal cost, respectively, for a single-family home prototype in climate zone 1A.

From the perspective of a building owner's economics, it is seen that all insulation level combinations are cost effective (i.e., negative lifecycle cost), except for the combinations involving no insulation on the exterior wall. Figure (1) also shows that R-29 on the attic floor assembly provides the smallest lifecycle cost for all R-values of the exterior wall. This is in alignment with the IECC 2021 which requires the minimum assembly U-factor on the attic floor for climate zone 1 to be 0.035 Btu/h.ft^2.°F (i.e., equivalent to ~R-29).[8] However, the minimum lifecycle cost is shown to occur at exterior wall insulation level of ~R-17, compared to IECC 2021 requirement of ~R-12. The lifecycle cost difference between the obtained optimum and the code requirement is found to be $285 (i.e., 5% less cost than the code requirement). This suggests that the energy and bill savings resulting from increasing the code-level R-value of the exterior wall assembly from R-12 to R-17 outweigh the incremental cost of added insulation.

Figure (2) presents the lifecycle emissions for various combinations of exterior wall and attic floor insulation levels. This figure emphasizes the balance between the embodied carbon in the insulation material and the lifecycle emission reduction associated with the operational energy savings due to increased insulation levels. All simulated cases are seen to be saving more emissions over the lifetime of insulation compared to the total embodied carbon. It is also shown that increasing the insulation level on the exterior wall and attic floor consistently results in lower lifecycle emissions. However, the trend of the curves seems to follow an asymptote, indicating diminishing returns from increasing insulation level beyond IECC 2021requirements (i.e., R-12 for exterior wall assembly and R-29 for attic floor assembly). The attic floor insulation level seems to have no impact on life cycle carbon emissions above the baseline level relative to exterior wall. This is because the attic floor insulation reaches a point of diminishing returns around R-29, where adding more insulation will not result in significant energy savings. Furthermore, the analysis matrix is coarser for attic floor insulation relative to exterior wall. As such, it is expected that with finer resolution between R-2 and R-29, the impact of attic floor insulation on the reduced emissions will be demonstrated.

The lifecycle societal cost function extends the boundaries of the insulation level impact to include the system level impacts (i.e., avoided energy and capacity generation) as well as policy-driven decarbonization aspirations, manifested by social cost of carbon estimates. Figure (3) demonstrates the lifecycle societal cost for various combinations of exterior wall and attic floor insulation levels. This figure shows a lot of similarities with the lifecycle cost results, indicating the dominance of the insulation cost and operational energy savings impacts over embodied carbon's impacts. It is worth noting that the key differentiators of the lifecycle societal cost from the lifecycle cost are that: (1) the operational energy savings are multiplied by the emission rates and social cost of carbon instead of energy retail rates, and (2) the avoided energy generation and capacity costs are accounted for by multiplying the operational source energy savings by the emission rates and social cost of carbon.

Although the lifecycle societal cost optimum insulation level is identical to lifecycle cost optimum's, Figure (3) shows that for climate zone 1A the lifecycle societal cost optimum increases only by 4% if the attic floor insulation is removed (i.e., R-2 for attic floor assembly instead of R-29). This, however, will result in an increase in the lifecycle cost of 8% relative to the optimum value.

Similar trends are observed on results obtained for the other climate zones. Table (5) summarizes the results for the single-family home prototype for all studied climate zones. The columns labeled with "% Difference" provide the percent deviation of optimum lifecycle cost, emissions, and societal cost from the respective code-level values.

---

[8] https://codes.iccsafe.org/content/IECC2021P1/chapter-4-re-residential-energy-efficiency#IECC2021P1_RE_Ch04_SecR402

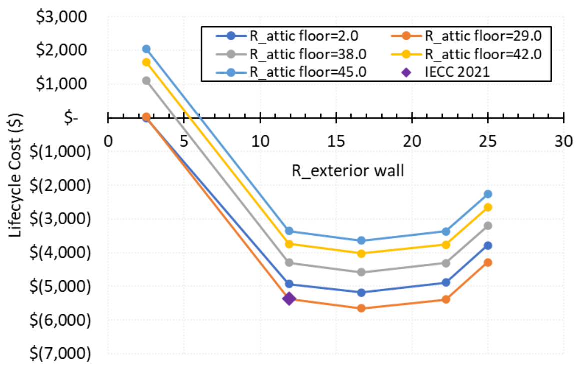

Figure 1. Lifecycle cost versus exterior wall and attic floor assembly R-values for a single-family home in climate zone 1A. Purple diamond represents the IECC 2021 requirements.

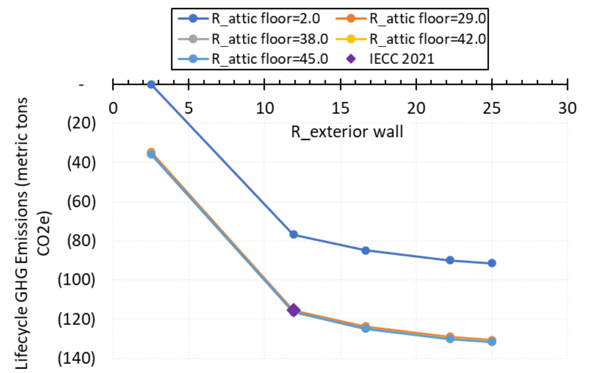

Figure 2. Lifecycle emissions versus exterior wall and attic floor assembly R-values for a single-family home in climate zone 1A. Purple diamond represents the IECC 2021 requirements. Note that the curves for attic floor R-value ≥ 29.0 are overlaying each other, making them indistinguishable on the graph.

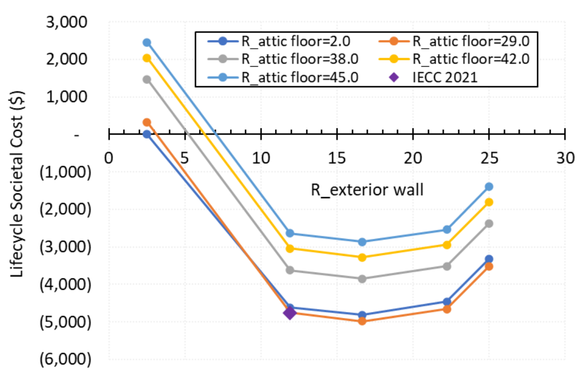

Figure 3. Lifecycle societal cost versus exterior wall and attic floor assembly R-values for a single-family home in climate zone 1A. Purple diamond represents the IECC 2021 requirements.

Table 5. Summary of results for single-family home prototype*

	IECC 2021		Lifecycle Cost Optimum			Lifecycle Emission Optimum**			Lifecycle Societal Cost Optimum		
CZ	Wall R-value	Attic Floor R-value	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference
1A	12	29	17	29	5%	25	45	14%	17	29	5%
2A	12	38	17	29	16%	25	45	13%	17	29	19%
3A	17	38	22	29	6%	25	45	5%	22	29	6%
4A	22	42	22	29	5%	25	45	1%	22	29	7%
5A	22	42	22	29	6%	25	45	1%	22	29	11%
6A	22	42	22	29	5%	25	45	1%	22	29	8%

[*]All R-values in the table are representative of the assembly effective R-value of the envelope component, rounded to the nearest whole number for conciseness.
[**] Note that the lifecycle emissions do not exhibit an optimum value within the analyzed optimization space, therefore, the largest R-values for wall and attic floor are considered as the optimum insulation levels.

Small Office Prototype

Figures (4-6) demonstrate the effect of various combinations of exterior wall and attic floor insulation levels on lifecycle cost, lifecycle emissions, and lifecycle societal cost, respectively, for a small office prototype in climate zone 3A.

Optimizing the envelope insulation of commercial buildings is crucial to ensure economic viability for the owner, while maintaining energy efficient performance and a minimal environmental footprint.

Figure (4) illustrates the effect of various combinations of exterior wall and attic floor insulation for a small office prototype on the lifecycle cost. It is seen that the attic floor insulation has a more dominant effect on the lifecycle cost compared to exterior wall insulation. This is primarily attributed to the fact that the area of the attic floor is approximately 2.6 times that of the exterior wall of the office building. It is worth noting that attic floor assemblies with effective R-value in excess of R-48 is not shown to be cost effective. The figure also shows that R-29 for attic floor provides the most cost-effective solution, which is lower than the ASHRAE 90.1-2019 standard requirement for attic insulation in conditioned nonresidential spaces (i.e., minimum assembly R-value required for climate zone 3 is R-37).[9] For this case, the upfront cost difference between the LCC optimum and the Standard requirement is $4,938, and the percent difference in LCC is 109% (i.e., the optimum LCC is approximately two times the LCC of the ASHRAE 90.1-2019 standard). Such discrepancy may be attributed to the differences in the assumptions utilized for energy retail rates, installed cost, discount rate and measure lifetime. For example, PNNL used a real discount rate of 3% and a 30-year measure life, while ASHRAE's Standing Standard Project Committee used pre-tax discount rate of 8.5% and a 40-year measure life.

Lastly, Figure (4) emphasizes the large gap between the uninsulated attic floor and the claimed optimum at R-29. Refining the optimization resolution in that range is recommended for future investigation to home in on a better optimum assembly R-value.

Figure (5) shows the lifecycle emissions under various combinations of exterior wall and attic floor insulation for a small office prototype in climate zone 3A. The results are very similar to those in the case of residential single-family home prototype. It is worth noting that the lifecycle emissions trend is essentially the mirror of the operational energy savings trend. Such trend indicates the insignificant impact of increasing insulation levels beyond R-11 for exterior wall and R-29 for attic floor on incremental operational energy savings.

It is seen from Figure (6) that the added benefits of avoided generation and capacity cost and the avoided social cost of emissions causes the lifecycle societal cost to shift downwards compared to the lifecycle cost. However, the optimum insulation level is shown to be similar.

Similar trends are observed on results obtained for the other climate zones. Table (6) summarizes the results for the small office prototype for all studied climate zones. It is worth noting that the instances with negative percent difference between optimum cost and ASHRAE 90.1-2019 standard requirement (CZ 1A and 2A) are because, with the economic parameters

[9] https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_90.1_2019

utilized in this study, the case with code-required insulation is not shown to be cost effective (i.e., the lifecycle cost is positive).

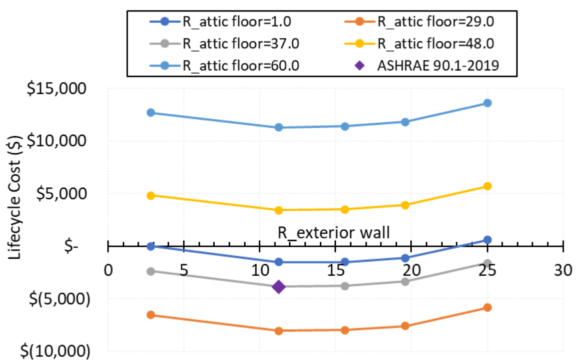

Figure 4. Lifecycle cost versus exterior wall and attic floor assembly R-values for a small office in climate zone 3A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements.

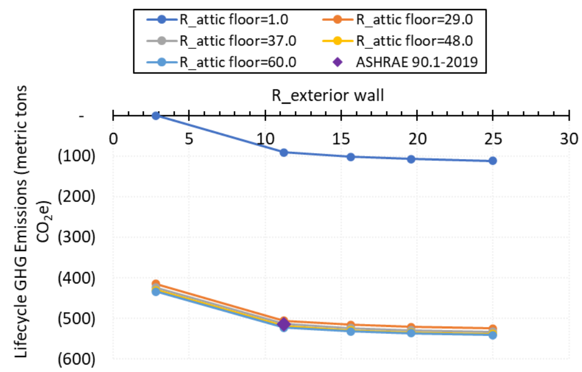

Figure 5. Lifecycle emissions versus exterior wall and attic floor assembly R-values for a small office in climate zone 3A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements. Note that the curves for attic floor R-value ≥ 29.0 are overlaying each other, making them indistinguishable on the graph.

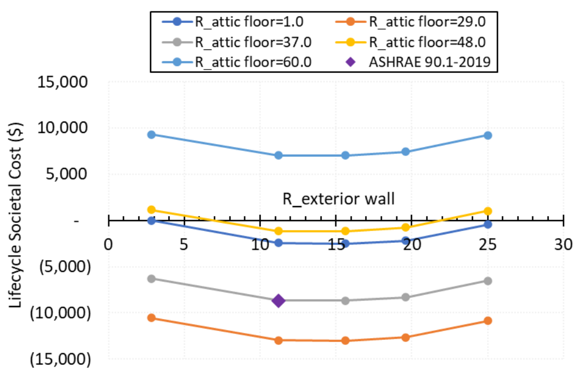

Figure 6. Lifecycle societal cost versus exterior wall and attic floor assembly R-values for a small office in climate zone 3A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements.

Table 6. Summary of results for small office prototype

	ASHRAE 90.1-2019		Lifecycle Cost Optimum			Lifecycle Emission Optimum*			Lifecycle Societal Cost Optimum		
CZ	Wall R-value	Attic Floor R-value	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference
1A	11	37	11	29	-120%	25	60	6%	11	29	2768%
2A	11	37	11	29	-107%	25	60	5%	11	29	-1051%

CZ	ASHRAE 90.1-2019		Lifecycle Cost Optimum			Lifecycle Emission Optimum*			Lifecycle Societal Cost Optimum		
	Wall R-value	Attic Floor R-value	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference
3A	11	37	11	29	109%	25	60	5%	11	29	50%
4A	16	48	16	29	210%	25	60	3%	16	29	103%
5A	20	48	20	29	57%	25	60	2%	20	29	44%
6A	20	48	20	29	26%	25	60	2%	20	29	23%

* Note that the lifecycle emissions do not exhibit an optimum value within the analyzed optimization space, therefore, the largest R-values for wall and attic floor are considered as the optimum insulation levels.

Strip Mall Prototype

Figures (7-9) demonstrate the effect of various combinations of exterior wall and roof insulation levels on lifecycle cost, lifecycle emissions, and lifecycle societal cost, respectively, for a strip mall prototype in climate zone 6A. The figures show similar trends to those observed in the previous prototypes with better alignment between the optimum insulation levels resulting from the three objective functions. Note that the curves for attic floor R-value ≥ 21.0 are overlaying each other, making them indistinguishable on the graph.

Similar trends are observed in results obtained for the other climate zones. Table (7) summarizes the results for the strip mall prototype for all studied climate zones.

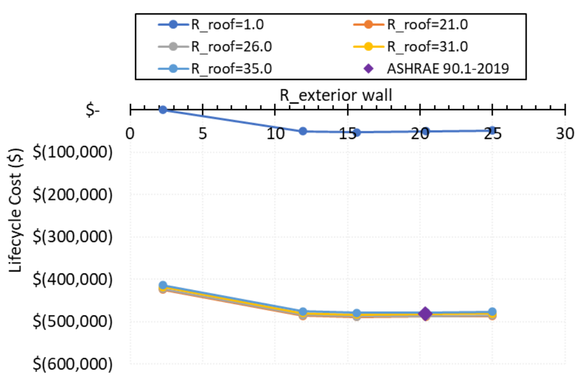

Figure 7. Lifecycle cost versus exterior wall and roof assembly R-values for a strip mall in climate zone 6A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements.

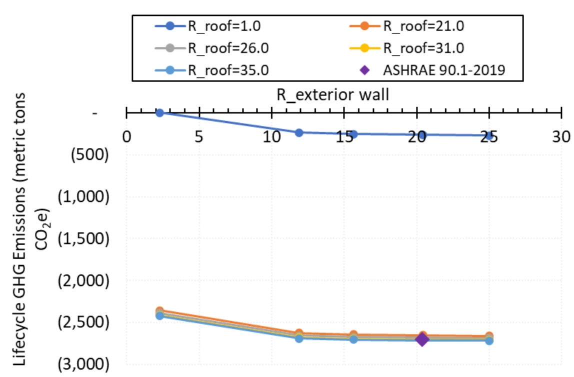

Figure 8. Lifecycle emissions versus exterior wall and roof assembly R-values for a strip mall in climate zone 6A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements.

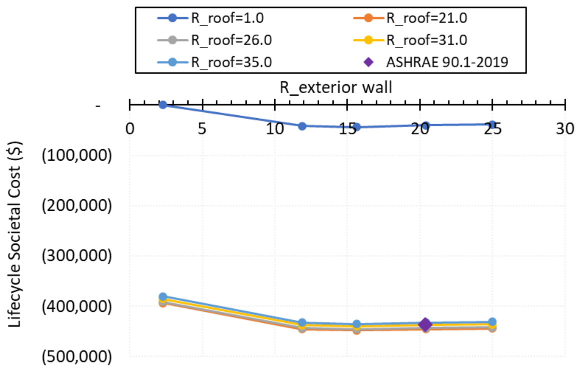

Figure 9. Lifecycle societal cost versus exterior wall and roof assembly R-values for a strip mall in climate zone 6A. Purple diamond represents the ASHRAE 90.1-2019 standard requirements.

Table 7. Summary of results for strip mall prototype

CZ	ASHRAE 90.1-2019		Lifecycle Cost Optimum			Lifecycle Emission Optimum*			Lifecycle Societal Cost Optimum		
	Wall R-value	Attic Floor R-value	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference	Wall R-value	Attic Floor R-value	% Difference
1A	12	26	12	21	7%	25	35	4%	12	21	5%
2A	12	26	12	21	5%	25	35	3%	12	21	5%
3A	12	26	12	21	3%	25	35	3%	12	21	3%
4A	16	31	16	21	4%	25	35	1%	16	21	4%
5A	20	31	16	21	3%	25	35	0%	16	21	5%
6A	20	31	16	21	1%	25	35	1%	16	21	2%

* Note that the lifecycle emissions do not exhibit an optimum value within the analyzed optimization space, therefore, the largest R-values for wall and attic floor are considered as the optimum insulation levels.

Conclusions

The current study investigates the optimum insulation level for three prototypes: residential single-family home, commercial small office and strip mall, in six climate zones (1-6 A). Unlike previous studies that generally focused on optimizing the insulation thickness of a single envelope component, this study conducts a 2-D optimization analysis on the assembly R-value of exterior wall and attic floor or roof of the prototypes. Three different objective functions are explored: lifecycle cost, lifecycle emissions, and lifecycle societal cost, to evaluate the optimum insulation levels from the perspective of building owner's economics, environmental impact, and societal impact.

The choice of the optimization function is subjective. For a homeowner, the lifecycle cost is likely the metric of choice while considering an insulation upgrade. Whereas the utility might prioritize minimizing the lifecycle societal cost of their insulation upgrade programs. The analysis framework presented herein can be generalized by considering a weighted average of the three cost functions, with the weighting factors adjusted to align with the objectives of the funding entity (Rad and Fallahi 2019).

For all prototypes investigated, there is a general alignment between the lifecycle cost and lifecycle societal cost optimums in all climate zones. However, the optimum insulation levels do not align with the IECC 2021 requirements for the respective climate zones, indicating room for improving cost effectiveness of envelope upgrades. The results also show the insignificance of embodied carbon relative to the lifetime operational emission savings.

While the optimum assembly R-values presented herein may not align precisely with existing model code requirements, it is important to note that this study does not indicate any inherent deficiencies within the model code cost-effectiveness approaches. Rather, it serves to underscore significant variances between methodologies, thereby emphasizing critical factors to be taken into account for future code assessments.

The current study relies on some assumptions that can be subject of refinement and sensitivity assessment in future studies: (1) the insulation material properties and embodied carbon data utilized in this study were collected from literature, which shows large variances in these values; (2) this study did not consider the limitation on the market availability of insulation materials of custom thickness, selecting the thickness of insulation that meets the desired assembly R-value with no regard to the availability of such thickness in the market; (3) a sensitivity analysis to future energy costs and emissions can be explored; (4) the optimization space can be refined around the obtained optima to ensure the conclusiveness of the results; (5) the analysis framework can be extended to include the effect of HVAC equipment sizing and operations; and (6) different insulation types and air tightness levels can be investigated.

References

Annibaldi, V., F. Cucchiella, P. De Berardinis, M. Rotilio, and V. Stornelli. 2019. "Environmental and Economic Benefits of Optimal Insulation Thickness: A Life-Cycle Cost Analysis." *Renewable and Sustainable Energy Reviews* 116, 109441, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109441.

Axaopoulos, I., P. Axaopoulos, J. Gelegenis, and E.D. Fylladitakis. 2019. "Optimum External Wall Insulation Thickness Considering the Annual CO_2 Emissions." *Journal of Building Physics* 42(4): 527-544. doi:10.1177/1744259118774711.

Bartlett, R., M.A. Halverson, and D.L. Shankle. 2003. "Understanding Building Energy Codes and Standards." United States: N. p., Web. doi:10.2172/900221.

Chen T., J. Burnett, and C. Chau. 2001. "Analysis of Embodied Energy Use in the Residential Building of Hong Kong." *Energy* 26 (4): 323–340.

EIA (Energy Information Administration). 2021. Annual Energy Outlook 2021. U.S. Energy Information Administration. Washington D.C. Available online: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2021&cases=ref2021&sourcekey=0

EIA (Energy Information Administration). 2023. "EIA Monthly Energy Review." Available online: https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

EIA (Energy Information Administration). 2023. "Annual Energy Outlook 2023." Available online: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2023&region=1-0&cases=ref2023&start=2021&end=2050&f=A&linechart=ref2023-d020623a.6-3-AEO2023.1-0&map=ref2023-d020623a.3-3-AEO2023.1-0&ctype=linechart&sourcekey=0

Grazieschi, G., F. Asdrubali, and G. Thomas. 2021. "Embodied Energy and Carbon of Building Insulating Materials: A Critical Review." *Cleaner Environmental Systems* 2, 100032, ISSN 2666-7894, https://doi.org/10.1016/j.cesys.2021.100032.

IEA (International Energy Agency). 2021. "Buildings: A Source of Enormous Untapped Efficiency Potential." Available online: https://www.iea.org/topics/buildings.

IWG - Interagency Working Group on Social Cost of Carbon. 2021. "Social Cost of Carbon, Methane, and Nitrous Oxide." *Interim Estimates under Executive Order 13990*. United States Government. Available online: https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

Kumar D., M. Alam, P.X.W. Zou, J.G. Sanjayan, and R.A. Memon. 2020. "Comparative Analysis of Building Insulation Material Properties and Performance." *Renewable and Sustainable Energy Reviews* 131, 110038, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2020.110038.

Li, X. and D.D. Tingley. 2023. "A Whole Life, National Approach to Optimize the Thickness of Wall Insulation." *Renewable and Sustainable Energy Reviews* 174, 113137, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.113137.

NREL (National Renewable Energy Laboratory). 2023. "2023 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/

Nyers, J., L. Kajtar, S. Tomić, and A. Nyers. 2015. "Investment-Savings Method for Energy-Economic Optimization of External Wall Thermal Insulation Thickness." *Energy and Buildings* 86: 268-274, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2014.10.023.

Rad, E.A. and E. Fallahi. 2019. "Optimizing the Insulation Thickness of External Wall by a Novel 3E (Energy, Environmental, Economic) Method." *Construction and Building Materials* 205: 196-212, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2019.02.006.

Salcido, V.R., Y. Chen, Y. Xie, and Z.T. Taylor. 2021. "National Cost Effectiveness of the Residential Provisions of the 2021 IECC." *Pacific Northwest National Laboratory*, Richland Washington. Available at https://www.energycodes.gov/sites/default/files/documents/2018IECC_CE_Residential.pdf

Salcido, V.R., Y. Chen, Y. Xie, and Z.T. Taylor. 2021. "Energy savings analysis: 2021 IECC for residential buildings." *Pacific Northwest National Laboratory (PNNL)*: Richland, WA, USA.

Touloupaki, E. and T. Theodosiou. 2017. "Optimization of External Envelope Insulation Thickness: A Parametric Study." *Energies* 10 (3): 270. https://doi.org/10.3390/en10030270.

Tyler, M.T., R. Hart, Y. Xie, M.I. Rosenberg, M. Myer, M.A. Halverson, C.A. Antonopoulos, and J. Zhang. 2021. "National Cost-Effectiveness of ANSI/ASHRAE/IES Standard 90.1–2019." United States: N. p. doi:10.2172/1823471.

Xie, Y., M. Tyler, J. Huckett, R. Bartlett, Y. Chen, V. Salcido, V. Mendon, and M. Rosenberg. 2023. "A Review of the Evaluation of Building Energy Code Compliance in the United States." *Energies* 16 (16): 5874. https://doi.org/10.3390/en16165874.