PROCEEDINGS

EVALUATION OF ROOFING RENOVATION METHODS BY AN ENERGY-BASED LIFE-CYCLE ANALYSIS

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ABSTRACT

As one of the most critical parts of the building enclosure, the roofing system has a significant impact on both the energy performance and the durability of the building. It is widely known that roofs of greater insulation value will provide greater energy savings in operational energy. However, very little consideration is given to the embodied energy of the roofing materials as it relates to the total energy of the assembly. This presentation takes a holistic approach in evaluating the energy performance of various conventional roofing replacement options, taking into account the embodied energy cost, operational energy savings, and expected service life of the roof construction to determine the actual life-cycle cost on an energy basis.

SPEAKERS

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IVAN LEE is the sustainable design coordinator at Morrison Hershfield's Burlington, ON, office. He has been involved in various sustainable-design and LEED projects as well as durability reviews of building enclosures for both institutional and residential buildings. Through his involvement in sustainable design, Lee has developed an expertise in energy modeling, hygrothermal analysis, sustainable building materials, and building-enclosure design. As a graduate student studying building science, he is familiar with good building-enclosure design principles and sustainability concepts. Having participated in sustainable design competitions, such as the 2009 DOE Solar Decathlon, Lee is familiar with the energy considerations of sustainable building design, particularly after collaborating with fellow students on the evaluation of the carbon footprint of various design options to produce a building that is comfortable, durable, and energy-efficient, resulting in a net-zero-energy solar home.

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STEVEN MURRAY, PENG, PMP, a principal with Morrison Hershfield, is the director of the Building Science groups in Ontario and Alberta and manages Morrison Hershfield's Burlington, ON, office. He has been practicing in the building science field for over 20 years and has developed particular expertise in envelope rehabilitation, roofing design, and infrared thermography through the investigation and repair of dozens of envelope failures. Steve regularly lectures and presents on technical issues. He has been the roofing module lead since the inception of OBEC's Building Science Certificate program at the University of Toronto School of Continuing Studies nearly ten years ago. Murray presented at ASHRAE 9 in Clearwater, Florida, and at BST 10 in Ottawa. Steve is a past board member of the RCI Ontario Chapter and a past winner of the RCI Horowitz Award for his paper "Solving Roof Leaks with Fans."

EVALUATION OF ROOFING RENOVATION METHODS USING AN ENERGY-BASED LIFE-CYCLE ANALYSIS

INTRODUCTION

As one of the most critical elements of the building enclosure, roofs have a significant impact on building performance in terms of both durability and energy performance since they are subjected to severe environmental loads. Like all parts of the building enclosure, the materials used in the roof assembly have a finite service life that requires maintenance and, ultimately, replacement. Traditionally, building and energy codes and capital costs have driven the design and approach to roof replacements and the specification of roofing materials. This approach has been slightly altered by the recent sustainability movement, particularly by the market transformation influences of green building rating systems such as LEED®. However, many of these rating systems are subjective and are single-criterion-orientated, choosing to focus only on materials containing higher recycled content levels rather than the impact of the material over its lifespan. Instead, a life-cycle approach is considered a much more effective way of determining the environmental impacts of building materials and construction, since environmental life-cycle assessments (LCA) provide a unique method of evaluating the environmental impact of a material or system. LCA reports on the environmental burden associated with the manufacture, transportation, maintenance, and disposal of the product throughout its life cycle.

Since LCA take into account the entire lifespan of the material or system, additional environmental benefits such as savings in operational energy may also be taken into account. When the environmental burden of a material or system is expressed in financial terms, LCA, in the form of life-cycle costing (LCC), can fiscally capture the environmental burden associated with the material itself, as well as its impact on the performance of the building on which it is used in terms of dollars. The effects of the environmental burden and potential benefits in building performance can be expressed as a payback period. For example, the use of additional insulation materials will incur a heavier environmental impact, but this will be offset by a reduction in operational energy. In this case, the payback period is simply the time in which the operational environmental benefit equals the embodied environmental effect of the increased insulation. This makes LCC a powerful tool in helping building owners and designers make the appropriate environmentally and fiscally responsible decisions.

The paper takes an LCC approach to determine the environmental burden associated with various roofing retrofit designs for a typical commercial/institutional building. The embodied environmental burden and operational energy benefits of these different roofing types will be evaluated over the expected lifespans as payback periods. The analysis is based on a case study of a typical commercial building located in southern Ontario.

All building materials require energy for production and transportation. The amount of energy used during this process is referred to as embodied energy. Embodied energy plays a significant role in sustainability because it is an important measure of the overall environmental impact of the product that goes beyond its service life. In most cases, products that have higher embodied energy typically have a much more severe impact on the environment since they typically require more energy to extract, process, and transport the necessary resources. Materials with higher embodied energy typically also have a higher carbon footprint. Therefore, materials with lower embodied energy are typically better for the environment.

Most materials used in a roof assembly can be typically categorized into two categories based on their function: thermal insulation and vapor protection. Because of the extreme conditions that most roofs are exposed to, in order to provide the adequate thermal and vapor resistance, most roof assemblies use specialized materials, each designed for a particular environmental load. For most commercial roofs, thermal insulation is typically provided by rigid insulation such as polyisocyanurate, while moisture protection is typically provided by a bitumen membrane, such as a two-sheet modified bitumen. The embodied energy of these materials, as well as roofing materials from the past, is provided in *Figure 1*. The embodied energy was calculated using software developed jointly by Morrison Hershfield and the Athena Institute. The

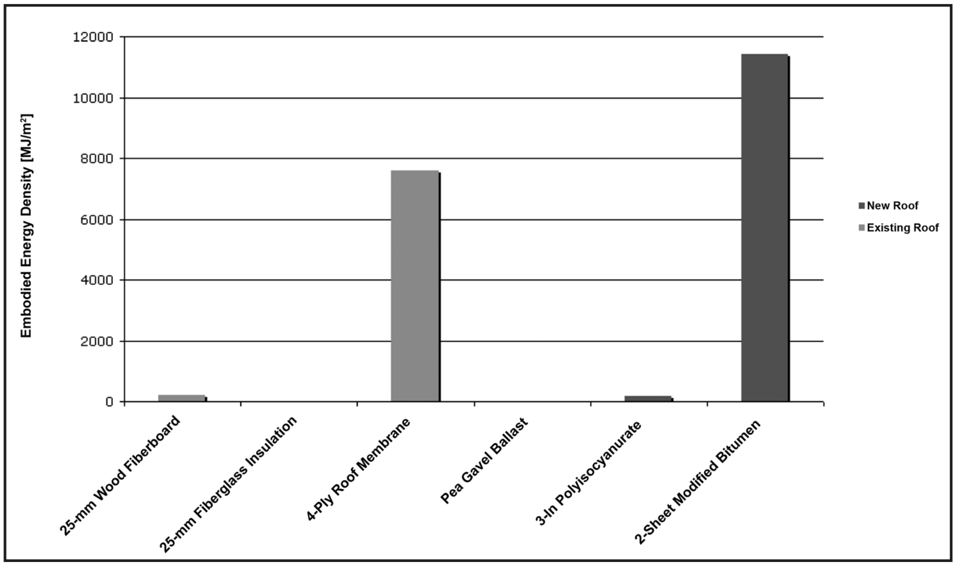

Figure 1 – Embodied energy of roof materials.

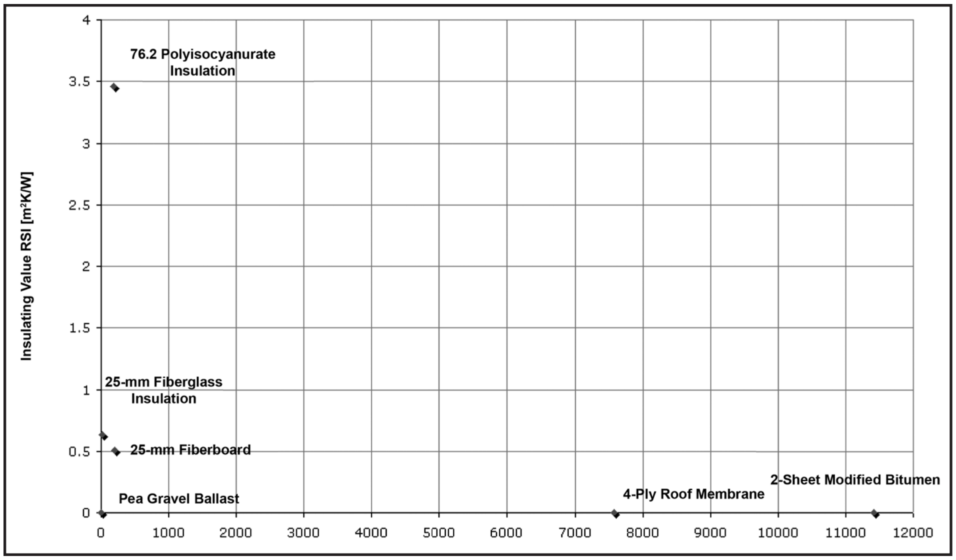

Figure 2 – Embodied energy and insulating value of roofing materials.

software is called Athena Impact Estimator for Buildings. It takes into account the full life cycle of the materials. The life cycle includes every step of the material's life, from resource extraction to disposal, including manufacturing, transportation, construction, and maintenance of the materials as a life cycle inventory (Athena Institute, 2010). Athena contains LCI profiles of a variety of building materials, including roofing materials. It covers a building's life-cycle stages from cradle to grave or end of life, encompassing the following stages:

- extraction (from nature or the technosphere); resource transportation; and manufacturing of materials, products, or building components.
- product /component transportation from point of manufacture to the building site and on-site construction activities.
- life cycle maintenance and replacement activities associated with the structure and enclosure components based on building type, location, and user-defined life for the building.
- “ ” simulates demolition energy and final disposal of materials incorporated in a building at the end of the building's life.

Athena's building materials databases are local to regions within North America, representing average or typical manufacturing technologies and appropriate transportation modes and distances. The databases are able to determine the embodied energy of various materials over 12 geographic regions (including Toronto, upon which this study was based).

From *Figure 1*, it is clear that roof membranes are the most energy-intensive material used in the roof assembly. This is due to the membrane's energy-intensive manufacturing process and the inability to effectively recycle these materials. Conversely, the insulation materials considered used only 1.6% to 2.6% of the roof membrane's embodied energy.

In the interest of life cycle energy performance, it is important to look at not only the embodied energy density but also the thermal performance, since any energy spent during the manufacturing process may be recovered through operational energy savings. *Figure 2* shows the difference in embodied energy and thermal resistance of the roofing materials.

Since sustainability takes into account both embodied energy and operational energy, it is important to look at both of these metrics when considering the overall energy performance of roofing materials to help choose which components provide the greatest potential in achieving an embodied and operational energy balance.

The operational energy of the various roofing designs was determined using a relatively simple method of heating degree days (HDD) and cooling degree days (CDD) based on the building code to which the building was designed. The HDDs and CDDs were based on a temperature of 18°C. The insulating value of the roof assemblies was calculated, and the HDD and CDD were applied to determine the heating and cooling loads, which were then converted into an annual operational cost through local utility rates, similar to the rates used to convert the embodied energy of the building materials. The HDD and CDD were from CWEC weather data provided by the U.S. Department of Energy that is typically used

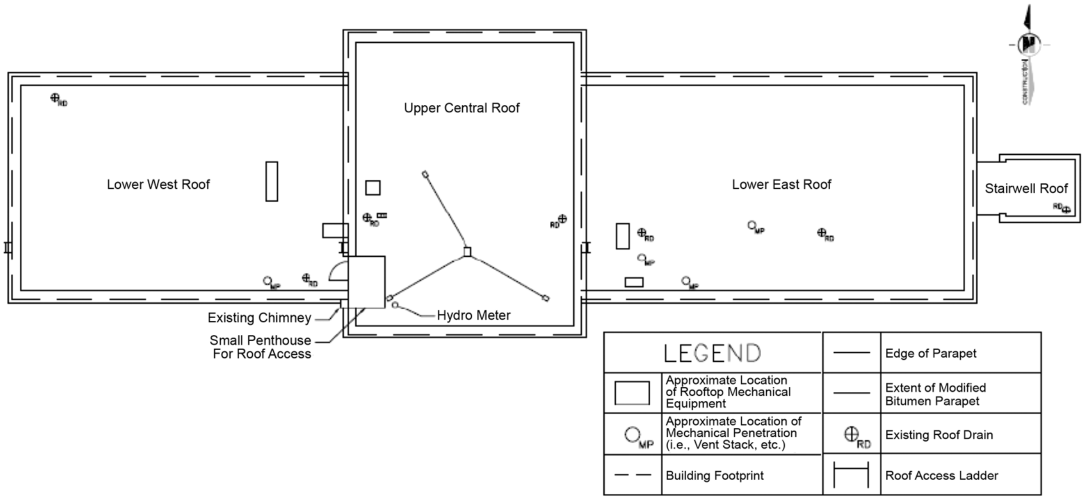

Figure 3 – Roof plan.

for building energy simulation software such as EnergyPlus and eQuest.

This method of analysis only takes into account the secondary energy associated with the embodied energy and operational energy of the roofing systems. As a result, it does not consider the overall environmental impact, such as expressing the overall energy consumption in terms of primary energy would have. To effectively convert from secondary to primary energy is difficult since such conversion is dependent on power generation sources. This method also does not take into account market forces that will have a significant influence on the overall payback period of these materials.

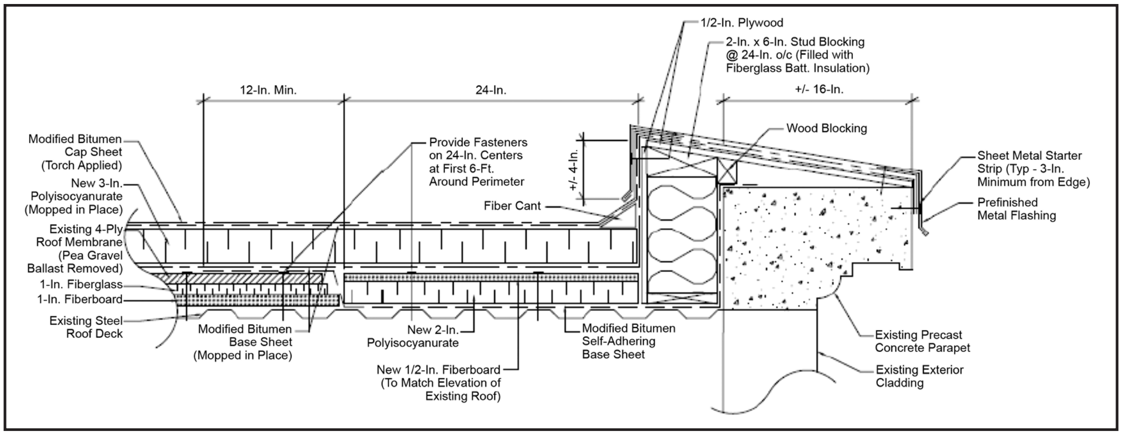

Figure 4 – Existing roof design cross-section.

CASE STUDY

The Royal Botanical Gardens (RBG), located at the west end of Lake Ontario in Burlington, ON, contain multiple buildings, 32 kilometers of trails, and many outdoor gardens.[1] The buildings on site were constructed at multiple time periods from the late 1950s to the 1980s. One section of the RBG Centre, an office block that was constructed in 1957, required a roof replacement.[2] The roof was estimated to have been constructed in the 1980s and was beyond its 25-year service life. Portions of the roof had leaked, and some sections of insulation were known to be wet. A layout of the roof is provided in *Figure 3*.

The existing roof was constructed of 25 mm of fiberglass insulation and 25 mm of wood fiberboard that were protected from moisture with a 4-ply roof membrane and a layer of pea gravel ballast. This assembly has a total R-value of R-6.5 (U=0.874 W/m^{2}K). A cross section of the existing roof is shown in *Figure 4*.

In order to bring the roof up to date with new construction standards required by the building code, the upgraded roof required an insulating value of R-20 (U=0.289 W/m^{2}K). It is noted that the local building code standards for renovations only require the roof's original overall R-value to be maintained as a minimum. Several alternatives were proposed using the existing building materials and newer polyisocyanurate insulation and modified-bitumen roof membrane. The roofing options are listed below:

1. Complete replacement of the existing roof; the new roof will be rebuilt using the same types of materials as the original to R-6.5.
2. Complete replacement of the existing roof; the new roof will be built to R-20.
3. Overlay new roofing materials over the existing roof with enough material to meet R-20.
4. Overlay new roofing materials over the existing roof with the same quantity of materials from option 2; this will bring the roof assembly to R-26.
5. Overlay of new roofing materials over the existing roof with an additional insulation from option 4 to provide a roof with an insulating value of R-33.

These five options were considered in the analysis to balance embodied energy with operational energy savings over the expected service life of the roof.

In order to determine the overall energy performance of the roofing options, both the embodied energy and operational energy performance were determined.

The embodied energy of the alternative designs were determined using the embodied energy densities from the Athena Impact Estimator for Buildings, while the operational performance was determined by calculating the overall thermal transmittance (U-value) of the roof assembly with the HDD and CDD for the Toronto, ON, climate. The roof assembly surface characteristics were assumed to be the same (i.e., emissions, albedo, and reflectance) because the granule surfaces of the modified-bitumen cap sheets were similar to the gravel ballast.

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This is the default option in which the entire existing roof assembly will be removed and replaced with new materials. The new roof will use the same types of materials as the existing roof and will have an R-value of R-6.5 (U=0.87 W/m^{2}K). Since this option removes the embodied energy built into the existing roof, it has the second-highest embodied energy density at 15,594 MJ/m^2 and also the highest annual heating and cooling loads at 17.52 MJ/m^2 and 308.79 MJ/m^2, respectively.

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The first option is a traditional roof replacement where the existing roof assembly is removed and is replaced with 76.2 mm (3 in.) of polyisocyanurate insulation and two-sheet modified-bitumen roofing membrane. This produces a roof assembly with an R-value of 19.7 (U=0.29 W/m^{2}K).

This option is the most embodied energy-intensive option since it not only removes the existing roofing material but also adds a significant amount of new materials to the roof. As a result, this option has an embodied energy density of approximately 19,392 MJ/m^2.

Since this option does not make use of the existing roof insulation, it has one of the lowest R-values. In the Toronto, ON, climate, it is expected to use 5.79 MJ/m^2 for

Roof Types	Embodied Energy [MJ/m^2]	Heating Load [MJ/m^2]	Cooling Load [MJ/m^2]	Total [MJ/m^2]
Default Option 1	7797.00	17.52	308.79	8,123.31
Option 2	19391.82	5.79	101.97	19499.58
Option 3	11539.66	5.80	102.31	11647.77
Option 4	11601.44	4.35	76.67	11682.46
Option 5	11663.22	3.48	61.31	11728.01

Table 1 – Energy performance of roof alternatives.

heating and 101.97 MJ/m^2 for cooling annually.

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In this option, the new roofing materials considered in Option 2 will be installed over the existing roofing assembly, while only the pea gravel ballast will be removed. However, in a conscious effort to reduce the amount of embodied energy density and materials, the amount of insulation will be reduced by 25.4 mm (1 in.) to 50.8 mm (2 in). This will give the roof assembly an overall R-value of R-19.7 (U=0.29 W/m^{2}K) and produce a roofing assembly of R-19.7 to meet that of Option 2, but with a 40% reduction in embodied energy at 11536 MJ/m^2. The annual heating and cooling load is expected to be 5.80 MJ/m^2 and 102.31 MJ/m^2, respectively.

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In this option, the same 76.2-mm polyisocyanurate insulation and 2-ply modified-bitumen roof membrane will be installed over the existing roof. Only the pea-gravel ballast will be removed. Like Option 3, this option makes use of the embodied energy and thermal insulation already invested in the existing roof, but this roof is more thermally insulating. As a result, the roof has an overall R-value of R-26 (U=0.22 W/m^{2}K), a significantly lower embodied energy density at 11,601 MJ/m^2 and has an annual heating and cooling load of 4.35 MJ/m^2 and 76.67 MJ/m^2, respectively.

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Similar to Options 3 and 4, Option 5 is another roof overlay. However, in anticipation of stricter energy codes, Option 5 increases the amount of insulation by 25.4 mm (1 in.), from 76.2 mm (3 in.) in Option 3 to 101.6 mm (4 in.). This is considered the practical limit of insulation that can be added to the roof. Adding any new materials to the roof would increase roof thickness and reduce curb heights, which would require reconstruction of the roof curbs and parapets. This would add an additional installation cost not applicable to other options in this analysis. This raises the R-value to R-34 (U=0.174 W/m^{2}K) and the expected heating and cooling load is 3.48 MJ/m^2 and 61.31 MJ/m^2, respectively.

A summary of the embodied energy and estimated heating and cooling loads is provided in *Table 1*.

From *Table 1*, it is clear that Option 2 is the most energy-intensive, with the highest embodied energy density and operational energy loads. This is effectively the industry default option given the conservative approach to dealing with potential retained moisture in the assembly. However, at this point it is difficult to determine which option uses less energy over its expected lifespan and which option offers the greatest payback. In order to quantify these performance metrics, a life cycle cost analysis must be performed.

The capital costs of the options include both construction and embodied energy costs. The construction costs can be considered as capital costs in a traditional roof rehabilitation project and include demolition, disposal, construction, and materials costs. The costs used in this analysis were based on costs from similar roof replacement projects, including the RBG project, where the existing roof was removed and replaced. The comparison projects were selected for their relevance to overlays versus complete removal and where competitive tender pricing was received for both options. This ensures that the cost analysis presented reflects that of current market pricing.

For options in which only partial demolition took place, such as the overlay options, the disposal costs were reduced by the proportion of the embodied material left in place. The remaining demolition costs, including mobilization, were constant throughout all options.

The tender-pricing data was used to determine the typical proportional costs for demolition and disposal for options not specifically tendered.

Similarly, the construction costs remained constant for all options, except for variations in the material cost of the insulation. For simplicity, the material cost of the insulation was assumed to be on a per-area, per-thickness basis. This made it easier to determine the costs of the polyisocyanurate insulation for the various thicknesses in this analysis.

A summary of the capital cost is provided in *Table 2*.

The operation costs were based on the heating and cooling loads of the roofing

Options	Demolition Costs ($/m^2)	Supply and Install Costs ($/m^2)	Total Cost ($/m^2)
Option 1	$104.53	$201.58	$306.11
Option 2	$104.53	$211.58	$316.11
Option 3	$30.05	$201.58	$231.63
Option 4	$30.05	$211.58	$241.63
Option 5	$30.05	$282.10	$312.15

Table 2 - Construction costs of roofing options.

Fuel Type	Rates ($/kWh)	Rates ($/MJ)
Electricity	$0.05	$0.18
Natural Gas	$0.05	$0.18

Table 3 – Utility rates.

options and average utility rates for electricity and natural gas. Since this analysis does not take into account the HVAC system of a typical building, it was assumed that the fuel type consumption is split evenly for both types of fuels at 50%. The utility rates used in this analysis are listed in *Table 3*.

In order to determine the full life-cycle cost of the roofing options, taking into account the capital and operations costs and expected service life, the future value of the heating and cooling costs were determined for the entire service life of the roof. This was determined using an assumed inflation rate of 3%. Since these rehabilitation techniques will likely have different service lives, full replacement (Options 1 and 2) at 25 years, and overlays (Option 3 to 5) at 20 years, the operation costs must be normalized such that these options can be compared. This was done by calculating the present value of the operation cost using an estimated interest rate of 5%. The resulting capital costs and present value operation cost are presented in *Figure 5*.

Figure 5 shows that while there is some variation in total cost, the capital costs remain relatively consistent across all five options. Much of the variation in this cost is from the heating and cooling loads as the options with increasing R-values have lower operational costs. *Figure 5* also suggests that there seems to be a limit in operational energy savings when compared to capital costs. For the assumed utility rates and southern Ontario climate, the optimal insulation thickness for a roof overlay design is approximately 76.2 mm (3 in.) or approximately an additional R-20. Increasing the insulation beyond this thickness will further reduce the operation costs; however, the savings will be less than the additional capital costs of the added material. This is expected, as the tendency of diminishing returns in more insulating materials is well understood.

This trend in diminished overall returns in cost is also clear when comparing the return on investment among the four roof upgrade options, Options 2 to 5. The capital and operation cost savings were calculated based on Option 2 costs for the overlay designs. *Figure 6* shows a comparison of the cost savings for Options 3 to 5 when compared to Option 2 costs. Since all three of these design options include an overlay of the existing roof, there are savings in construction and demolition costs.

As in *Figure 5*, Option 4 showed the greatest return on investment, yielding a total savings of $140.43 and a good balance between capital and operation savings. This balance was not found in Options 3 and 5, where much of the savings in Option 3 was from capital costs, while the significant savings in Option 5 were from operation costs. It is interesting to note that the total savings of Option 5 are actually lower than Option 3. This indicates that at current utility market rates, a decrease in energy consumption of 12 kWh/m^2/yr. does not offset the added capital cost from the extra 50.8 mm (2 in.) of polyisocyanurate insulation.

The life-cycle cost analysis, however, does not take into account the embodied energy of the materials required and disposed. Instead, a life-cycle energy balance

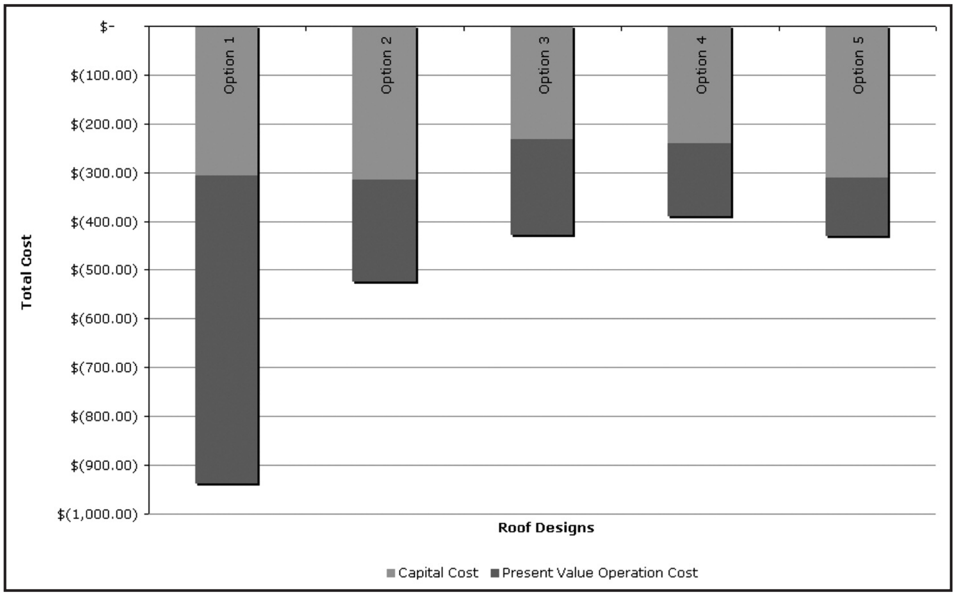


Figure 5 – Capital and operation cost of roof options.

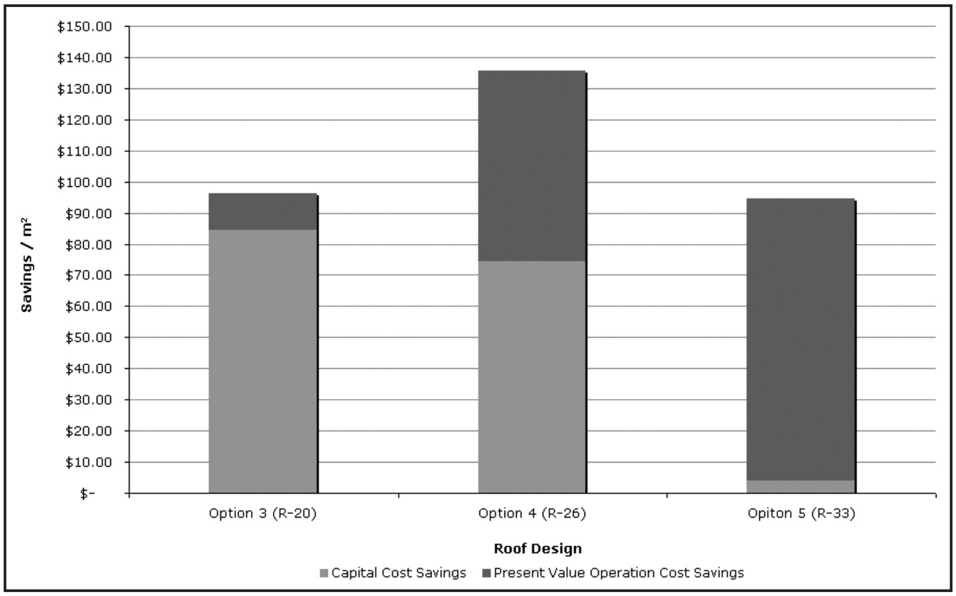
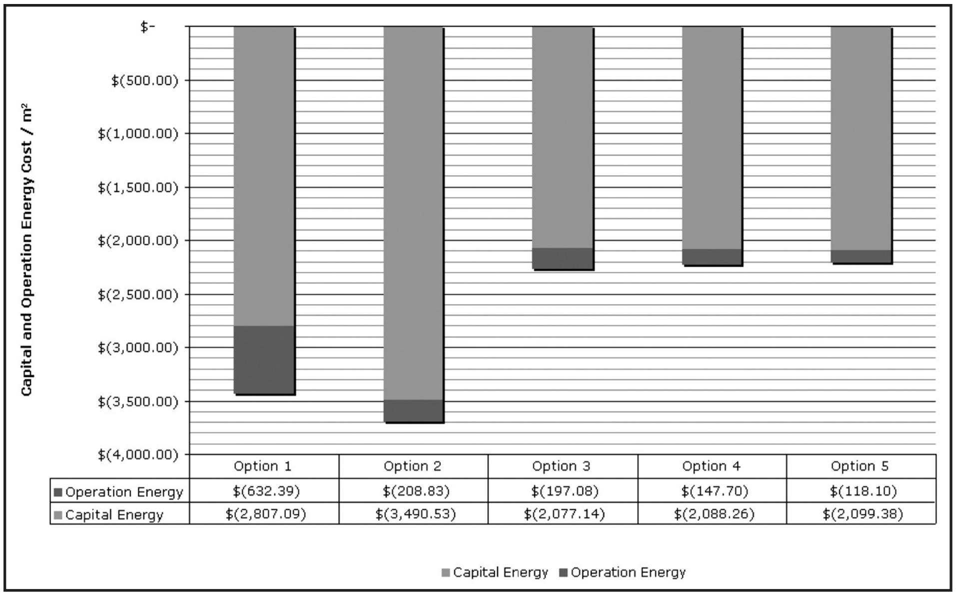


Figure 6 – Return on investment of capital amongst roof overlay options.



	Option 1	Option 2	Option 3	Option 4	Option 5
■ Operation Energy	$(632.39)	$(208.83)	$(197.08)	$(147.70)	$(118.10)
■ Capital Energy	$(2,807.09)	$(3,490.53)	$(2,077.14)	$(2,088.26)	$(2,099.38)

Figure 7 – Life-cycle energy balance of roof options.

was conducted to determine the economic and environmental impact of the different roof rehabilitation options.

In order to effectively take the embodied energy into account in an economic way, the embodied energy of the materials referenced from Athena were converted into a capital energy cost, using the same utility costs listed in *Table 3*. Although the actual utility costs associated with manufacturing and transportation will vary, using the same rates for both the embodied and operational energy keeps the associated energy costs consistent between both types of energy. The embodied energy costs were then added to the present value of the operation energy costs to provide an energy balance. *Figure 7* shows the energy balance expressed as a cost for all roofing options.

From *Figure 7*, it is clear that, among all roof designs, the embodied energy significantly dwarfs that of the operation energy. This is especially the case for Option 2, which is considered the typical roofing rehabilitation design that replaces the existing roof with new materials. The roof overlay designs, by comparison, use significantly less energy by reusing the existing roofing material. The savings are significant despite having a shorter service life of 20 years as opposed to 25.

While the operation costs are relatively small compared to the embodied energy costs, the delicate balance in operation energy and embodied energy from using various thicknesses of insulation does affect the total energy cost. Since the additional embodied energy cost from the additional insulation is relatively small compared to the embodied energy of the roofing membranes, the operational energy saved from the insulation is significant. From *Figure 7*, the optimal design in terms of energy balance is Option 5 as opposed to Option 4 due to the operational cost savings. However, the difference in the overall energy balance is very small.

In addition to the base analysis, a sensitivity analysis of some of the variables was also taken to determine how the results would be altered. Among the variables considered were the following:

1. A shorter service life of 15 and 20 years for the overlay and replacement designs, respectively
2. Equal service lives of 20 years for overlay and replacement designs
3. Increased fuel cost, up to double the cost for both electricity and natural gas
4. Higher interest and inflation rates from 5% and 3%, to 15% and 13%, respectively

The results of these factors on the overall trends of the capital and operation costs are presented in *Figure 8*. This figure shows that altering the service lives, fuel cost,

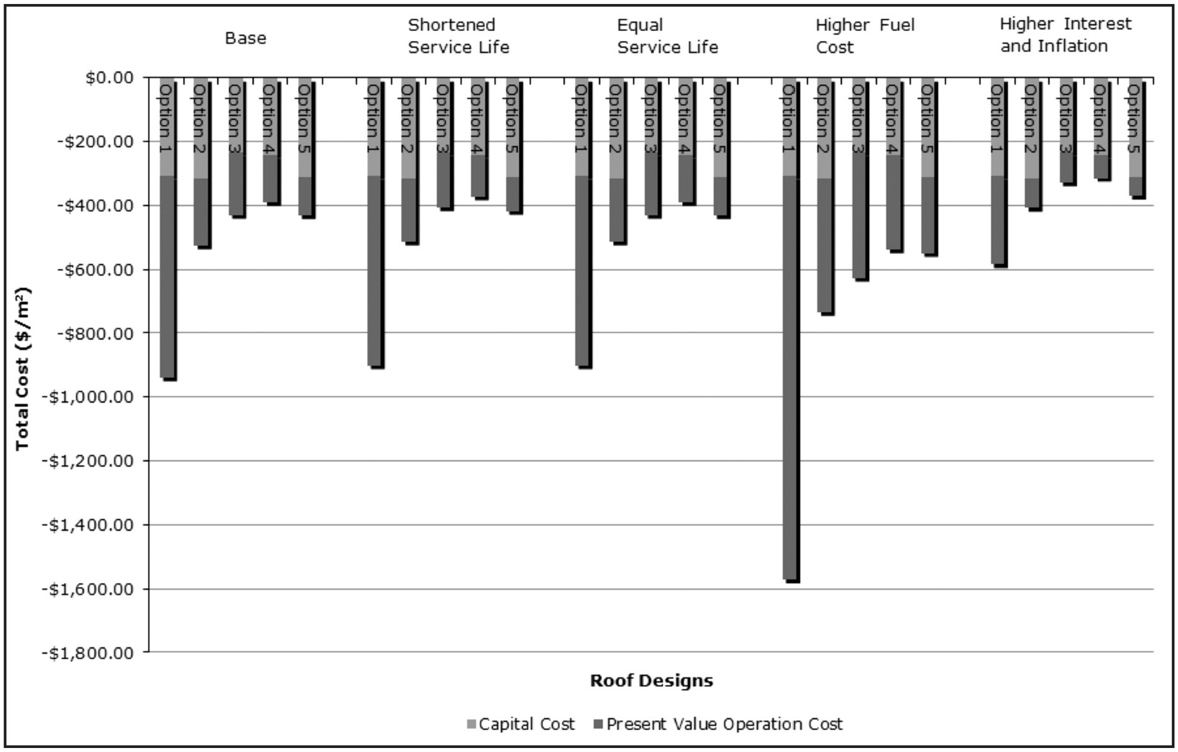


Figure 8 – Sensitivity analysis of capital and operation cost of roof options.

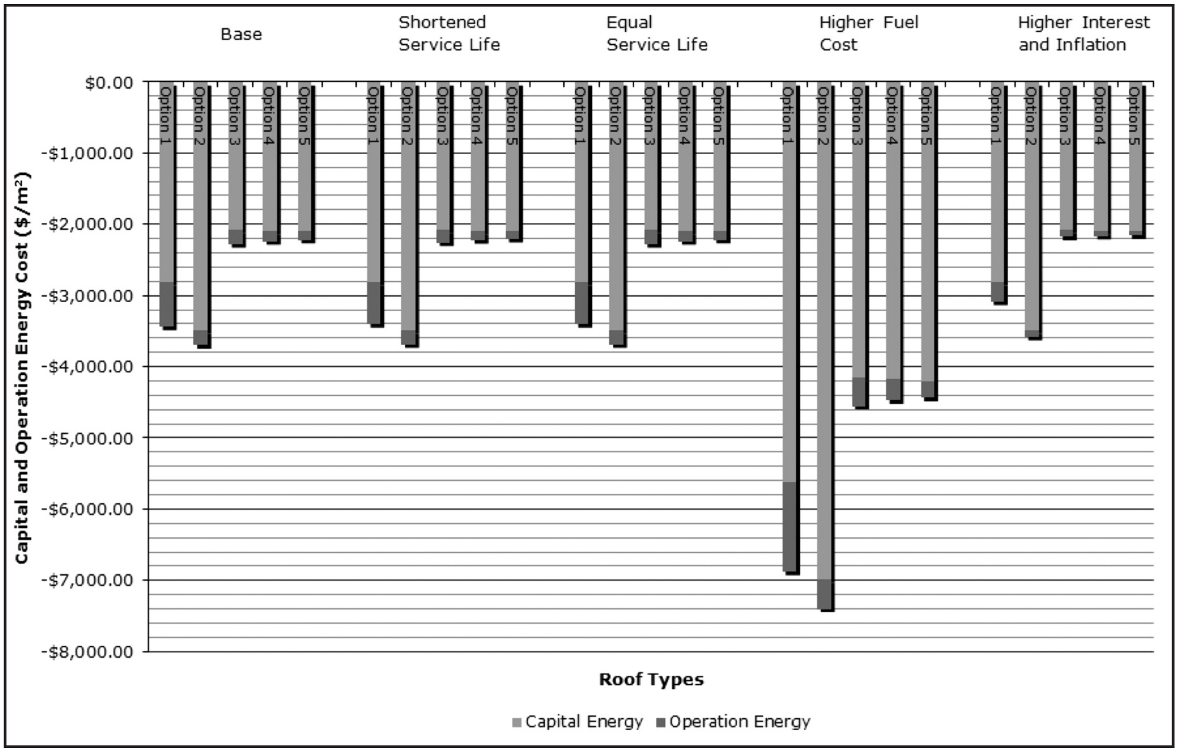


Figure 9 – Sensitivity analysis of life-cycle energy balance of roof options.

interest, and inflation rates does not significantly alter the trends observed from the base case. The capital and operational cost trends did not significantly change for service lives between 15 and 25 years, suggesting that service lives within this range have very little effect on the life-cycle costs of the project. Doubling the fuel costs did increase overall life-cycle cost by raising the operational cost. It also resulted in greater savings for heavily insulated designs such as Options 4 and 5. The cost difference between these designs significantly decreased. However, the increase in fuel costs was not significant enough to change the optimum design from Option 4 to 5. If fuel costs were to continue to climb, the more insulating design would be favored. Conversely, increasing both the interest and inflation rates significantly decreased the operation cost to favor the less-expensive construction designs, such as Options 3 and 4. However, even at extremely high interest and inflation rates of 15% and 13%, respectively, Option 4 is still the most cost-effective design over a 20-year lifespan.

Similar trends were also noted on the life-cycle energy balance as shown in *Figure 9* as Option 5 has the least energy cost and is still the optimum design for all scenarios. The service life showed very little effect on the overall energy balance, while higher fuel costs tended to favor the heavily insulated designs, and higher interest and inflation rates favored the least capitally expensive designs.

CONCLUSIONS

From the results of this life-cycle cost analysis, it is clear that roof overlay designs for major roof rehabilitation projects provide an environmentally sustainable and cost-effective method of repairing roofs. This design approach makes use of the existing roofing materials by prolonging the roof's service life. This reduces the demand for virgin or recycled process materials and waste materials sent to the landfill, resulting in significant savings in embodied energy.

With the assumed market utility rates and a typical service life of 20 years, a roof overlay project with approximately 76.2 mm (3 in.) of insulation provides the optimal savings in both capital and operations cost. Providing less insulation will result in greater heating and cooling costs that will offset the savings in material cost. Similarly, providing more insulation will yield operations savings that are less than the additional materials cost. However, from an energy-balance perspective, the optimal design is to provide an additional inch of insulation to the roof overlay. This results in energy savings that are significantly greater than the additional embodied energy used in the insulation. From these results, it is likely that the optimal design in terms of both life-cycle cost and energy balance is between 76.2 mm and 101.6 mm (3 and 4 in.).

Similarly, a sensitivity analysis revealed that altering the service life from 15 to 25 years showed very little change in the overall cost and energy balance, while increasing the fuel cost favors the more-insulating roof designs, and increased interest and inflation rates favor the less-capital-cost designs. However, doubling the fuel cost and raising the interest and inflation rates by 10% did not shift the optimum points from Options 4 and 5 for overall costs and energy balance, respectively.

LESSONS LEARNED

Owners and designers often reject the option of an overlay system due to perceived risks such as these:

- Water retention within the original assembly,
- Structural concerns due to added dead load,
- Adequacy of securement of the original assembly, and
- Reduced life expectancy compared to a complete replacement option.

In addition, there is often a perception that pursuing more environmentally sustainable options incurs extra costs.

The authors have termed the efforts required to address these risks as the "repair and prepare" provisions; i.e., repair the existing assembly, remove wet materials, and prepare the surface of the assembly for the overlay application. The case study design included repair and prepare provisions such as these:

- Potential areas of retained water

were locally removed.

- The dead load of the new assembly was offset by the removal of the original gravel ballast.
- A small perimeter strip of the original assembly was removed and replaced to effect system securement. (see *Figures 3* and *4*).

The financial analysis used actual construction costs, procured through competitive tendering, to capture the costs of these "repair-and-prepare" provisions, and the analysis assumed that the overlay would have a shorter lifespan than the complete replacement.

The authors believe that this case study has demonstrated that there are actually financial benefits possible from the intelligent integration of environmental benefits. The option selected and installed at the subject facility achieved capital cost savings and operational cost savings. This is an attractive proposition for building owners and managers normally faced with decisions based on trade-offs of capital versus operational costs.

The embodied energy of the materials in the original assembly can continue to reduce operational energy usage through another life cycle. This effectively amortizes the embodied energy investment over twice the time frame and extends the time frame to receive the dividends of the investment. Extending this logic further, it is possible to fully offset the embodied energy investment if a long enough service life is achieved.

The concepts and design options presented in this paper are relatively simple; however, they provide a unique framework by which to assess roof renewal projects. The authors hope that owners and designers may make use of the framework to more critically evaluate roofing renovation options by utilizing energy-based life-cycle analysis.

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FOOTNOTES

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