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The Environmental Impact of Roofing Systems: Ten Life Cycle Indicators

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Abstract

The environmental implications of roofing system selection will be discussed during this intermediate presentation intended for all stakeholders in the design process (consultants, engineers, architects, and building owners). These environmental implications vary by building location, building archetype, insulation levels, and roof membrane selection. Life cycle assessments of 432 combinations of these variables have been completed and results formulated into a database of use within major Canadian urban centers. This will be presented and discussed.

Speaker

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THE ENVIRONMENTAL IMPACT OF ROOFING SYSTEMS: TEN LIFE CYCLE INDICATORS

ABSTRACT

This paper analyzes 10 environmental impact indicators attributed to six typical roof assemblies within the Canadian roofing industry on six building archetypes in six of Canada's major urban centers. The analysis also considers two insulation scenarios by modeling each combination of roof assembly, building type, and location, with both the code-stipulated minimums, as well as a "code+" scenario. The result of the analysis is the creation of a comprehensive life cycle assessment (LCA) database with 432 different combinations of roof assembly, building type, insulation level, and location within Canada. Although the results are unique to the Canadian climate, the methodology may be expanded to any other geographical area where historical weather is tabulated if variances in the local building codes and construction practices are considered.

The life cycle of each roofing assembly was divided into four phases for analysis: raw materials acquisition and product manufacture, construction, building operation, and end-of-life disposal, with transportation effects also considered between each of the four phases. Athena™ software modeled 10 environmental impact indicators attributed to each of the raw materials acquisition, product manufacture, transportation, and end-of-life disposal phases under each scenario, and Sefaira™ modeling software was used to model the building operations phase.

The authors created an Excel-based comparative design tool that utilizes the comprehensive LCA database. This innovative research will better allow designers to provide clients with practical recommendations regarding roofing system selection based on fundamental principles of environmental stewardship.

INTRODUCTION

The rapid, unchecked growth of cities within the developed world has caused unquestionable impacts to the biosphere. Buildings comprise a large portion of this rapid growth, and the resulting impact to the environment is often quantified and tracked using one or more LCA indicators (Junnila & Horvath, 2003). Ten life cycle indicators representing total primary energy, fossil fuel consumption, global warming, acidification, respiratory effects, eutrophication, ozone depletion, smog, solid waste, and water use were included in this research. Although all 10 environmental effects may not be applicable to any given building decision, all alterations or additions to our buildings will impact the environment in at least one of the aforementioned ways. Stakeholders in construction decision-making processes have been placed under increasingly stringent regulatory pressures, such as municipal bylaws, to reduce and document the negative environmental consequences of their actions. This study aims to assist in identifying and quantifying the environmental impact attributable to roofing systems.

Roofing systems are unique building enclosure elements due to their extreme environmental exposures and impact on whole-building energy consumption, the amount of which varies for different building typologies. The decision of which roofing system to implement during new construction and/or roof replacement projects can greatly impact the long-term environmental impact of that building. The most environmentally responsible roofing system to install is dependent upon the building type and geographical location. No roofing system should be declared the "greenest" or "most sustainable," independent of context.

This research completes a screening-level LCA on six common roofing systems, for six common building archetypes, in six of Canada's major metropolitan areas using two levels of insulation, resulting in 432 unique scenarios. Each scenario tracks the 10 environmental impact indicators noted above. The research has culminated in the creation of a screening-level comparison design tool that stakeholders throughout Canada can use to approximate the life cycle environmental consequences of their roofing system decisions.

METHODOLOGY

Building Archetypes

Recognizing the variety of buildings based on size and function alone, this research defined six commonly encountered building archetypes that reflected common portfolio buildings for mid-to-large property ownership firms and/or real estate investment trusts in Canada. Since each building archetype performs different functions, direct comparison of life cycle effects between the different building types hold little merit, as this would not be a fair comparison of environmental impacts. This research is intended for relative comparison of various roofing systems on an identical building. Schematics of the building arche-

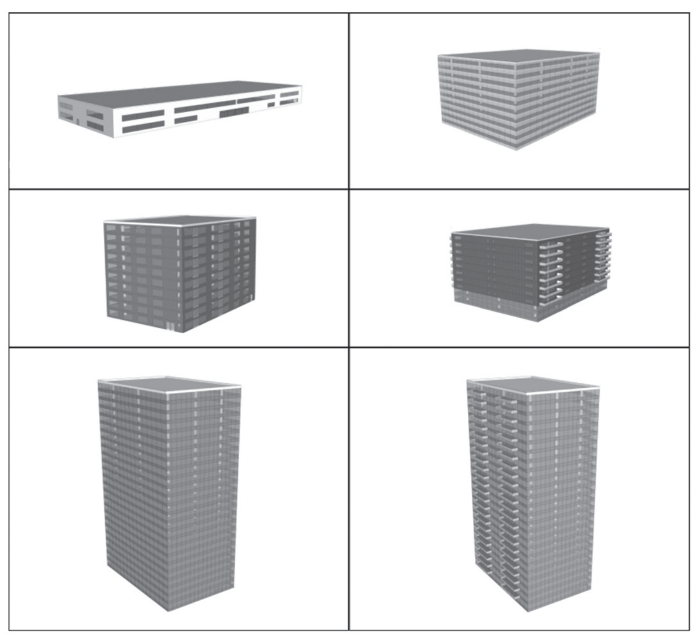

Figure 1 – Overview of six building archetypes. Clockwise from top left: industrial, mid-rise office, mid-rise mixed use, high-rise residential, high-rise office, and mid-rise residential.

1. Conventional Built-Up Roof
• 10-mm pea gravel and asphalt flood coat • 4-ply organic felts • 13mm asphalt-saturated fiberboard • Rigid polyisocyanurate insulation (thickness varies) • Kraft paper vapor retarder
2. Inverted 2-Ply Modified-Bitumen Roof
• 32-mm stone ballast • Woven polyolefin ballast separation sheet • Extruded polystyrene ship-lapped insulation (thickness varies) • 2-ply modified-bitumen membrane
3. White Inverted 2-Ply Modified-Bitumen Roof
• 32-mm stone ballast (white) • Woven polyolefin ballast separation sheet • Extruded polystyrene ship-lapped insulation (thickness varies) • 2-ply modified-bitumen membrane
4. White Thermoplastic Polyolefin (TPO) Roof
• 6-mm single-ply white TPO • 13-mm fiberboard • Rigid polyisocyanurate insulation (thickness varies) • Kraft paper vapor retarder
5. White Polyvinyl Chloride (PVC) Roof
• 6mm single-ply white PVC • 13mm fiberboard • Rigid polyisocyanurate insulation (thickness varies) • Kraft paper vapor retarder
6. Extensive Vegetated (Green) Roof
• Vegetation (low coverage) • 100 mm engineered soil • Woven polyolefin filter fabric • Extruded polystyrene ship lapped insulation (thickness varies) • Drainage board with integral filter fabric • Root barrier • 2-ply modified-bitumen membrane

Table 1 – Summary of roof assemblies within design tool.

Life Cycle Impact	Units of Measurement
Total primary energy[1]	MJ
Fossil fuel consumption[1]	MJ
Global warming potential[2]	kg CO_2 eq
Acidification potential[2]	moles of H+ eq
Human health criteria[2]	kg PM10 eq
Eutrophication potential[2]	kg N eq
Ozone-depletion potential[2]	kg CFC-11 eq
Smog potential[2]	kg O_3 eq
Solid waste[1]	kg
Water use[1]	L

[1] indicator is a summation of life cycle inventory resource use or emissions.
[2] indicator is a summation of life cycle inventory emissions characterized according to TRACI 2 v4 methodology.

Table 3 – Indicators of negative life cycle impacts.

types are provided in *Figure 1*. (For descriptions of each archetype, refer to *Appendix A*.)

Roof Systems and Insulation Levels

For each building archetype/geographic location combination, the following six common roofing systems were modeled with construction as provided in *Table 1* (exterior to interior). Each roofing system was also modeled with ancillary materials such as metal flashings, fasteners, etc. (Refer to *Figure B1* of *Appendix B* for a full list of ancillary materials included within the models.)

Each roofing system was modeled with "code" and "code+" insulation levels, the latter of which are approximately 30% better than the code minimum values. The code minimum values are based on the 2008 Ontario Building Code, SB-10 – Energy-Efficient Supplement, using Toronto, Ontario, as the baseline. The code and code+ values are provided in *Table 2*, based on commercial availability of required insulation thicknesses and modeling limitations in RSI. See *Equation 1*.

$$\{\frac{m^2.k}{W}\}$$

Equation 1

Roof Type	Insulation Type Used	Code (RSI) [R-Value]	Code+ (RSI) [R-Value]
BUR	Polyisocyanurate	4.931 [28.0]	7.397 [42.0]
Green Roof	Extruded Polystyrene	4.403 [25.0]	7.925 [45.0]
Inverted 2-Ply – Gray	Extruded Polystyrene	4.403 [25.0]	7.397 [42.0]
Inverted 2-Ply – White	Extruded Polystyrene	4.403 [25.0]	7.397 [42.0]
TPO	Polyisocyanurate	4.931 [28.0]	7.397 [42.0]
PVC	Polyisocyanurate	4.931 [28.0]	7.397 [42.0]

Table 2 – Summary of code and code+ insulation levels.

Geographic Locations

Roofing-related decisions are largely dependent upon climate, which varies widely across Canada. To investigate the variation of results with climate, six of Canada's largest urban centers were modeled: Halifax, Montreal, Toronto, Edmonton, Calgary, and Vancouver. Climatic metrics for these locations are provided in *Figure B2* of *Appendix B*.

Model Structure

To complete the research objectives, a computational comparative design tool was created, which provides a screening level comparison to aid in the selection of roofing membranes based upon total life cycle impacts as listed in *Table 3*.

The model primarily utilizes data derived from the Athena Impact Estimator for Buildings (Athena IE), (Athena Sustainable Materials Institute, 2013) software to quantify the 10 environmental indicators through raw materials acquisition, construction, and end-of-life disposal phases.

A whole-building energy simulation was used to quantify the environmental indicators associated with the operations phase, which provides increased accuracy compared to the approximated values within the Athena program. The whole-building energy simulation was completed using Sefaira by Sefaira Inc. (Sefaira 2013), and the energy implications attributed to the roofing systems were determined based on methodical alteration of the program inputs.

The life cycle environmental effects associated with each roofing system and building archetype are strongly dependent upon the building location, since the primary energy source mix and delivery infrastructure vary with location. For example, electricity generation within Quebec is predominantly hydroelectric, which is less impactful (in terms of global warming potential) to the environment compared to the primarily coal-based generation utilized in Nova Scotia.

The model quantifies the 10 environmental indicators through the four life cycle phases (extraction, construction, operating, and disposal) using select Athena IE defaults and published literature, manufacturer's product data, and unique Sefaira inputs. The LCA boundaries were defined as the point of raw material extraction to the point the material enters the landfill. The model does not incorporate effects (such as leachates or off-gassing) following the material being placed in landfills. The model also does not incorporate second-order effects of the roofing systems during the roof operations phase. These include: local cooling, improved air quality, reduction of stormwater runoff, carbon sequestration of vegetated roofs, etc. Many of these second-order effects have been previously investigated (Ries and Kosareo, 2007; Currie and Bass, 2008; Krayenhoff and Bass, 2003) and may be incorporated into the model in the future. The model methodology is outlined in *Figure 2*.

The comparative design tool references the created LCA database to model 10 environmental indicators over 432 permutations of roofing type, building type, building location, and insulation thickness—making this research one of the largest LCAs of its kind with a focus on roofing decisions. The model expresses results not only based on percentage of roof area but also as an approximated percentage of whole-building

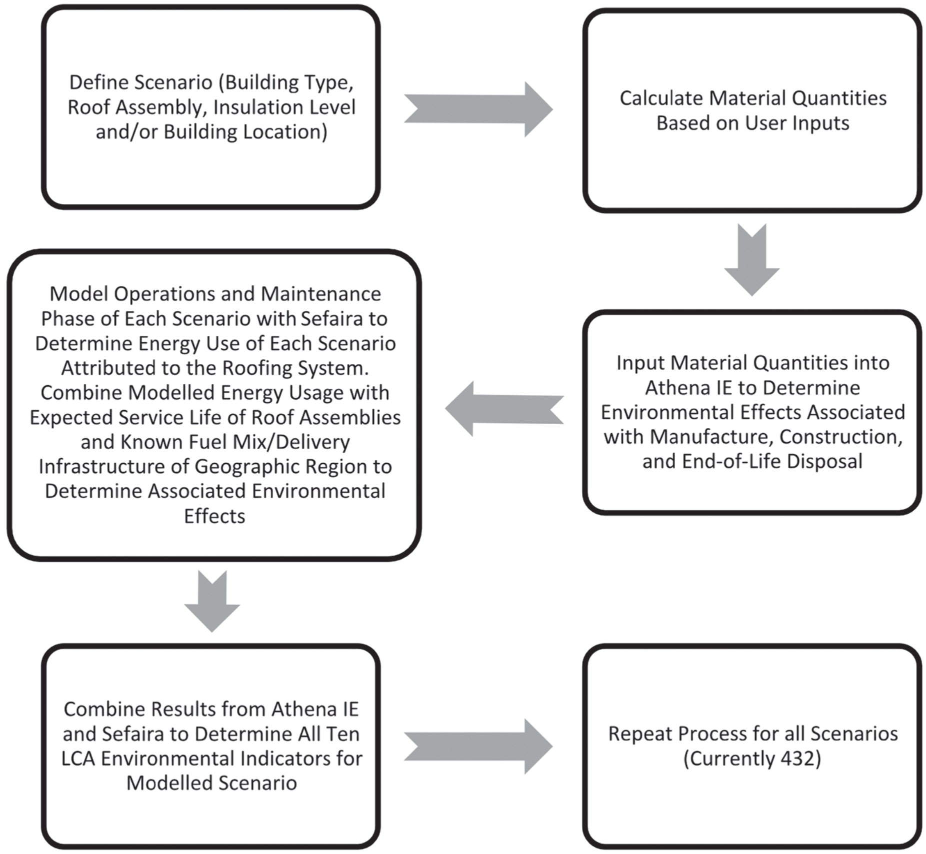

Figure 2 – Flowchart of LCA methodology.

LCA environmental impacts. The whole building is modeled using the same process throughout the stages of the LCA, based on the defined building archetypes in *Figure 1*. The building archetypes are less defined than the roofing assemblies, and, as such, whole-building LCA environmental impacts should be used for relative comparison purposes only. The building archetypes (excluding the roof) were modeled within the Athena IE and the results were tabulated within the database. The roofing systems are modeled within the design tool based on user inputs using material data from the Athena IE database. The modeled roofing system results are combined with the predetermined building archetype results and Sefaira-simulated building energy usage to generate whole-building LCA results.

Design Tool Assumptions

The current version of the design tool is intended to be used for relative comparison of various roofing systems. The assumptions made to create the design tool result in variances from the actual measured life cycle environmental impacts. These assumptions are consistent across all models, which permit the design tool to be used as a means of comparison of the various roofing systems:

1. The six building archetypes outlined above were roughly defined based on commonly encountered building types that best reflected the average portfolio for mid-to-large owners and/or real estate investment trusts in Canada based on the experience of the authors. Each building archetype has a specific fenestration ratio, cladding system, and glazing system. Sefaira assumes the entire building behaves as one climatic zone with values that are generally fixed to a cooling set point of 22˚C and a heating set point of 18˚C (slight variations were used based on archetype modeled).
2. The LCA data for TPO membrane was not made available by membrane manufacturers at the time of this research. However, Athena has recently incorporated TPO data into its Impact Estimator, which will be utilized during future improvements of the database. PVC membrane values were assumed for TPO membrane as a placeholder while the

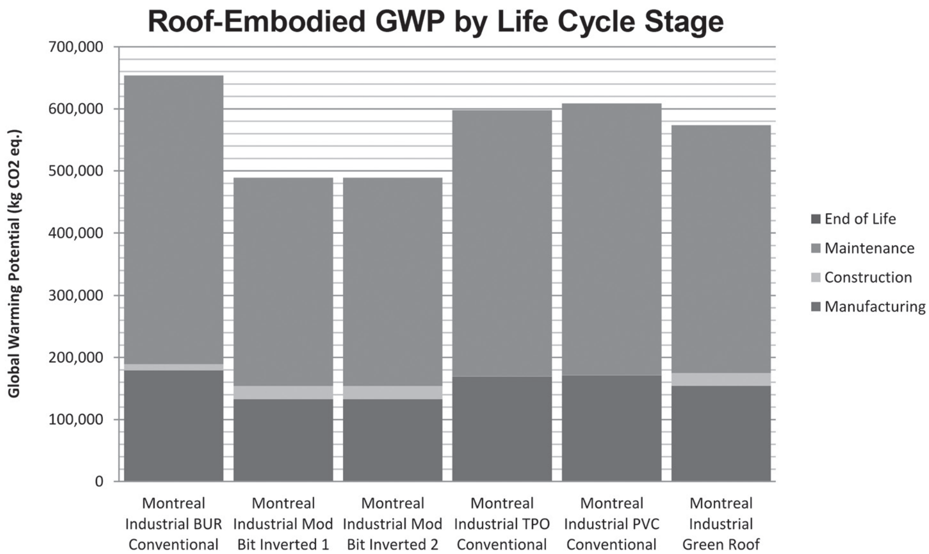

Figure 3 – Relative comparison of six roofing systems with 20-year service lives on a 60-year industrial building in Montreal.

TPO values are added to the tool.

3. The whole-building embodied effects results were modeled within the Athena IE, based on construction assemblies that are less defined than those of the roofing systems. As a result, the whole-building embodied effects results should be treated as relative values rather than absolutes.
4. Crane diesel usage for construction and maintenance phases vary for each building archetype. Usage was estimated using data within the Athena IE.
5. Unless otherwise noted, localized roofing repairs are assumed to be required across 1.5% of the roof area annually.
6. TPO and PVC membranes are assumed to be mechanically fastened on all building archetypes, although only the roof deck of the industrial building was modeled as metal.
7. A consistent partial material reuse factor has been assumed during roof replacement activities (ballast, insulation, etc.). This has resulted in an assumed reduction of material inputs during roof replacements.
8. Transportation distances of roofing membranes to site are as per Life Cycle Inventory of ICI Roofing Systems: On-Site Construction Effects (2001). Transportation distances of other materials to site are determined based on data within the Athena IE, except for vegetated roof assembly components, which are as per LEED product literature.
9. All space heating is provided using natural gas, and all space cooling is provided using electricity.

DESIGN TOOL APPLICATIONS AND CONCLUSIONS

The design tool can be used under various scenarios to test the relative differences in 10 life cycle environmental indicators, over six building archetypes, with six various roof assemblies with two insulation levels in six major Canadian cities, resulting in 432 scenarios with 4,320 life cycle indicators modeled. Environmentally conscious stakeholders can utilize the design tool to analyze relative environmental consequences associated with roof assembly selection. Within this section, effects of the variables on global warming potential (measured in kg of CO_{2eq}) attributed to the roofing assemblies are discussed through sample scenarios of application of the design tool.

Effect of Roof Assembly Selection

The design tool can be utilized for a relative comparison of environmental effects of different predefined roofing systems if all other variables (location, building archetype, insulation levels, and building and roof service lives) are held constant. *Figure 3* shows the relative comparison of the embodied CO_{2eq} emissions attributed to six roofing systems on an industrial building in Montreal if all service lives were equal at 20 years and the service life of the building was assumed to be 60 years. Within this scenario, the inverted modified-bitumen examples have the lowest embodied CO_{2eq} emissions.

Figure 4 presents the output of all 10 environmental indicators for the same 60-year industrial building in Montreal based on the same scenario presented in *Figure 3*. *Figure 4* shows that the inverted modified bitumen with white ballast scenario (Mod Bit Inverted 2) has the highest total life cycle CO_{2eq} emissions, while a built-up roof (BUR) has the lowest. The result of a

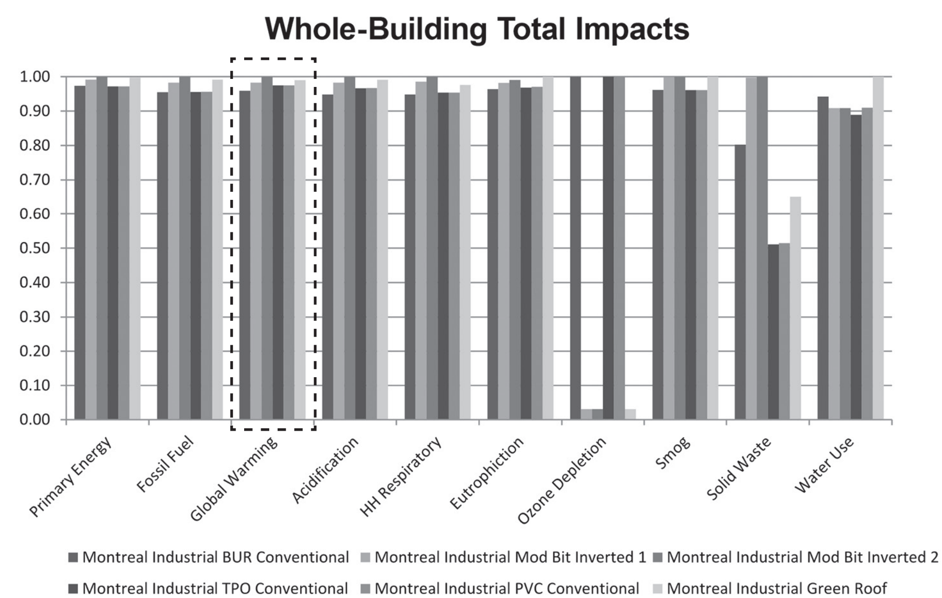

Figure 4 – Life cycle impacts of 60-year industrial building in Montreal with various 20-year roofing systems.

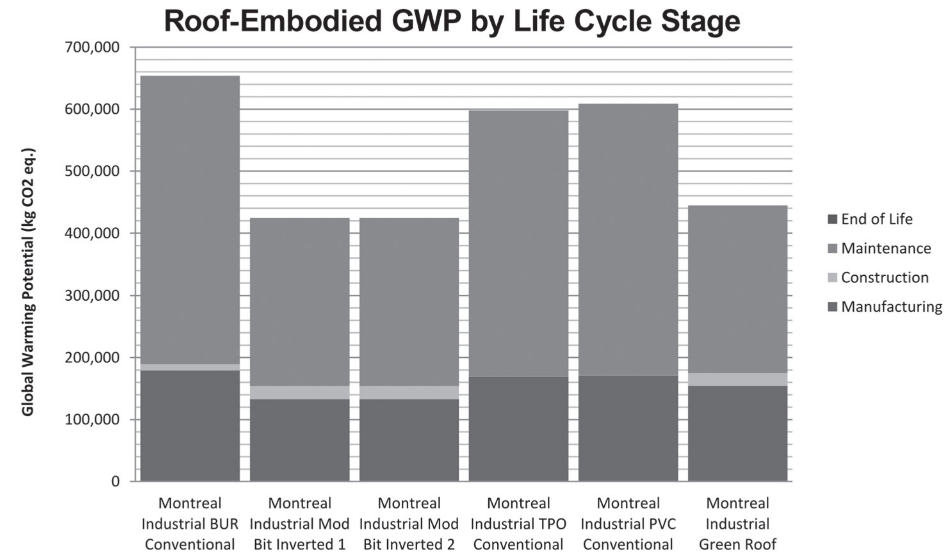

Figure 5 – Relative comparison of six roofing systems with realistic service lives on a 60-year industrial building in Montreal.

bitumen roofs, as the single plies will only require 2.0 replacements during the 60 years, whereas the modified-bitumen roofs require 2.4 replacements. The BUR will now have 3.0 replacements, resulting in the highest embodied energy.

In order to improve the performance of the single plies such that they have the lowest life cycle CO_{2eq} emissions, what would happen if insulation levels were increased on only the single-ply options, keeping the other options maintained at code-minimum levels? The results are shown in Figure 6. The single plies would now be the most desirable option to minimize life cycle CO_{2eq} emissions, as well as most other environmental indicators. This indicates the sensitivity of the analysis to the operational energy, which is largely proportional to roof insulation levels.

BUR having the lowest life cycle CO_{2eq} emissions may not seem correct; however, the modeling results are logical. Montreal has a heating-dominated climate, and BURs have exposed black membranes with high sol-air temperatures, which reduce heat loss through the roof assembly in the winter months, resulting in higher effective insulation levels in colder months. The TPO and PVC roofing systems (single plies), are also exposed but are white (high albedo) with lower sol-air temperatures than the BUR alternative, but maintain higher temperatures in the winter months directly over the insulation than do the inverted systems. They have higher energy requirements to manufacture as well, as shown in *Figure 3*.

The results for life cycle implications on environmental metrics are presented as whole-building results, since determining effects attributed to the operations phase require energy modeling of a whole building to be completed. Since the purpose of the design tool is to provide a relative comparison between alternative scenarios, this approach appears appropriate.

The results shown in *Figure 4* are not an accurate representation of reality, since we have assumed all roof assemblies have equal service lives. Inverted systems are often selected to protect the membrane from damaging environmental conditions such as temperature cycles and UV radiation. As such, the expected service lives of inverted systems are generally greater than conventional systems, resulting in fewer replacements required over the life of the building.

Single-ply roofs are typically conventional systems; however, they are assumed to have a slightly higher service life than the bitumen-based roofs, according to available data (Beer, 2014). Based on the experience of the authors, service lives typically are 20 years for BUR, 25 years for inverted modified-bitumen and single-ply roofs, and 30 years for green roofs. With varying service lives considered, the results of *Figure 3* change as shown in *Figure 5*.

With service lives considered, the embodied energy required to manufacture the single-ply materials no longer represents a large increase over the modified-

Effect of Building Location

The results presented in the last section on roof assembly selection are not universal. The selection of roofing systems is location- and context-dependent, as each location will utilize a different mix of energy sources with the environmental implications of different energy sources also varying. As can be seen in *Figure 7*, all variables are held constant with the exception of building location, and life cycle CO_{2eq} impacts vary across the cities.

As can be seen in *Figure 7*, Vancouver and Montreal are the cities with the lowest life cycle CO_{2eq} emissions, followed closely

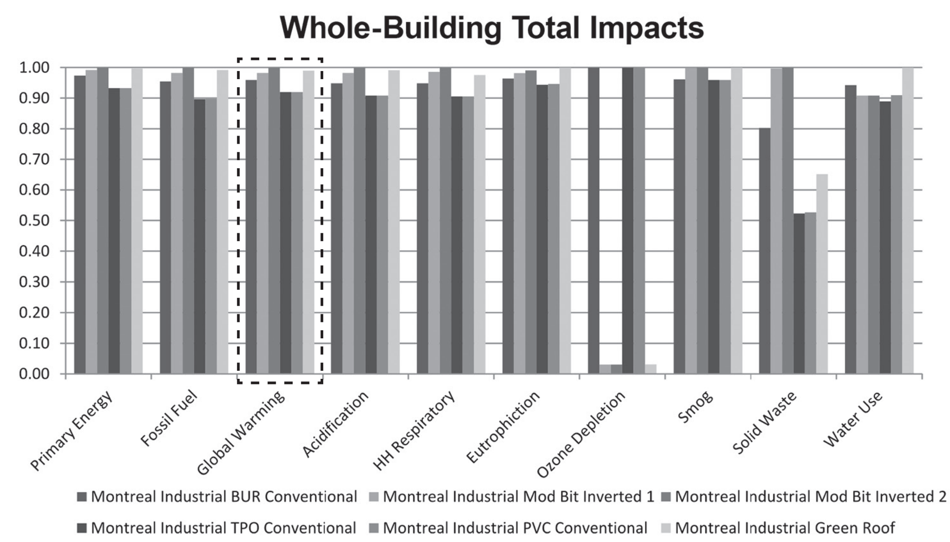

Figure 6 – Life cycle impacts of 60-year industrial building in Montreal with various roofing systems where only single plies have increased insulation levels.

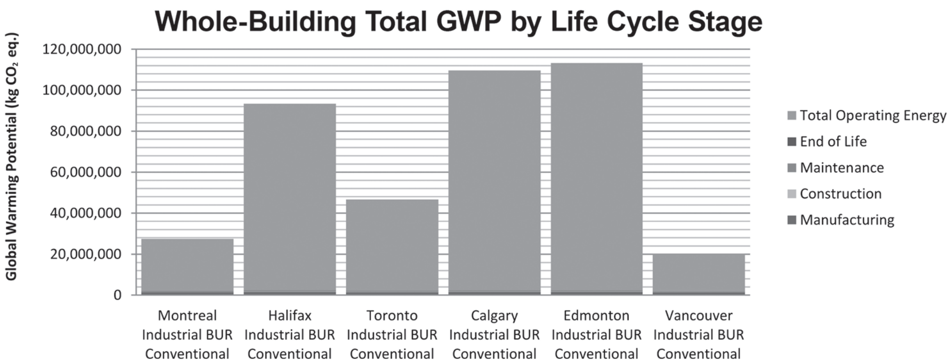

Figure 7 – Effect of location on life cycle CO_{2eq} emissions.

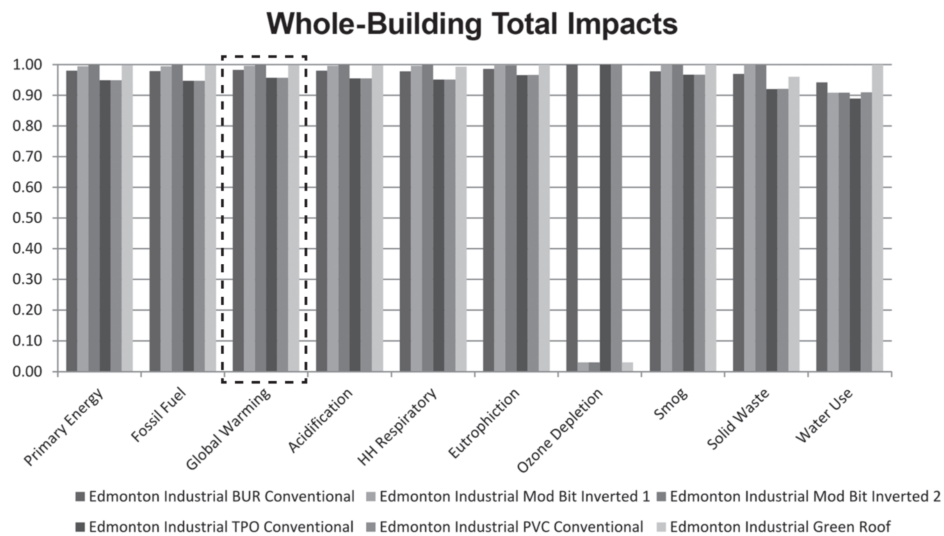

Figure 8 – Life cycle impacts of 60-year industrial building in Edmonton with various roofing systems where only single plies have increased insulation levels.

by Toronto; whereas Halifax, Calgary, and Edmonton are far greater due to the greater portion of carbon-based fuel sources in the local energy mix. What would happen if the scenario outlined in *Figure 6* were repeated in Edmonton? Since the whole-building total impacts are normalized based on the roofing assembly with the most impact (green roof), the results of *Figures 6* and *8* are similar, even though the location has changed; however, there is now a reduction in the relative differences, indicating the impact of energy supply mix in the calculation.

Effect of Insulation Level

Although energy usage is found to have the largest relative impact on life cycle performance, and the most energy-intensive city out of the six cities studied was selected (Edmonton), increasing insulation levels on the single plies was found to not offer a significant increase in performance. To determine the reasoning behind the results, the BUR insulation was increased to the level of the single plies as shown in *Figure 9*. The results show a minor improvement to the thermal performance of the roof assembly that appears to be attributable to the effect of changing insulation levels on the sol-air temperature of the roof membrane, which appears to dominate the assembly's performance in cold climates. Increasing insulation below the membrane separates the hot membrane surface from the interior, and the system no longer benefits from significant natural heat gain in the colder months.

If insulation level is increased on all roof assemblies, this phenomenon becomes more apparent. As shown in *Figure 10*, the performance is now governed by the thickness of insulation, and membrane selection generally does not impact the life cycle performance of the assembly with respect to CO_{2eq} emissions.

If analyzed in detail, there is a difference in embodied energy of each membrane scenario indicating the variation in manufacturing; however, the life cycle performance is still governed by energy use in the operations phase. Energy usage is found to be dependent on insulation thickness, not membrane selection, once the insulation levels are increased beyond the code minimums. Thus, the less insulation a roof assembly has, the more importance the roof membrane plays on the thermal performance of the assembly and, by extension, the life cycle CO_{2eq} emissions associated with that assembly.

CONCLUSIONS

It is intended that the design tool presented will be periodically updated and refined based on new and adjusted product information or in order to minimize the assumptions required. Further, it is planned that the life cycle assumptions and life cycle information will be reviewed by third parties to obtain verification to EN15978 (Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method). The short-term aim of the comparative design tool is to be able to guide stakeholders through the life cycle environmental implications of roofing decisions across Canada with custom building inputs and custom roof assemblies. To accomplish this, the database will need to be enhanced (i.e., adding more materials), the assumptions reduced, and the methodology adjusted to allow for simulations based on situations comprised of single components rather than predefined archetypes.

Although usage and detailed analysis of all of the 432 permutations from the design tool are beyond the scope of this paper, important conclusions can be made regarding the roof life cycle impacts in Canada based on the scenarios investigated above:

1. Although results vary based on inputs, approximately 1-3% of the whole-building life cycle CO_{2eq} emissions result from the embodied energy of the roofing system. If the primary intent of the roof assembly selection is to minimize contribution to climate change, focus should be placed on minimizing operational building energy usage.
2. In Canada, buildings are primarily heating-dominated, resulting in a noted lower energy requirement for space conditioning from installing black roofs vs. high-albedo (white

reflective) roofs due to the difference in sol-air heat gain potential when insulation is at code-minimum values.

3. When insulation is increased beyond code-minimum values, the importance of membrane selection on thermal performance decreases. When the thermal resistance is increased to 60% above the code-minimum values (the code+ option), the differences in thermal performance of the membranes becomes statistically insignificant.
4. The importance of membrane selection on life cycle CO_{2eq} emissions was found to vary across Canada, depending on the energy supply mixes of each city. In Edmonton, usage of an exposed black membrane was found to reap a greater benefit than in Montreal with respect to reducing CO_{2eq} emissions.
5. While the design tool indicates that operational and maintenance energy are the areas in which to focus on reduction, as buildings become more energy-efficient, it is more important to consider embodied environmental impacts as the roofs become relatively larger, and in particular for net-zero buildings. It is also more important to consider embodied energy implications in cities with a "cleaner" energy supply mix such as Vancouver, since embodied energy makes up a greater percentage of total life cycle energy usage.
6. Apart from life cycle CO_{2eq} emissions (which largely occur in the operations and maintenance phase), environmental indicators are dependent on manufacture of the roof assembly materials. For all cases, the negative environmental implications are minimized as the service lives of the roof assemblies are maximized, indicating that good design, construction, and maintenance remain critical to reducing environmental impact by extending the useful life of roof systems.

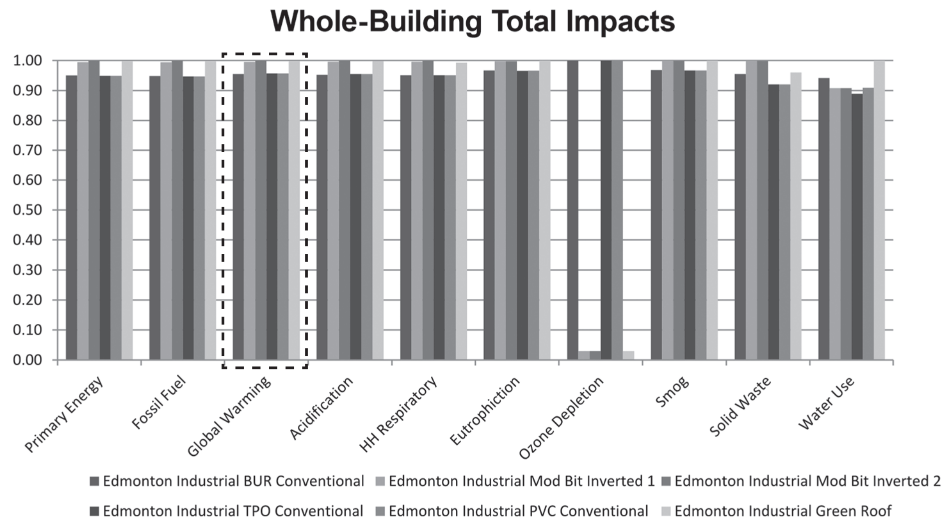

Figure 9 – BUR with same insulation level as single plies in Edmonton.

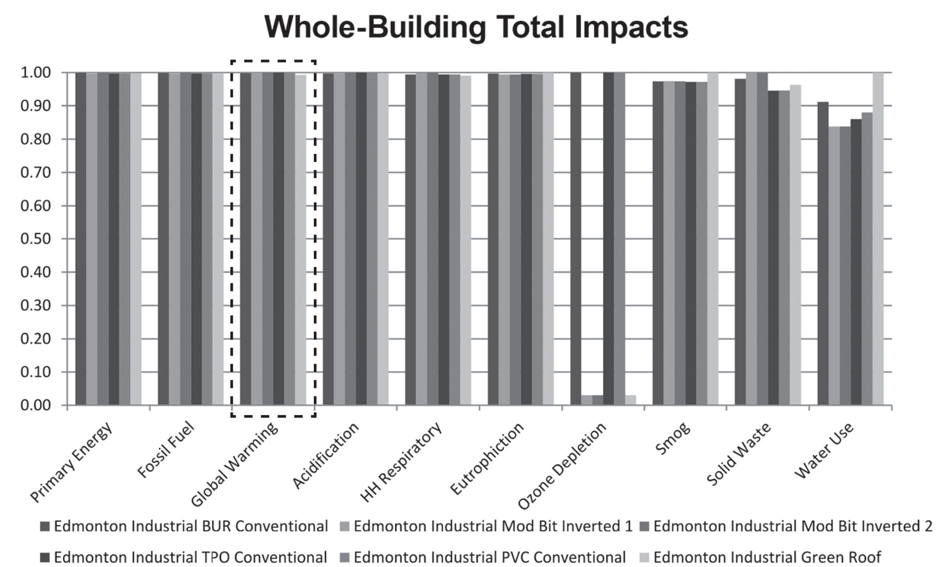

Figure 10 – Edmonton with all roof assemblies at code+ insulation levels.

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APPENDIX A

Building Archetype Descriptions

INDUSTRIAL

The rectangular-footprint, single-story building provides a total of approximately 5,400 m^2 of floor space with a footprint of 45 m by 120 m. The building is clad with full-height precast concrete sandwich panels with two-stage joints and 50 mm of extruded polystyrene rigid insulation within the panels. The precast panels extend 200 mm above the roof deck on all sides to form the roof parapet.

The building has a window/wall ratio of 25%, comprised mainly of standard shop-front glazing assemblies centered along the longer elevation.

The building structure is structural steel construction with flat-steel decking supported by open-web steel joists spaced 1.83 m on center, which in turn are supported by steel columns. The foundations is comprised of concrete strip footings and caissons with a cast-in-place slab-on-grade.

MID-RISE OFFICE BUILDING

The rectangular-footprint, 10-story building provides a total of approximately 27,000 m^2 of floor space with a footprint of 45 m by 60 m. The building is clad with double-glazed strip windows in curtain wall framing along every floor with prefinished metal panels between floors. The fenestration ratio of the building is 45%. The metal panels are supported on thermally broken z-bars attached to a block back-up wall. Semi-rigid insulation is used to fill in the cavity between the metal panels and the back-up wall.

The building is constructed of normally reinforced cast-in-place concrete floors, slabs, and columns. The roof deck is reinforced concrete construction, which is sloped to drain. An insulated built-up parapet runs 200 mm tall around the roof perimeter.

MID-RISE RESIDENTIAL BUILDING

The rectangular-footprint 10-story building provides a total of approximately 13,500 m^2 of floor space with a footprint of 45 m by 30 m. The building is clad with brick masonry veneer and a concrete block back-up wall. 50 mm of extruded polystyrene rigid insulation is installed along the outboard face of the concrete block back-up wall, followed by a 25 mm air gap between the insulation and the brick veneer.

The building has operable, thermally broken, aluminum-framed, double-glazed units in punched openings around the building. The fenestration ratio of the building is 40%.

The building is constructed of normally reinforced concrete floors, slabs, and columns with concrete block installed around the building perimeter between floor slabs. The roof deck is reinforced cast-in-place concrete, which is sloped to drain. An insulated built-up parapet runs 200 mm tall around the roof perimeter.

MID-RISE MIXED-USE (RESIDENTIAL AND OFFICE) BUILDING

The rectangular, 10-story building provides a total of approximately 27,000 m^2 of floor space with a footprint of 45 m by 60 m. The bottom two stories (5,400 m^2) are dedicated to office use. The building is predominately clad with precast panels over an insulated stud back-up wall. Installed on the outboard face of the back-up wall is 75 mm of semi-rigid insulation, followed by a 25 mm air gap between the insulation and the precast.

The building typically has operable, thermally broken, aluminum-framed, double-glazed units in punched openings around the residential portion of the building. The office floors comprise a curtain wall system with insulated spandrel panels. The fenestration ratio of the building is 35%.

The building is typically constructed of normally reinforced concrete floors, slabs, and columns with concrete block installed around the building perimeter between floor slabs. The roof deck is reinforced cast-in-place concrete, which is sloped to drain. An insulated, built-up parapet runs 200 mm tall around the roof perimeter.

HIGH-RISE OFFICE BUILDING

The rectangular 25-story building provides a total of approximately 33,750 m^2 of floor space with side lengths of 45 m and 30 m. The building is clad with a fully glazed, thermally broken, aluminum-framed curtain wall system. The building uses floor-to-floor double-glazed units with single-glazed insulated spandrel panels used across floor slabs. Each spandrel panel has an aluminum back pan, 100 mm deep, filled with semi-rigid insulation.

The building is typically reinforced concrete floor slabs and columns. The roof deck is reinforced concrete construction, sloped to drain. An insulated, built-up parapet runs 900 mm tall around the roof perimeter.

HIGH-RISE RESIDENTIAL BUILDING

The rectangular 25-story building provides a total of approximately 29,400 m^2 of floor space with side lengths of 42 m and 28 m. It is clad with a fully glazed, thermally broken, aluminum-framed window wall system. The building uses floor-to-floor double-glazed units with single-glazed spandrel panels across floor slabs. Each spandrel panel has an aluminum back pan, 75 mm deep, filled with semi-rigid insulation.

The building typically has reinforced concrete floor slabs and columns. The roof deck is reinforced concrete construction, sloped to drain. An insulated, built-up parapet runs 900 mm tall around the roof perimeter.

APPENDIX B

List of Materials Within Athena IE LCA

ROOF ASSEMBLIES		
#15 organic felt	Kraft paper vapor retarder	SOPRADRAIN ECO-5
½-in. fiberboard	MICROFAB	SOPRAFLOR
¾-in. HDPE pipe	Modified bitumen	Steel fasteners
Active AQUAMAT JARDIN	Polyisocyanurate	TPO membrane
Asphalt adhesive	PVC membrane	Electricity
Ballast	Roofing asphalt	Propane
Extruded polystyrene	Small-dimension lumber	Diesel
Filter fabric	Softwood plywood	
Galvanized steel sheet	SOPRA STICK	

Figure B1a – List of materials modeled with Athena IE. Note that all materials may not be applicable to every roof assembly or building archetype.

WHOLE-BUILDING ASSEMBLIES		
5/8” regular gypsum board	Glass-based shingles, 25-year	Polyester felt
6-mil polyethylene	Glass-based shingles, 30-year	Polyethylene filter fabric
Air barrier	Glass fiber	Polyisocyanurate foam board
Aluminum	Glass-reinforced facer	Polypropylene
Ballast (aggregate stone)	Glazing panel	Polypropylene scrim Kraft vapor retarder cloth
Batt fiberglass	Glulam sections	Precast concrete
Batt rock wool	Hollow structural steel	Precast insulated panel
Blown cellulose	Hot-rolled sheet	Precast insulated panel with brick veneer
Cedar wood bevel siding	Insulated metal panel	Precast panel
Cedar wood shiplap siding	Joint compound	PVC
Cedar wood tongue-and-groove siding	Laminated veneer lumber	PVC membrane 48-mil
Clay tile	Large-dimension softwood lumber, green	Rebar, rod, light sections
Cold-rolled sheet	Large-dimension softwood lumber, kiln-dried	Residential (30-ga.) steel cladding
Commercial (26-ga.) steel cladding	Low-e silver argon-filled glazing	Roofing asphalt
Concrete 20 MPa (fly ash 25%)	Low-e tin argon-filled glazing	Screws, nuts, and bolts
Concrete 20 MPa (fly ash 35%)	Low-e tin glazing	Small-dimension softwood lumber, green
Concrete 20 MPa (fly ash avg.)	MDI resin	Small-dimension softwood lumber, kiln-dried
Concrete 30 MPa (fly ash 25%)	Metric modular (modular) brick	Softwood plywood
Concrete 30 MPa (fly ash 35%)	Mineral-surface roll	Solvent-based alkyd paint
Concrete 30 MPa (fly ash avg.)	Modified-bitumen membrane	Solvent-based varnish
Concrete 60 MPa (fly ash avg.)	Mortar	Split-faced concrete block
Concrete blocks	Nails	Spruce wood bevel siding
Concrete brick	Natural stone	Spruce wood shiplap siding
Concrete tile	Ontario (standard) brick	Spruce wood tongue-and-groove siding
EPDM membrane (black, 60-mil)	Open-web joists	Standard glazing
EPDM membrane (white, 60-mil)	Organic felt shingles, 20-year	Steel tubing
Expanded polystyrene	Organic felt shingles, 25-year	Stucco over metal mesh
Extruded polystyrene	Organic felt shingles, 30-year	Stucco over porous surface
Fiber cement	Oriented strand board	Type-III glass felt
Foil facer	Paper tape	Type-IV glass felt
Galvanized decking	Parallel strand lumber	Vinyl siding
Galvanized sheet	Pine wood bevel siding	Water-based latex paint
Galvanized studs	Pine wood shiplap siding	Welded wire mesh/ladder wire
Glass-based shingles, 20-year	Pine wood tongue-and-groove siding	Wide flange sections

Figure B1b – List of materials modeled with Athena IE. Note that all materials may not be applicable to every roof assembly or building archetype.

Location	Average Yearly Minimum Temperature (°C)	Average Yearly Maximum Temperature (°C)	Average Annual Precipitation (mm)
Halifax	1.6	11	1,450
Montreal	1.4	11.1	980
Toronto	2.5	12.5	790
Edmonton	-1.2	9	475
Calgary	-2.4	10.5	415
Vancouver	6.5	13.7	1,200

Figure B2 – Climate differences between cities included in design tool (Environment Canada, 2012).