BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

Insulation Value Optimization for Low-Slope Roofs

Thomas J. Taylor,

James Willits,

Christian A. Hartwig,

and James R. Kirby

GAF

1 Campus Drive, Parsippany, NJ 07054

Phone: 973-897-3705 • E-mail: Thomas.taylor@gaf.com

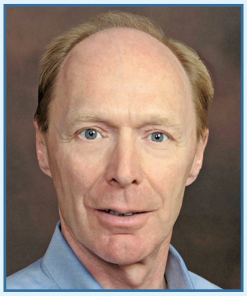
RCI, Inc.®

Abstract

Low-slope roofing assemblies include a wide range of insulation and single-ply membrane attachment methods. Often ignored is the effect of fasteners on the overall R-value of the system. This presentation will discuss R-value differences based on fastener densities and their location within the system. The analysis shows the often-significant reduction in R-value due to thermal short-circuiting and the economic cost of that due to unrealized R-value. This economic cost is contrasted with the costs of fasteners and adhesives for a range of possible attachment scenarios. Finally, the cost of reduced energy efficiency for a number of different locations is factored into the analysis. The study shows that when the costs of long-term energy efficiency and lost R-value are included in the cost/benefit analysis of various roofing assemblies, then simple mechanical attachment is not necessarily the lowest-cost long-term approach. The study has implications for future codes development because insulation is often considered to be continuous. However, this study suggests that there can be a significant difference between a designed insulation value and the effective value due to attachment method.

Speaker

Dr. Thomas J. Taylor, PhD — GAF, Parsippany, NJ



TOM TAYLOR is the executive director, Building & Roofing Science, for GAF. This position is focused on the relationships between individual roofing materials and the overall roof system and building envelope performance. Dr. Taylor is a frequent presenter at both national and regional industry meetings. He has over 20 years' experience in the building products industry, all working for manufacturing organizations in a variety of new product development roles. He received his PhD in chemistry and holds approximately 35 patents.

Nonpresenting Coauthors

James Willits, Christian Hartwig, and James Kirby

Insulation Value Optimization for Low-Slope Roofs

INTRODUCTION

The journey towards more energy-efficient commercial buildings has generally involved reducing heat-energy flow across or through various components of the building envelope. Thus, roof systems have incorporated greater thicknesses of insulation, often dictated by increasing code requirements. Also, the introduction of thermoplastic roof membranes, starting with polyvinyl chloride (PVC) in the 1960s, and followed by thermoplastic polyolefin (TPO) in the 1990s, marked the beginning of an accelerating trend towards reflective roofing. White and highly reflective membranes are considered advantageous for their impact on building energy-efficiency improvements and also urban-heat-island reduction.[1–3] Thermal insulation directly reduces heat flow, while reflective membranes can reduce the external to internal temperature differential and thereby indirectly lower heat flow. Importantly, the cost effectiveness of continuing to add insulation thickness has reached a point of rapidly diminishing returns, and other strategies, such as reducing or eliminating leakage of conditioned air using air barriers, are now being implemented.[4] The goal of this study is to expand on the work of others (reviewed here) showing that thermal short circuits caused by metal insulation fasteners are significant. Methods to reduce the bridging in a cost-effective way are discussed.

The study considers the effective insulation value (R-value, °F ft^2 hr/Btu) of a common low-slope roofing assembly. Such roofs are generally considered to have a slope of less than 2:12. The analysis was done for an assembly consisting of a steel deck, two layers of polyisocyanurate foam insulation (polyiso), and TPO single-ply membrane. Some assemblies included a high-density (HD) polyiso board at the deck level. The goal was to evaluate differences between the design and effective total system thermal insulation values caused by attachment methods commonly in use in the roofing industry. Design R-value refers to the R-value intended for the building or sub-component, such as the roof assembly by the architect or other design professional. The effective R-value refers to the insulation value that is actually achieved after such practical matters as installation methods are taken into account. In this study, the impact of various methods of fastening a roof assembly are evaluated for their effect on the difference between the design R-value intended by the design professional and the effective R-value achieved after actual construction. It is important to note that in this study, R-value refers to the thermal resistance of the material or entire assembly, depending on context.

BACKGROUND

When specifying an insulation value for a low-slope system, designers rely on published material insulation values provided by the manufacturer. They may calculate the total system R-value by also taking into account the insulating value of cover boards, when used, and all other subcomponents. Importantly, the International Energy Conservation Code (IECC)[5] and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1 state that insulation above deck must be continuous. ASHRAE 90.1 defines continuous insulation (ci) as "insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and service openings."[6]

A possible conclusion from ASHRAE's ci definition is that thermal bridging due to fasteners is not significant or is unavoidable and, therefore, tolerated. An analysis by Burch, Shoback, and Cavanaugh found that metal fasteners reduced the overall thermal resistance of insulated metal deck assemblies from 3–8%, depending on insulation thickness.[7] They used a finite difference model to analyze overall thermal resistance for assemblies using 50 fasteners per 100 sq. ft. (5.38 per square meter). The results were in reasonable agreement with earlier work based on simpler estimation methods.

A more recent analysis of thermal bridging by Olson, Saldanha, and Hsu used finite-element modeling to evaluate the impact of metal fasteners and other penetrations in a model single-ply system.[8] Their assembly comprised the following components, listed in ascending order:

1. Interior air film
2. 22-ga corrugated steel deck
3. ½-in.-(1.27-cm-)thick gypsum board to serve as substrate for a vapor retarder (R 0.45)
4. 4.5-in.-(11.4-cm-)thick polyiso insulation, installed in two layers; insulation joints assumed to be staggered with no losses (R-25.2.)
5. Either ½-in.-(1.27-cm-)thick gypsum board (R-0.45) or ½-in.-(1.27-cm-) thick polyiso cover board (R-2.5), depending on the model
6. Roofing membrane with insulation value of 0
7. Exterior air film

Their analysis examined heat transfer in three zones of a model rectangular roof: field, corner, and perimeter, with #12 insulation fasteners and 3-in. (7.6-cm) metal plates. Such zones have different fastener densities, depending on wind uplift requirements related to location and building codes. Olson, Saldanha, and Hsu based their analysis on a 19,200-ft^2 (1,784-m^2)

Roof Zone	Fastener Density Per ft^2 (per m^2)	% Loss from Designed R-Value	
		Gypsum Cover Board	Polyiso Cover Board
Field	0.375 (4.04)	13.95	12.82
Perimeter	0.75 (8.08)	22.94	22.72
Corner	0.1 (10.78)	28.85	27.64

Table 1 – The percent loss in effective insulation value in different roof zones, as modeled by Olson et al.[8]

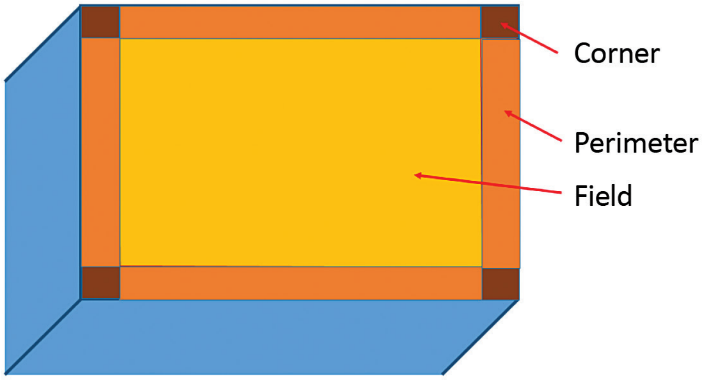


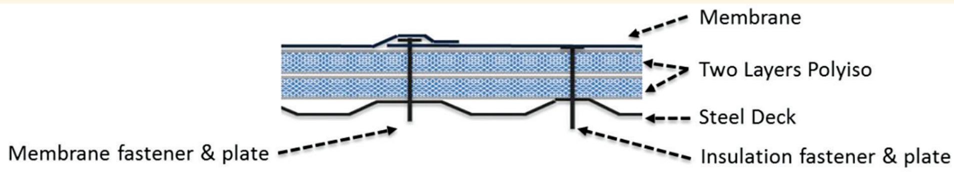
Figure 1 – A big-box, rectangular roof showing the three zones: field, perimeter, and corner.

rectangular roof with fastener densities required to resist wind uplift according to Factory Mutual (FM) Class 1–90. The interior temperature was assumed to be 69.8°F (21°C) with an exterior ambient temperature of -0.4°F (-18°C). Such a roof was found to have reductions in R-value as compared to an assembly having zero fasteners as shown in *Table 1*.

The loss of R-value shown in *Table 1* was calculated for fasteners that extended from above the cover board down through the steel deck. The area-weighted overall losses in effective insulation value shown were found to be 17% and 16% for gypsum and polyiso cover boards, respectively.

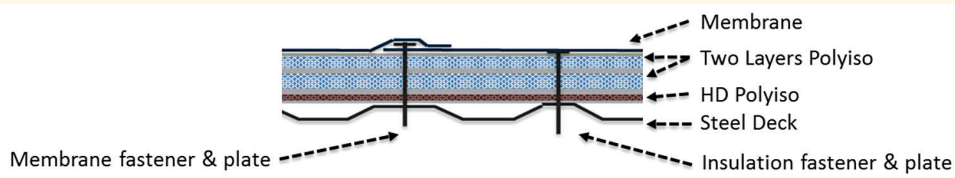
Singh et al. carried out a similar analysis—again using finite-element modeling—but considered system U-factor [i.e., the overall coefficient of heat transfer, Btu/(hr ft^2 °F) or W/(m^2 K)],

Case IA



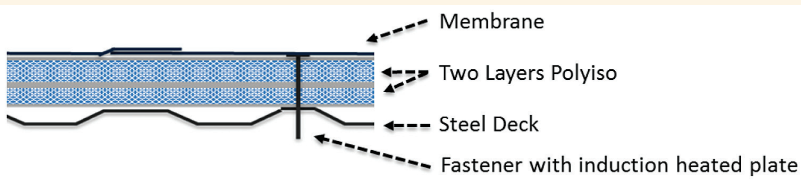
Insulation—R-30 total, installed as two layers, 3 in. (7.62 cm) R-17.4 and 2.2 in. (5.59 cm) R-12.6. Mechanically attached.
Membrane—mechanically attached.

Case IB



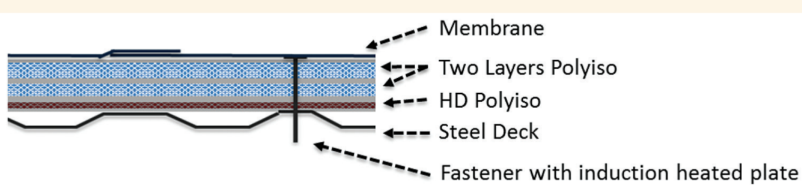
Insulation—R-30 total, installed as three layers, ½ in. (1.27 cm) R-2.5, 2.5 in. (6.35 cm) R-14.4, and 2.3 in. (5.84 cm) R-13.1, mechanically attached.
Membrane—mechanically attached.

Case IIA



Insulation—R-30 total, installed as two layers, 3 in. (7.62 cm) R-17.4 and 2.2 in. (5.59 cm) R-12.6. Mechanically attached using induction welding plates.
Membrane—attached via induction welding to insulation plates.

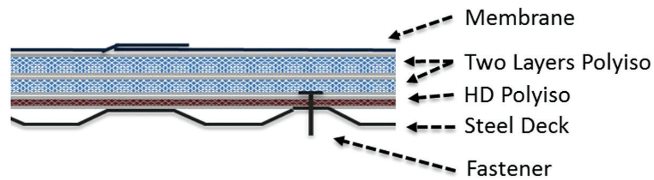
Case IIB



Insulation—R-30 total, installed as three layers, ½ in. (1.27 cm) R-2.5, 2.3 in. (5.84 cm) R-13.1, and 2.5 in. (6.35 cm) R-14.4. Mechanically attached using induction welding plates.
Membrane—attached via induction welding to insulation plates.

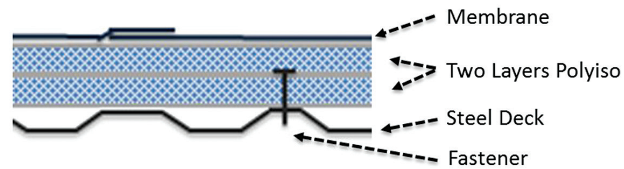
Table 2 – Description of roofing assemblies analyzed in this study, with above-steel-deck components listed.

Case III



Insulation—R-30 total, installed as three layers, ½ in. (1.27 cm) R-2.5, mechanically attached, 2.3 in. (5.84 cm) R-13.1 and 2.5 in. (6.35 cm) R-14.4, each adhered.
Membrane—fully adhered.

Case IV



Insulation—R-30 total, 1.5 in. (3.81 cm) R-8.6 mechanically attached, 3.8 in (9.65 cm) R-21.4, adhered.
Membrane—fully adhered.

Table 2 continued – Description of roofing assemblies analyzed in this study, with above-steel-deck components listed.

and modeled based on temperatures within three climate zones represented by Orlando, FL; Atlanta, GA; and St. Paul, MN, U.S.[9] They assumed a total roof area of 10,000 ft² (929 m²) and a higher overall fastener density compared to Olson et al. The reduction from designed R-value for a similar system to that of Olson et al. was found to be about 35%. For a roof zone having a fastener density of 1.0/ft² (10.78/m²), Singh et al. calculated a loss from designed R-value of 32%—this comparing well with about 28% and 29% for the corner zone per Olson et al.

The modeled losses from designed R-value, per Olson et al. and Singh et al., are such that designers considering the mechanical attachment of insulation and a roof membrane should possibly consider significant reductions in the assumed system R-value. Such reductions have implications for both building energy efficiency and the specification of heating, ventilation, and air conditioning (HVAC) systems. This study aims to examine alternative installation strategies based on adhesive attachments that reduce the loss of effective R-value. Loss of insulation R-value has an economic cost that was modeled and compared to the increased cost of alternate attachment methods. Replication of the prior work was outside of the scope of this effort; the goal was to evaluate the reduction from designed R-value using the loss data obtained in the two studies cited here.

GENERAL DESCRIPTION OF THE ROOF ASSEMBLIES

The roof systems used in this study were based on three single-story buildings less than 35 ft. (10.67 m) high. The largest was based on that of a so-called "big box" building, with a roof area of 125,000 ft² (11,613 m²) in a rectangular configuration of approximately 290 × 431 ft. (88.4 × 131.4 m). Two smaller buildings were also considered, with areas of 50,000 ft² (4,645 m²) and 15,000 ft² (1,394 m²), each with width-to-length ratios of 1:1.5. In every case, the roof was assumed to be a new installation, i.e., new construction or a total roof replacement. The zones of a roof assembly are as shown in *Figure 1*.

The mechanical attachment used #12 fasteners and 3-in.-(7.6-cm-)diameter plates throughout. Fastener patterns and densities were calculated based on a wind uplift requirement of 120 pounds per sq. ft. (5.746 kPa), a 22-ga metal deck, and a 60-mil (1.52-mm) single-ply thermoplastic membrane having a width of 10 ft. (3.05 m). The roof assemblies, shown in order for each case considered, are described in *Table 2*.

Two membrane scenarios were used: a new membrane with an initial solar reflectance of 76 and emittance of 90, and a three-year aged reflectance of 68 and emittance of 83, the latter representing long-term roof performance. These values would be typical of a TPO membrane.[10]

Description of the Membrane Attachment Methods

For Cases IA and IB, the membrane was mechanically attached using #12 (5.48-mm) fasteners and 3-in.-(7.6-cm-)diameter plates, installed 6 in. (15.24 cm) on center, as shown in *Figure 2*.

In Cases IIA and IIB, the plates were coated to enable induction welding of the membrane to the plates. For Cases III and IV, the membrane was attached to the top layer of insulation using a conventional adhesive designed for smooth, unbacked membranes.

Description of the Insulation Attachment Methods

In Cases IA and IB, the insulation boards were attached using five fasteners through each of the topmost 4- x 8-ft. (122- x 244-cm) layer boards down through the steel deck.

Cases IA and IB were essentially identical except for the possibility of installing a vapor retarder on top of the first layer of ½-in.-(1.3-cm-)thick insulation in Case IB. In Cases IIA and IIB, the fasteners were applied through the topmost layer of insulation down through the steel deck. For Cases III and IV, the bottom insulation layer only was attached to the steel deck. All subsequent layers were adhered using conventional insulation adhesive.

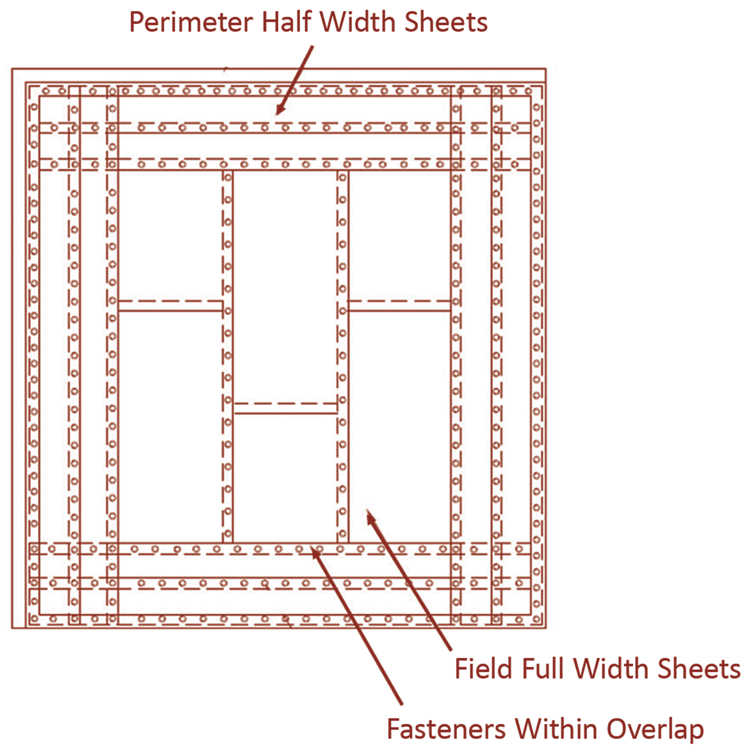


Figure 2 – Schematic showing single-ply membrane layout and mechanical fastening.

The insulation fastener densities (i.e., use rates) per 4- x 8-ft. (122- x 244-cm) polyiso board, were identical for each building size, and are summarized in *Table 3*.

Total Fastener Densities and Loss of Effective R-Value

Taking into account both membrane and insulation fasteners, the overall roof fastener densities were calculated to be as shown in *Table 4*.

The work of Olson et al. was used as a basis for predicting loss of insulation value in this study. Their modeling focused on a single roof and provided changes in U-factor for three different fastener densities corresponding to the field, perimeter, and corner zones. Their data were recalculated here as percent reductions from design R-value as a function of fastener density, with the resulting relationships being shown in *Figure 3*.

The relationship shown in *Figure 3* was calculated to be y = 23.851x + 5.0192 (or y = 2.216x + 5.0192 when fastener density was expressed as #/m^2).

BUILDING ENERGY-USE MODELING

Petrie et al. used the simplified transient analysis of roofs model (STAR)[11,12] as the basis of the energy calculator tool known as CoolCalc, published by Oak Ridge National Laboratory (ORNL).[13] The tool was developed to provide estimated energy-cost differences associated with changing reflectivity and emissivity properties for roofing membranes and thermal insulation values. Subsequently, a modified version, CoolCalcPeak, was published that calculated savings when demand charges were factored in.[14] Demand charges are a cost per kilowatt at the highest level of demand during a specific billing period (typically 15 minutes) and are added to the total kilowatt-per-hour usage level in that period. The tool also enables the costs/savings associated with changing insulation levels to be calculated. The tools incorporate climate data for 263 U.S. cities to establish outdoor temperatures. Indoor temperatures of 73°F (23°C) for summer and 70°F (21°C) for winter are used as indoor boundary conditions.

CoolCalc and CoolCalcPeak make no assumption as to building geometry. They simply calculate energy loads on a building due to roof design (reflectance, emissivity, and insulation values) and local climate factors. Those energy loads might be a large percentage of the total for a wide, low building, or a small percentage for a tall, narrow building. The calculators are estimating energy loads due to the roof alone. For this study, CoolCalcPeak was used throughout.

MODEL INPUT DATA

According to the Department of Energy Buildings Energy Data Book, electricity is used to supply less than 20% of space heating energy demand for commercial buildings.[15] Therefore, natural gas was the assumed heat source for this study, with costs based on the annual average by state for commercial customers using 2016 U.S.

Assembly	Roof Zone, Fastener per 4- × 8-ft. Polyiso Board			Roof Zone, Fastener per m^2 Polyiso Board		
	Field	Perimeter	Corner	Field	Perimeter	Corner
Case IA Case IB	5	5	5	1.68	1.68	1.68
Case IIA Case IIB	8	15	20	2.69	5.04	6.72
Case III	16	24	32	5.37	8.06	10.75
Case IV	8	12	16	2.69	4.03	5.37

Table 3 – Insulation fastener densities (i.e., use rates), per 4- × 8-ft. (122- × 244-cm) polyiso board.

Building Area	Fastener Density, per ft^2			Fastener Density, per m^2		
	125,000 ft^2	50,000 ft^2	15,000 ft^2	11,613 m^2	4,645 m^2	1,394 m^2
Case IA Case IB	0.4166	0.4266	0.4843	0.0387	0.0396	0.0450
Case IIA Case IIB	0.2751	0.2693	0.2860	0.0256	0.0250	0.0266
Case III	0.5289	0.5221	0.5417	0.0491	0.0485	0.0503
Case IV	0.2644	0.2611	0.2708	0.0246	0.0243	0.0252

Table 4 – Overall fastener densities, calculated as number of fasteners per square foot of roof area.

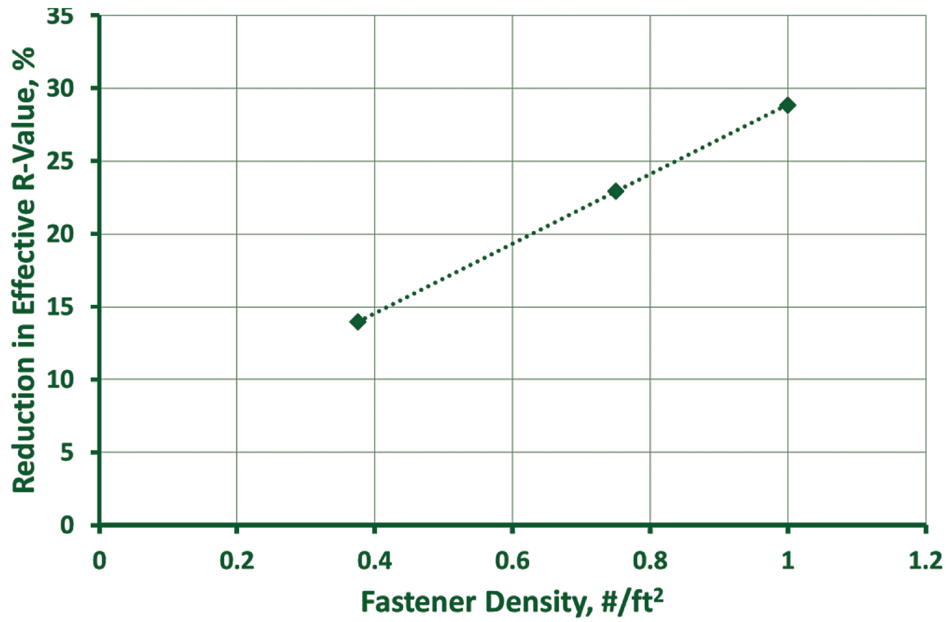


Figure 3 – Analysis of the effects of insulation fastener configuration on insulation value results shown by Olson et al.[8] to show percent reduction from design R-value (y) as a function of overall roof fastener density (x), where the straight-line fit is expressed as y = 23.851x + 5.0192.

Energy Information Administration data.[16] Electricity costs were based on annual averages for 2016, for commercial customers by state, obtained from the U.S. Energy Information Agency.[17]

Demand charges were obtained per utility for each city being studied, from a Utility Rate Database.[18] Rates are checked and updated annually by the National Renewable Energy Laboratories, in partnership with Illinois State University's Institute for Regulatory Policy Studies. In cases where multi-tiered demand charges were cited, these were averaged across the applicable months to provide the single input required by CoolCalcPeak.

The energy cost data used are shown in *Table 5*. Electric demand charges were obtained for the cities being evaluated, based on medium-sized commercial customers' tariffs. Gas costs were the annual averages for 2016 for commercial customers by state.

Although this study is, necessarily, limited to the use of the most recent published energy cost information, projections to 2040 do not suggest significant changes. The Annual Energy Outlook 2017, U.S. Energy Information Administration, projects gas costs rising from $8 to $12 per thousand cubic feet between 2016 and 2040.[19] Similarly, average electric costs were projected to increase from $0.105 to $0.115 per kWhr across the same period.

The CoolCalcPeak calculator compares energy costs relative to a nominally nonreflective (e.g., dark, absorptive) roof membrane. Two scenarios were used: an initial solar reflectance of 76 and emittance of 90, and a three-year aged reflectance of 68 and emittance of 83—these representing long-term roof performance. This would be typical of a thermoplastic membrane such as TPO. A design insulation value of R-30 was used throughout, which was a conservative average of the insulation requirements in the 2015 International Energy Conservation Code.

The energy savings were first calculated using the design R-value and then for the effective R-value, each being calculated relative to a dark absorptive membrane per CoolCalcPeak. The difference between these two values represented the loss in energy efficiency due to the difference between design and effective R-values.

The building air-conditioning coefficient of performance was set as 2.5, and the natural gas heating efficiency was set as 0.8. Both are high-efficiency values and would be more typical of today's heating and air-conditioning systems installed in new construction.

RESULTS

This analysis evaluates the costs associated with a prescribed roof design based on R-30 and the resultant effective R-value due to attachment methodology. These costs are the lost economic value of R-value purchased but not achieved due to fastener thermal short circuits. Also, there is the cost of those fasteners and, in the case of adhered systems, the adhesive cost. None of the costs include labor charges due to the difficulty of determining typical values. Labor costs vary significantly by location and by the approach taken by installers. For example, some contractors use a fixed crew size and vary the installation time, while others use different-size crews, depending on the type of installation.

Loss of Insulation Value Due to Fasteners

Using the fastener densities shown in *Table 4*, together with the relationship between fastener density and percent reduction in R-value, the effective R-values are as shown in *Table 6*.

The percent reduction from designed insulation values are shown in *Table 7*, these being the effective values shown in *Table 6* as a percent of the R-30 design.

The effective R-values for each assembly and roof size are significantly lower than the design R-30 in most cases, which questions the

City, State	Climate Zone	Electric Cost, USD/kWhr	Demand Charge, USD/kW	Gas Cost, USD/1000 cu. ft.	Gas Cost, USD/Therm
Miami, FL	1	0.0911	9.2	10.42	1.042
Houston, TX	2	0.0771	5.477	6.89	0.689
Fresno, CA	3	0.1515	13.32	8.42	0.842
Nashville, TN	4	0.1003	9.67	7.8	0.78
Albany, NY	5	0.1447	10.27	6.18	0.618
Minneapolis, MN	6	0.0988	12.32	6.44	0.644

Table 5 – Energy cost data for commercial customers, averaged for 2016.

Building Size	Effective Insulation Value, R-Value		
	125,000 ft^2	50,000 ft^2	15,000 ft^2
Case IA Case IB	25.514	25.442	25.029
Case IIA Case IIB	26.526	26.568	26.447
Case III	29.559	29.563	29.552
Case IV	28.709	28.718	28.691

Table 6 – Effective R-values for each of the modeled assemblies, all based on an R-30 design.

Building Size	Reduction in Insulation Value		
	125,000 ft^2 (11,613 m^2)	50,000 ft^2 (4,645 m^2)	15,000 ft^2 (1,394 m^2)
Case IA Case IB	85.05%	84.81%	83.43%
Case IIA Case IIB	88.42%	88.56%	88.16%
Case III	98.53%	98.54%	98.51%
Case IV	98.53%	98.54%	98.51%

Table 7 – Effective R-values shown as a percentage of the R-30 design. (This was calculated using the effective insulation values shown in Table 6.)

assumption that the insulation is effectively continuous. For Case III, which uses a ½-in. (1.3-cm) layer of mechanically attached high-density polyiso with all subsequent layers of insulation being adhered, the reduction in insulation value was small. Note that the loss of insulation value is largest for Cases IA and IB, at about 15%. This is lower than the approximately 30% shown by Olson et al. and Singh et al., but for both studies, the fastener densities corresponded to those used in the corners of mechanically attached assemblies. The results shown in *Table 7* are representative of the entire roof assembly.

Examination of the effective insulation values shown in *Table 7* indicates that the greatest percent reduction in R-value is for the smallest building size. This is due to the smaller roof areas having the largest percentage of perimeter and corner areas, with their associated higher fastener densities for mechanically fastened assemblies.

Loss of Installed Economic Value Due to Fasteners

The reduction from designed R-value, indicated in *Tables 6* and *7*, has an immediate cost, i.e., the economic value of the "lost" insulation. This was calculated in terms of U.S. dollars per R-value lost, i.e., purchased material that did not contribute to insulation, assuming that the installation costs would remain the same regardless of any difference between design and effective R-value. The costs are summarized in *Table 8*. For the standard polyiso boards, a material-based cost to the building owner of $0.10 per sq. ft. per R-1 was assumed. For the ½-in. product used in Cases IB, IIB, and III, a material cost of $1.00 per sq. ft. per R-1 was assumed.

The insulation cost in lost R-value for a fully mechanically attached system is $56,057 for the 125,000-sq.-ft. (11,613-m^2) big-box-type construction as indicated in Table 8 for Case IA. This is a significant loss in economic value, and Case IB is almost double that, due to the use of the ½-in. (1.3-cm) HD polyiso. This is also seen in a comparison of the costs for Case IIB with IIA. It should be noted that the loss in R-value for HD polyiso could be compensated for by its benefits, such as rigidity and compressive strength. However, the use of HD polyiso in this manner is not proven in terms of code requirements or flute-spanning capability.

The lowest cost and most effective assembly in terms of R-value is Case IV. That assembly uses a first layer of mechanically attached 1½-in. (3.8-cm) polyiso that could act as a base for a vapor retarder. The remainder of the assembly is all adhered, including the top layer of HD polyiso. In general, it is clear that reductions in effective R-value due to fasteners are "expensive" for HD versus standard polyiso.

In addition to the cost of reduction from design to effective R-value, the mechanically attached assemblies have a higher fastener material cost versus those that only mechanically attached the first insulation layer. In *Table 9*, the fastener material cost is shown, which takes into account fastener length (shorter being lower-cost),

Building Size	Cost of Lost Insulation Value, USD		
	125,000 ft^2 (11,613 m^2)	50,000 ft^2 (4,645 m^2)	15,000 ft^2 (1,394 m^2)
Case IA	$56,079	$22,792	$7,456
Case IB	$98,138	$39,885	$13,048
Case IIA	$43,424	$17,162	$5,329
Case IIB	$75,991	$30,033	$9,325
Case III	$55,103	$21,841	$6,727
Case IV	$16,140	$6,410	$1,963

Table 8 – Economic cost of reduction from design to effective insulation value for each assembly, in terms of the cost of an equivalent thickness of polyiso.

Building Size	Cost of Fasteners, USD		
	125,000 ft^2 (11,613 m^2)	50,000 ft^2 (4,645 m^2)	15,000 ft^2 (1,394 m^2)
Case IA Case IB	$13,892	$5,691	$1,938
Case IIA Case IIB	$19,099	$7,478	$2,384
Case III	$7,470	$2,950	$918
Case IV	$3,900	$1,540	$479

Table 9 – Total fastener costs for each roofing system – material only.

Building Size	Cost of Adhesive, USD		
	125,000 ft^2 (11,613 m^2)	50,000 ft^2 (4,645 m^2)	15,000 ft^2 (1,394 m^2)
Case IA Case IB	$0	$0	$0
Case IIA Case IIB	$0	$0	$0
Case III	$85,000	$34,000	$10,200
Case IV	$60,000	$24,000	$7,200

Table 10 – Adhesive costs for each roofing assembly – material only.

added fastener plate for inductive attachment costs for Cases IIA and IIB, as well as fastener densities for each assembly.

Cost Due to Adhesive Use

For Cases III and IV, there is the added cost of adhesives. For the purposes of this analysis, two types of adhesive attachment were considered:

1. Low-rise foam adhesive for adhering polyiso insulation to the substrate. This was used in Case III to attach the first layer of polyiso to the mechanically attached HD polyiso board and the second layer of polyiso insulation to the first. In Case IV, the low-rise foam adhesive adhered the second layer of polyiso insulation to the first. The cost of the adhesive was assumed to be $0.20 per sq. ft. of roof assembly.
2. A solvent-based adhesive for attaching the membrane to the substrate. This was assumed to cost $0.28 per sq. ft. of roof assembly.

Thus, the adhesive costs are as shown in *Table 10*.

Total Material Costs Associated with System Attachment and Lost R-Value

The total costs involved in deviating from the design R-30, due to lost R-value caused by thermal shorts, and fastener and adhesive costs for each case and building size, are shown in *Figures 4* to *6*.

The lowest cost-deviation system is Case IIA for all building sizes, this being an inductive plate attachment. It is followed by Case IA, a conventional mechanically attached system. However, based solely on lost insulation value, Case IV is the preferred system for all building sizes. This is based on two layers of polyiso, the first being mechanically attached and each subsequent layer being adhered. Also, as noted previously, whenever HD polyiso is used, there is a high cost associated with mechanically attaching it.

It is instructive to compare Case IA versus IV. As noted earlier, Case IA is widely regarded as the lowest-cost option for single-ply membrane installation. The calculations summarized in *Figure 6* indeed show that the fastener costs in Case IA are far lower than the fastener and adhesive costs for Case IV. However, overall Case IA is higher in costs

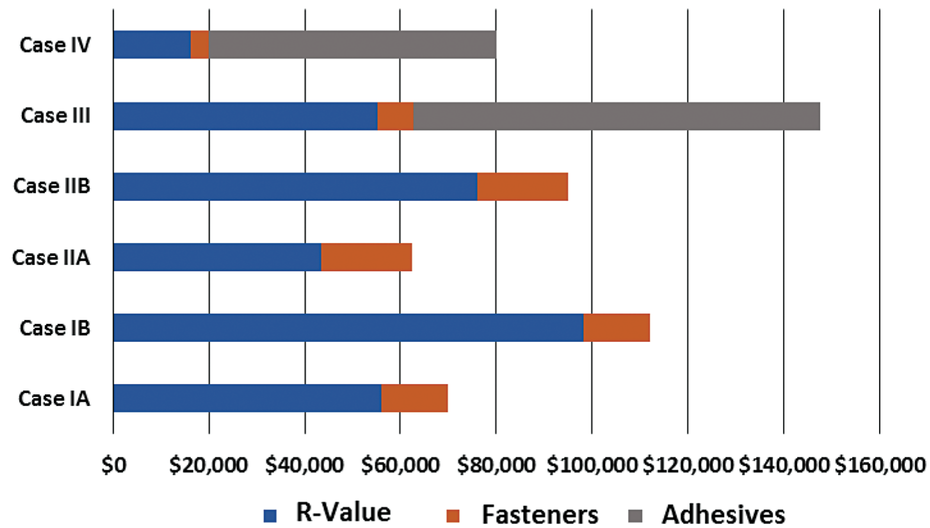


Figure 4 – The costs associated with deviating from a design R-30, due to lost R-value and fastener and adhesive costs for a 125,000-sq.-ft. (11,613-m²) building.

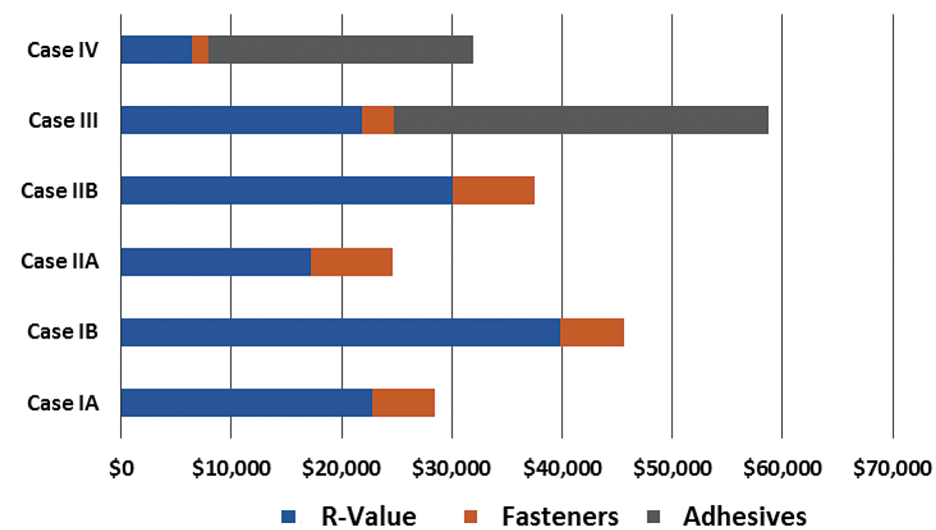


Figure 5 – The costs associated with deviating from a design R-30, due to lost R-value and fastener and adhesive costs for a 50,000-sq.-ft. 11,613-m²) building.

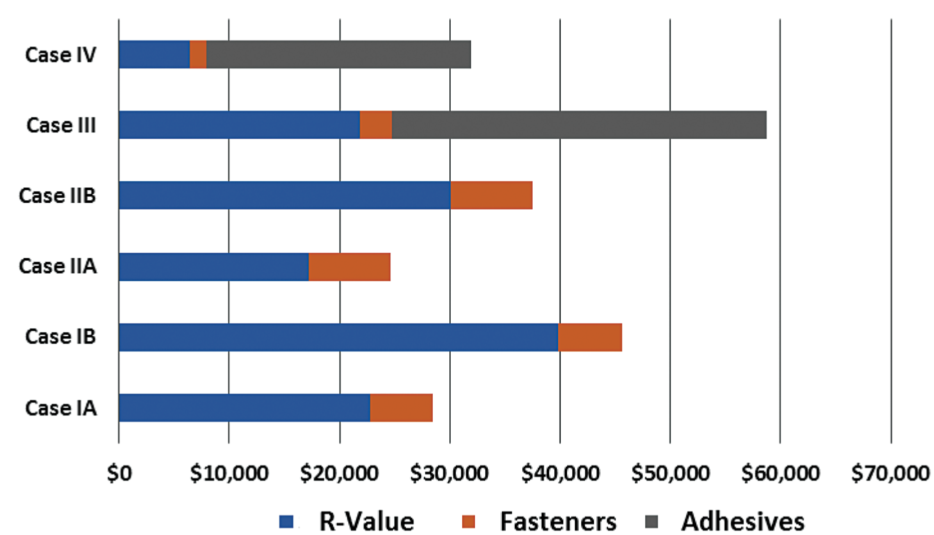


Figure 6 – The costs associated with deviating from a design R-30, due to lost R-value and fastener and adhesive costs for a 15,000-sq.-ft. (1394-m²) building.

Assembly	Cases IA & IB			Cases IIA & IIB			Case III			Case IV		
Building Size, s.f.	125,000	50,000	15,000	125,000	50,000	15,000	125,000	50,000	15,000	125,000	50,000	15,000
Building Size, m^2	11,613	4,645	1,394	11,613	4,645	1,394	11,613	4,645	1,394	11,613	4,645	1,394
Miami, FL	$18,750	$7,500	$2,250	$15,000	$6,000	$1,800	$3,750	$1,500	$450	$7,500	$3,750	$1,125
Houston, TX	$11,250	$4,500	$1,350	$9,375	$3,750	$1,125	$1,875	$750	$225	$5,625	$2,250	$675
Fresno, CA	$22,500	$9,000	$2,700	$18,750	$7,500	$2,250	$3,750	$1,500	$450	$9,375	$3,750	$1,125
Nashville, TN	$13,125	$5,250	$1,575	$11,250	$4,500	$1,350	$1,875	$750	$225	$5,625	$2,250	$675
Albany, NY	$11,250	$4,500	$1,350	$9,375	$3,750	$1,125	$1,875	$750	$225	$5,625	$2,250	$675
Minneapolis, MN	$11,250	$4,500	$1,350	$9,375	$3,750	$1,125	$1,875	$750	$225	$3,750	$1,500	$450

Table 11 – Total 15-year cost of lost energy efficiency due to the effective R-values compared to the design R-30, all values being in U.S. dollars (USD). Three-year aged membrane reflectance and emissivity values were assumed.

than is generally recognized due to the lost R-value. This lost R-value also has long-term implications due to energy-efficiency reduction, which is discussed next.

Loss of Energy Efficiency Due to Fasteners

The effective R-values shown in *Table 6* were used to calculate the cost of a building's reduced energy efficiency relative to the design R-30 over a 15-year time frame. The latter was chosen based on the published R-values representing the time-weighted 15-year long-term thermal resistance.[20,21] Given that reflective membranes lose some of their reflectivity over time, the three-year aged membrane data was used, with the results being summarized in *Table 11*.

A close examination of *Table 11* suggests that the ORNL CoolCalcPeak model is causing some rounding discrepancies due to the sometimes-small differences between R-design and R-effective. However, the data are believed to be directionally correct based on the overall trends.

It was previously noted by Taylor and Hartwig that energy efficiency costs do not correlate with location and climate but are dependent on local energy costs (for both heating and cooling) and, specifically, electricity demand

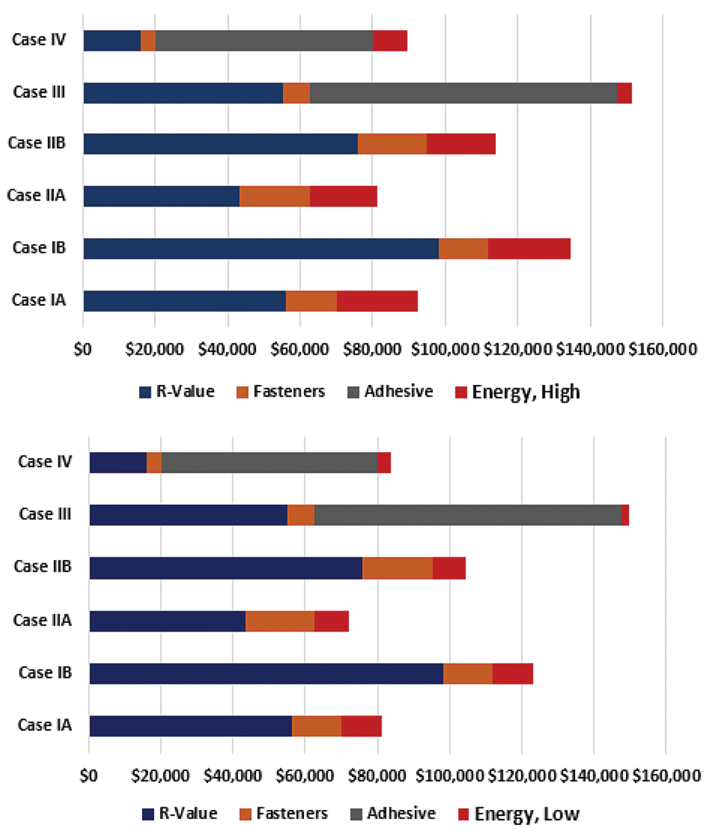


Figure 7 – The costs associated with deviating from an R-30 design, due to lost R-value, fastener and adhesive costs, and lost energy efficiency for a 125,000-sq.-ft. (11,613-m²) building. The upper chart is for the largest potential cost of lost energy efficiency, and the lower chart is for the smallest potential cost of lost energy efficiency. All costs are in USD.

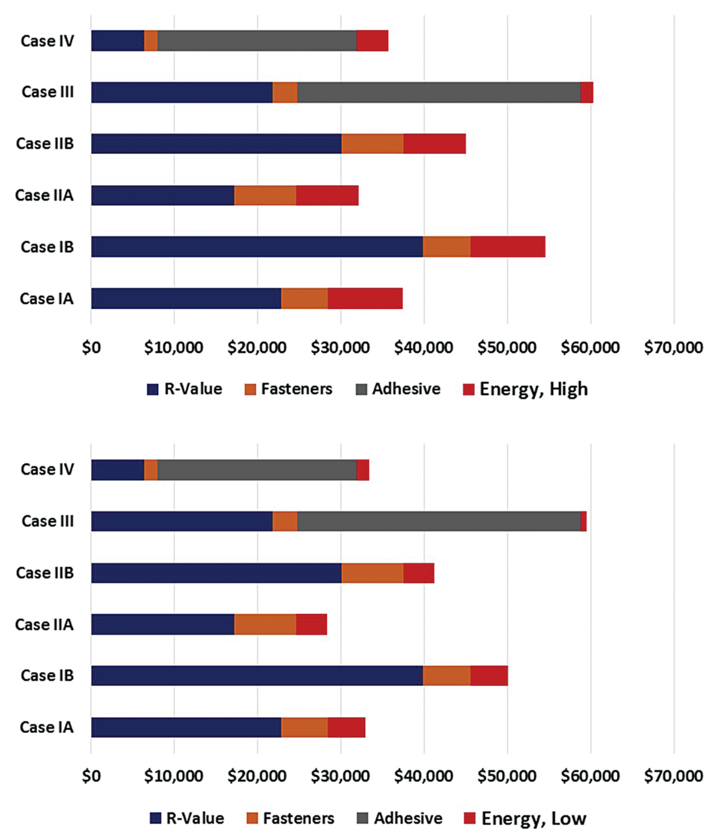


Figure 8 – The costs associated with deviating from an R-30 design, due to lost R-value, fastener and adhesive costs, and lost energy efficiency for a 50,000-sq.-ft. (4,645-m²) building. The upper chart is for the largest potential cost of lost energy efficiency, and the lower chart is for the smallest potential cost of lost energy efficiency. All costs are in USD.

charges, membrane reflectivity, and insulation level.[22] Therefore, the highest and lowest costs of lost energy efficiency were used to compare the total overall costs, as shown in *Figures 7* to *9* for the three building sizes.

In the analysis for a 15,000-sq.-ft. (1,394-m^2) building (*Figure 9*), the fully adhered system described by Case IV has the lowest total cost compared to the mechanically attached system, Case IA. For the 50,000-sq.-ft. (4,645-m^2) building, Cases IA and IV are essentially equivalent, while for the 125,000-sq.-ft. (11,613-m^2) building, the mechanically attached system, Case IA, has a slightly lower overall cost versus the fully adhered Case IV.

DISCUSSION

As described earlier, energy and building codes assume that roof insulation is continuous and that, therefore, the thermal insulation value intended by the design professional is achieved. However, as indicated by prior work, the use of metal fasteners to attach insulation causes significant loss of insulation thermal value. Furthermore, single-ply roofing uses mechanical fastening as a cost-effective attachment method. To achieve required wind uplift resistance, fastener densities must be quite high. This study has evaluated the thermal insulation losses caused by metal fasteners and found the losses to be high. In fact, the economic costs of lost insulation value are significant. As shown here by modeling, the mechanically attached roof system with two layers of polyiso insulation modeled loses a little over $56,000 in purchased material in the case of the 125,000-sq.-ft. (11,613-m^2) roof. For 2017, this type of system represents about 80% of the market.[23] The cost of lost insulation value is increased in each system that uses high-density polyiso (i.e., Cases IB, IIB, and III), as would be expected due to the higher cost of such a product.

The system having the lowest loss in R-value is Case III, which uses a first layer of mechanically fastened high-density polyiso board. This achieves a system insulation level around 98.5% of the design insulation value. However, that system has a high economic cost due to the use of adhesives combined with the high-density polyiso insulation board that is applied in a manner that is beyond its typical use as a coverboard.

Interestingly, the lowest total economic cost system is represented by Case IIA. This uses two layers of polyiso insulation and inductively heated plates for attachment. The overall fastener densities for this system are lower than for conventional screws and plates. This system could be improved upon by lowering the thickness of the bottom insulation board so long as wind uplift, flute span, and other design requirements are met.

Once the loss of energy efficiency is factored in, then the fully adhered system is of similar or slightly lower total economic cost than the mechanically attached system, depending on building size. This suggests that the mechanically attached assembly is only cost effective from an initial installation perspective. After the loss of energy efficiency over a 15-year time frame is factored in, then the Cases IIIA and III systems are similar.

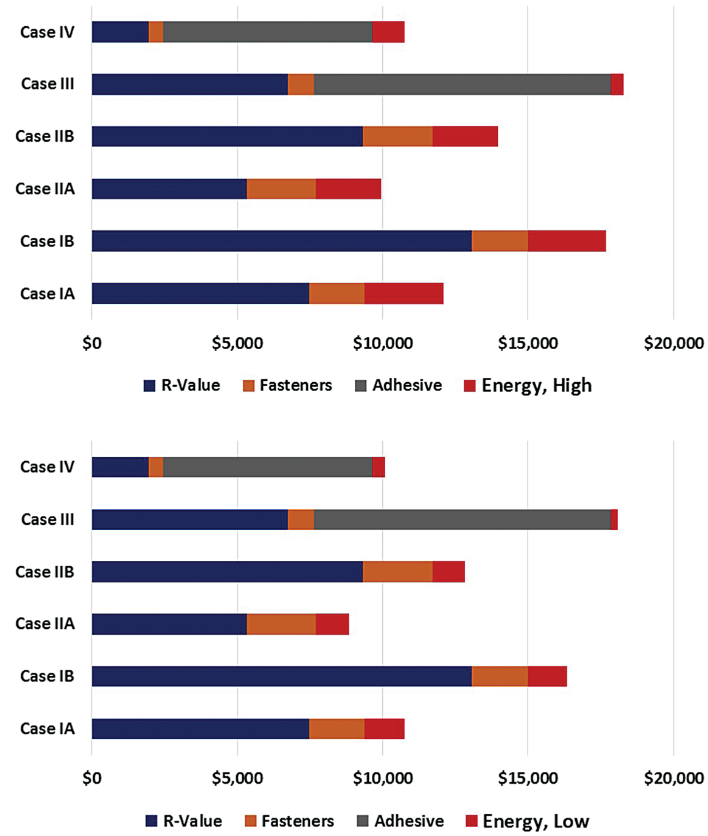


Figure 9 – The costs associated with deviating from an R-30 design, due to lost R-value, fastener and adhesive costs, and lost energy efficiency for a 15,000-sq.-ft. (1,394-m^2) building. The upper chart is for the largest potential cost of lost energy efficiency, and the lower chart is for the smallest potential cost of lost energy efficiency. All costs are in USD.

Taken overall, a number of points can be made if the goal is to improve the energy efficiency of buildings while factoring in the economic cost of doing so:

1. Systems that are solely mechanically attached carry a high hidden economic cost due to the loss in insulation caused by thermal short-circuiting. In other words, the insulation level specified by the architect is not actually achieved due to the high number of fasteners used. The insulation level that was paid for is not actually achieved. Furthermore, this has long-term energy-efficiency costs for the building owner. The amount of additional insulation required to compensate for thermal bridging is unknown and would need to be modeled on a case-by-case basis. However, as stated here, this would increase construction material costs for the owner.
2. When the 15-year cost of lost energy efficiency is added to the system costs associated with effective versus designed insulation levels, then a fully adhered system can be cost-effective, depending on building, profile, and height. This argues that the initial cost savings achieved by using mechanical attachments are negated by the longer-term cost of reduced building energy efficiency.
3. Case IV, a lower layer of mechanically attached polyiso insulation with all subsequent layers being fully adhered, had the lowest overall total cost once material and long-term energy-efficiency costs were calculated, and is worthy of further analysis. The loss in insulation level is the lowest and could potentially be reduced further if the lower layer could also be fully adhered. This might be achievable if a self-adhered vapor retarder were used at the deck level, for example.

4. Fully adhered systems do not flutter or billow during high-wind events, thereby eliminating the drawing of interior conditioned air up into the roof assembly (e.g., infiltration). This latter phenomenon would naturally further reduce energy efficiency (see Pallin et al.[24] and Molleti et al.[25] for examples).
5. Fully adhered systems such as those described by Case IV have higher wind-uplift strengths, so this may provide options in some areas of the country, and with projects needing to adhere to increased uplift design requirements.
6. With such significant deviations from design insulation value, there could be unintended impacts on dew point calculations for mechanically attached assemblies. It should be noted that the modeled R-values used represent system averages. In practice, fasteners cause localized and far more dramatic shifts in dew point (e.g., corners) which would be out of the scope of this type of analysis to consider. However, by "burying" fasteners within a system, such as Case IV, any risks of condensation will be reduced.

It should be noted that the analysis shown here was based on material costs and did not take into account the cost of installation. Labor rates vary significantly by location and would need to be taken into account during any validation work. Also, as the costs of materials have been assumed for this study, the assembly costs and ROI could change significantly from those published in this paper.

RECOMMENDATIONS

This study was a modeling exercise to evaluate whether thermal bridging caused by metal fasteners in low-slope single-ply roofing assemblies can be reduced or minimized cost effectively. The data suggest that certain roof assemblies—notably those described by Cases III and IV—are worthy of further study. The following are considerations for future studies:

1. Conduct further study based on Cases III and IV, but include labor rates and more refined material costs.
2. Further develop the roofing systems to identify an assembly of materials that utilizes an insulated substrate board that would span commonly used fluted steel decks.
3. Construct roofing assembly test decks in order to experimentally verify the extent of thermal bridging shown in prior modeling studies.
4. Conduct thermal analysis comparison between #12 screws with 3-in. plate used throughout this and prior studies and #15 screws with 2⅜-in. plate to provide comparison between the modeled assemblies and more common applications.
5. Develop a calculator that would allow design professionals to accurately compare the short- and long-term costs associated with mechanical attachment vs. partially or fully adhered assemblies.

REFERENCES

1. H. Akbari, S. Bretz, B. Fishman, J. Hanford, H. Taha, D. Kurn, and W. Bos. "Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulation, and Results." LBNL No. 34411, Lawrence Berkeley National Laboratory. Berkeley, CA, U.S. 1993.
2. S. Bretz, H. Akbari, and A. Rosenfeld. "Practical Issues for Using Solar-Reflective Materials to Mitigate Urban Heat Islands." *Atmospheric Environment*. Vol. 32, 1998: pp. 95-101.
3. R. Levinson, H. Akbari. "Potential Benefits of Cool Roofs on Commercial Buildings: Conserving Energy, Saving Money, and Reducing Emission of Greenhouse Gases and Air Pollutants." *Energy Efficiency*. Vol. 3, 2010: pp. 53–109.
4. IEA. *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. OECD. Paris, France. 2013.
5. International Code Council. *International Energy Conservation Code*. Washington, DC, U.S. 2015.
6. American Society of Heating, Refrigerating, and Air Conditioning Engineers. ANSI/ASHRAE/IES Standard 90.1-2013, *Energy Standards for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, U.S. 2013.
7. D.M. Burch. P.J. Shoback, and K. Cavanaugh. "A Heat Transfer Analysis of Metal Fasteners in Low-Slope Roofs." *Roofing Research and Standards Development*. ASTM International: West Conshohocken, PA, U.S. 1987: pp. 10–22.
8. E.K. Olson, C.M. Saldanha, and J.W. Hsu. "Thermal Performance Evaluation of Roofing Details to Improve Thermal Efficiency and Condensation Resistance." *Roofing Research and Standards Development*, STP1590. S. Molleti and W.J. Rossiter, Eds. ASTM International: West Conshohocken, PA, U.S. 2015. Volume 8: pp. 10–22.
9. M. Singh, R. Gulati, R.S. Srinivasan, and M. Bhandari. "Three-Dimensional Heat Transfer Analysis of Metal Fasteners in Roofing Assemblies." *Buildings*. June 2016: 49.
10. Cool Roof Rating Council. Available online: http://coolroofs.org/products/results (accessed on 11 October 2017).
11. T. W. Petrie, J.A. Atchley, P.W. Childs, and A.O. Desjarlais. "Effect of Solar Radiation Control on Energy Costs—A Radiation Control Fact Sheet for Low-Slope Roofs." In *Performance of the Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*. ASHRAE: Atlanta, GA, U.S. 2001.
12. T. W. Petrie, K.E. Wilkes, and A.O. Desjarlais. "Effect of Solar Radiation Control on Energy Costs—An Addition to the DOE Cool Roof Calculator." In *Performance of Exterior Envelopes of Whole Buildings IX*. ASHRAE: Atlanta, GA, U.S. 2004.
13. ORNL Roof Savings Calculator. Available online: http://rsc.ornl.gov/ (accessed on 11 October 2017).
14. ORNL Cool Roof Calculator with Peak Demand. Available online: http://web.ornl.gov/sci/buildings/tools/cool-roof/peak/ (accessed on 11 October 2017).
15. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. *Buildings Energy Data Book*; EERE: Washington, DC, U.S., 2011.
16. Energy Information Agency. Available

online: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm (accessed on 11 October 2017).
17. Energy Information Agency. Table 5.6B. Available online: https://www.eia.gov/electricity/monthly/archive/february2017.pdf (accessed on 11 October 2017).
18. OpEI Utility Rate Database. Available online: https://openei.org/wiki/Utility_Rate_Database (accessed on 11 October 2017).
19. U.S. Energy Information Administration. *Annual Energy Outlook 2017*. Available online: https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf (accessed on 5 January 2017).
20. Polyiso Manufacturers Association. Available online: http://www.polyiso.org/?page=LTTRQM (accessed on 6 November 2017).
21. M. Cusick, L. Wang, and C. Griffin. "New LTTR Values and What They Mean for Roofing Industry Professionals." *Roofing Contractor*: Troy, MI, U.S., 2014.
22. T.J. Taylor, and C. Hartwig. "Cool Roof Use in Commercial Buildings in the United States: An Energy Cost Analysis." In *Proceedings of the ASHRAE Winter Conference, (ASHRAE, CH-18-009)*. Chicago, IL, U.S.: pp. 20–24. January 2018.
23. GAF internal sales data for 2017.
24. P. Pallin, M. Kehrer, and A. Desjarlais. "The Energy Penalty Associated With the Use of Mechanically Attached Roofing Systems." In *Proceedings of the RCI Symposium on Building Envelope Technology*, Tampa, FL, U.S.: pp. 20–21. October 2014.
25. S. Molleti, B. Baskaran, P. Kalinger, M. Graham, J.F. Cote, J. Malpezzi, and J. Schwetz. "Evaluation of Air Leakage Properties of Seam-Fastened Mechanically Attached Single-Ply and Polymer-Modified Bitumen Roof Membrane Assemblies." In *Roofing Research and Standards Development*: STP1590. S. Molleti and W.J. Rossiter, Eds. ASTM International: West Conshohocken, PA, U.S. 2015. Volume 8: pp. 30–43.