Sustainability of Rooftop Technologies in Cold Climates
Comparative Life Cycle Assessment of White Roofs, Green Roofs, and Photovoltaic Panels

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Summary

Sustainable building rooftop technologies, such as white roofs, green roofs, and photovoltaic(s) (PV) panels, are becoming increasingly implemented as a result of their associated environmental benefits. Studies of these rooftop technologies are often located in hot climates and do not assess their full environmental consequences. Further, current studies tend to focus on one technology and often do not evaluate the full range of technology options using a systematic framework with common assumptions and boundaries. This article evaluates the environmental performance on a life cycle basis of white roofs, green roofs, and roof-mounted PV in the cold Canadian climate. Solar PV demonstrates the highest environmental performance in all impact categories considered (see complete list in Results section) and is the preferred option from an environmental perspective. Green roofs result in beneficial environmental impacts, although much less significant than those obtained with PV, and are the only rooftop technology that reduces both heating and cooling energy use. The environmental performance of white roofs in cold climates is strongly affected by the heating penalty (i.e., the increase in heating energy use resulting from the high solar reflectance). Although white roofs have been proven an outstanding option in warmer climates, in cold climates, net negative environmental impacts lead to white roof technology not being recommended for general applications in cold climates. A sensitivity analysis shows that the conclusions in this study provide robust insights across Canada and cold climates in general.

Keywords:
building energy use
green roofs
industrial ecology
life cycle assessment (LCA)
solar photovoltaics
white roofs

Introduction

Rooftops in urban areas have large potential to increase the environmental performance of buildings owing to their large surface area, which are greatly underutilized. Several technologies are available, but the trade-offs between options are complex. Designing or retrofitting rooftops with sustainable technologies, such as green roofs, white roofs, and photovoltaic(s) (PV) panels, may offer beneficial and/or adverse environmental impacts associated with energy, air, and water quality over their life cycle. These technologies are often evaluated only in terms of their thermal performance and/or associated building energy use in the use phase (Wong et al. 2003a, 2003b; Niachou et al. 2001; Del Barrio 1998; Jim and Tsang 2011; Levinson and Akbari 2010), which is only one of their several facets. Further, most green and white roof technology studies apply to hot climates and do not address their environmental performance in cold climates. Despite widespread interest in professional
Table 1  Impact categories and criteria

| Impact category                  | Criterion                  |
|----------------------------------|----------------------------|
| Carcinogens                      | kg C\textsubscript{6}H\textsubscript{5}Cl-equiv. |
| Noncarcinogens                   | kg C\textsubscript{6}H\textsubscript{5}Cl-equiv. |
| Respiratory inorganics           | kg PM\textsubscript{2.5}-eq. |
| Respiratory organics             | kg C\textsubscript{2}H\textsubscript{4}-eq.  |
| Aquatic eco-toxicity             | kg TEG water               |
| Terrestrial eco-toxicity         | kg TEG soil                |
| Terrestrial acidification/hu trification | kg SO\textsubscript{2}eq |
| Aquatic acidification           | kg SO\textsubscript{2}eq    |
| Aquatic eutrophication          | kg PO\textsubscript{4} P-lim |
| Global warming                   | kg CO\textsubscript{2}-eq   |
| Nonrenewable Energy             | MJ Primary                 |

Note: PM\textsubscript{2.5} is particulate matter smaller than 2.5 \(\mu\)m; kg = kilograms; C\textsubscript{6}H\textsubscript{5}Cl = vinyl chloride; eq. = equivalent; C\textsubscript{2}H\textsubscript{4} = ethylene; TEG = triethylene glycol; SO\textsubscript{2} = sulfur dioxide; PO\textsubscript{4} = phosphate; CO\textsubscript{2} = carbon dioxide; MJ = megajoule; P-lim considers that phosphorus is the limited factor in water for nutrient enrichment.

communities and third-party environmental certification systems, such as Leadership in Energy and Environmental Design (US GBC 2010), the full positive and negative impacts of these technologies over their life cycle may not be considered in design decisions. This study performs a comparative life cycle assessment (LCA) addressing the environmental performance of green roofs, white roofs, and PV panels in the cold climates of three Canadian cities: Vancouver, Calgary, and Toronto.

**Objective and Scope**

This LCA analyzes the environmental impacts from cradle to end of use (i.e., manufacturing, transportation, installation, and use phases), as shown in figure 1, and assumes a 50-year building lifespan to be consistent with similar studies (Berggren et al. 2013). Disposal is not included within the scope because the methods of disposal for each technology are not standardized across jurisdictions and there is a lack of available data for this phase (Saiz et al. 2006). Future work should explore impacts associated with disposal. The functional unit for the assessment is a 1,340-square-meter (m\textsuperscript{2}) roof of an office building, following the archetype titled “large office” used in the development of the National Energy Codes for Buildings 2011 (Government of Canada 2011). Environmental impacts associated with manufacturing, transportation, installation, and changes in energy production and consumption associated with the technologies are assessed using SimaPro version 8.0.2 (PRé Consultants 2008), which uses the ecoinvent database (SCLCI 2014) and the IMPACT 2002+ impact assessment method (Jolliet et al. 2003). This method is chosen because it has a broad range of midpoint categories pertaining to impacts affecting human health, air, and water quality, which, in turn, are consistent with the assessment principles in International Organization for Standardization (ISO) 14042 (ISO 2010). The three sustainable rooftop technologies assessed in this study perform a variety of different functions (e.g., insulation and stormwater retention). The large number of midpoint categories allows for a broader perspective to address a wide variety of impacts, as opposed to energy use and/or global warming potential (GWP), which is common in many studies. This study aims to be as comprehensive as the data allow. Table 1 lists the impact categories considered in this study along with their corresponding evaluation criteria.

**Background**

**White Roofs**

White roofs or cool roofs have high solar reflectance and high thermal emittance (Levinson and Akbari 2010). Solar reflectance and thermal emittance are dimensionless parameters between 0 and 1 that describe a material’s relative ability to reflect sunlight (spectrum, 0.3 to 2.5 \(\mu\)m) and emit thermal radiation (spectrum, 4 to 80 \(\mu\)m), respectively. In a given wavelength range, emittance is equivalent to absorptance. Absorptance and reflectance are complementary parameters (i.e., absorptance = 1 – reflectance) for opaque materials. The solar reflectance of dark roofing materials typically range from 0.05 to 0.2, whereas the solar reflectance of white roofs typically range from 0.55 to 0.85 (Urban and Roth 2010; Levinson 2009). Roof materials with high solar reflectance reduce the amount of heat absorbed, resulting in lower surface temperatures compared to materials with low solar reflectance. Thermal emittance does not depend on color. Thermal emittance of nonmetallic materials, such as roof paints, is typically 0.8 to 0.95 (Urban and Roth 2010), whereas thermal emittance of a clean, bare zincalume steel surface can be as low as 0.05 (Levinson 2009). Therefore, white roofs offer the advantage of being 3 to 10 times better at reflecting sunlight than gray roofs while maintaining the ability to emit thermal radiation.

The potential benefits of white roofs include: (1) reduction of building cooling energy use; (2) increased longevity of the roof membrane owing to smaller temperature fluctuations; (3) reduction in local air temperatures and urban heat-island effect, which improves air quality and slows smog formation; and (4) reduction of peak electric power demand, derived from the cooling energy savings (Urban and Roth 2010). On the other hand, the lower solar absorptance of white roofs can increase heating energy requirements, particularly in cold climates (Levinson and Akbari 2010). This is referred to as a heating penalty.

Previous white roof studies focus on quantifying thermal performance (Suehrcke et al. 2008; Synnefa et al. 2007), associated energy-use changes, and cost reductions at the scale of an individual building (Jo et al. 2010; Akbari et al. 2005). Studies on white roof energy performance are typically conducted in hot climates and conclude that white roofs offer substantial energy savings and short payback periods. However, Levinson and Akbari (2010) show that white roof energy performance in cold climates is poor.

**Green Roofs**

A green roof, also referred to as an eco-roof, living roof, or vegetated roof, is a roof that is covered with vegetation and
a growing medium. Construction typically includes a drainage layer, root barrier, and waterproof membranes, whereas vegetation and growing medium compositions vary depending on climate (Peck et al. 1999). These roofs are well suited to highly developed areas and their benefits include aesthetic appeal, natural habitat creation, air-quality improvement, urban heat-island effect reduction, stormwater retention and quality improvements, sound insulation, increased longevity of the roof membrane, and building energy savings (Oberndorfer et al. 2007). They also represent a potential carbon sink (carbon dioxide [CO₂] absorption by plant growth) in urban environments (Mohareb and Kennedy 2012). Green roofs reduce building cooling loads through latent heat loss (evapotranspiration), shading, and increased solar reflectance from the vegetation, compared to conventional gray roofs (Jim and Tsang 2011). The thermal mass of a green roof contributes to stabilizing roof temperatures year round (Castleton et al. 2010), protects the roof membrane from ultraviolet light, and provides an extra layer of thermal insulation. Their thermal performance can vary depending on moisture content in the growing medium. Vegetated roofs improve urban air quality by absorbing gaseous pollutants and cooling ambient urban air, which affect the formation of photochemical smog (Currie and Bass 2008; Rowe 2011). Green roofs are classified as either intensive or extensive. Intensive roofs have the appearance of conventional ground-level gardens and are typically used to increase living space. They feature a variety of plant communities on a relatively heavy and deep substrate layer (20 centimeters [cm] or more). Extensive roofs are more strictly functional in purpose. They feature low-growing plant communities (e.g., sedum) on a shallower and lighter substrate (2 to 15 cm). Extensive roofs require little or no maintenance and do not require structural improvements (Oberndorfer et al. 2007). Further background on green roofs may be found in the Supporting Information on the Web site.

**Roof-Mounted Solar Photovoltaic**

Roof-mounted PV is a form of on-site electricity generation that can offset the emissions from more environmentally intensive sources of electricity and reduce electricity transmission losses. Electricity production profiles of roof-mounted PV match electricity loads in commercial buildings (e.g., air conditioning on summer afternoons), which reduces peak electricity demand from the grid. The solar PV panels provide shading of the roof, reducing summer cooling loads but increasing winter heating loads.

Stoppato (2008) presents a comprehensive LCA of solar PV technologies. In addition to compiling extensive and detailed inventory data, Stoppato concludes that the energy payback time of PV is shorter than its operation lifespan, even in the least...
ideal geographical conditions. Muller and colleagues (2005) focus on the recycling process of solar PV panels. Sherwani and colleagues (2010) review solar PV system LCAs and conclude that the estimated energy payback time for amorphous, monocrystalline, and polycrystalline solar PV systems is on the order of 2.5 to 3.2, 3.2 to 15.5 and 1.5 to 5.7 years, respectively. Other energy payback time estimates (de Wild-Scholten 2011) for optimally inclined modules installed in Southern Europe (1,700 kilowatt-hours per square meter per year [kWh/m²/yr] solar irradiation) are 1.7 to 1.8 years for mono- and polycrystalline and as little as 0.8 to 1.3 years for new thin-film technologies (cadmium telluride, micrometer-scale silicon, and copper indium gallium selenide).

**Previous Comparative Life Cycle Assessments: Findings and Limitations**

Previous LCAs present the environmental performance of individual roofing technologies. To our knowledge, there is no study that compares white roofs, green roofs, and PV panels accounting for a range of environmental impacts (impact categories) using a systematic framework with common assumptions and boundaries for the assessment of all three technologies. A review of studies that partially compare these technologies may be found in the Supporting Information on the Web.

**Method**

The current study specifies a functional unit of one “large office” building roof assuming a 50-year building lifespan (Berggren et al. 2013). The building is designed to the specifications of the building archetype used in the Model National Energy Code for Buildings (Government of Canada 2011) and meets the envelope requirements in the National Energy Code of Canada for Buildings 2011 (hereafter referred to as NECB 2011) in three selected locations: Vancouver, Calgary, and Toronto (i.e., building envelope characteristics were modified to match the requirements in each location).

Each technology retrofits an existing building with a standard gray roof. Given that this study assumes that a gray roof is already installed, the manufacturing, transportation, and installation of the existing gray roof are not accounted for. Envelope components (i.e., walls, windows, initial construction processes, and so on) are not accounted for in the life cycle inventory. EnergyPlus (US DOE 2013), a building performance simulation software, is used to compare the changes in building energy use for each technology in comparison to the baseline roof. Table 2 summarizes the main assumptions. The SimaPro products used for upstream impact assessment may be found in the Supporting Information on the Web.

**Manufacturing, Transportation, and Installation**

**Green Roof**

An extensive green roof, as opposed to intensive, is chosen for this study, owing to the simplicity of the installation on a building retrofit without requiring structural alterations. The lifespan is assumed to be 50 years because it is a common lifespan used in studies as reviewed in Saadatian and colleagues (2013). Extensive green roofs in this study are composed of a low-density polyethylene (LDPE) drainage panel, a LDPE root barrier, a 150-millimeter-thick growing medium, and vegetation. Growing medium composition includes compost, expanded clay, and sand and varies depending on the city assessed. Expanded clay (or pumice or stallite) is a porous material manufactured in a high-temperature kiln to provide increased water retention with a low density. The growing medium of the green roof installed in Vancouver is based on the design used in Connely and colleagues (2006) with 33.3% expanded clay, 33.3% sand, and 33.3% compost. The growing medium of the green roof installed in Calgary consists of 65% expanded clay, 15% sand, 15% compost, and 5% sawdust based on Tolderlund’s (2010) design recommendations for a semi-arid and arid climate. We could not identify any case studies documenting successful growing medium composition in Toronto. Therefore, it is assumed that the green roof installed in Toronto has a composition that is 45% expanded clay, 25% sand, 25% compost, and 5% sawdust. These values are in between the growing medium compositions used in Vancouver, which are suited for a relatively warmer and wet climate, and Calgary, which are suited for a dry and cold climate. The green roof area densities for Vancouver, Calgary, and Toronto are 150, 96, and 125 kilograms (kg)/m², respectively, which is within the range of extensive green roofs requiring no structural changes (Oberndorfer et al. 2007). Vegetation is assumed to consist of prairie grass and sedums specific to each region. Although vegetation in each region is different, it is assumed that the leaf area index (LAI) would remain constant. The LAI is the projected leaf area per unit area of soil and influences the energy performance of the green roof.

It is assumed that the green roof’s associated transportation impacts are negligible, which is reasonable owing to the low density of expanded clay and small mass of the LDPE. The installation is done on site, and the materials are lifted by crane for an estimated duration of 10 hours.

It is also assumed that the growing medium materials are sourced locally, and compost and sawdust are waste products; therefore, no impacts are associated with their production. The model does not include framing of the extensive green roof, given that the impacts are deemed negligible.

**White Roof**

The white roof is installed over the existing gray roof using white alkyd paint. Paint, as opposed to tiles with low emissance, is used, because it is more cost-effective. To our knowledge, no literature exists detailing average lifespan of a gray roof or different types of white roofs. This study assumes that over the 50-year lifespan, the roof is repainted every 10 years, which is at the low end of the values suggested in Levinson and Akbari (2010). The transportation and installation assumptions are summarized in Table 2. Owing to the lack of reported membrane lifespan information and the fact that manufacturing, transportation, and
Table 2 Summary of assumptions

|                     | Roof manufacturing, transportation, and installation |
|---------------------|------------------------------------------------------|
|                     | White roof                                           | Green roof                                           | Roof-mounted PV                                      |
| **Materials**       | Alkyd white paint                                    | LDPE drainage panel, LDPE root barrier, 150 mm thick growing medium | Polycrystalline PV panels, BOS                       |
| **Manufacturing**   | China                                                | Local (Cal, Van, Tor)                                | China                                                |
| **Transportation means** | Freighter+train                                       | N/A                                                  | Freighter+train                                       |
| **Lifespan (years)**| 10                                                   | 50                                                   | 25                                                   |

**Building characteristics**

|                     | Calgary | Vancouver | Toronto |
|---------------------|---------|-----------|---------|
| **Roof area (m²)**   | 1,340   |           |         |
| **Heating system**   | Natural gas boiler: 83% seasonal efficiency          |           |         |
| **Cooling system**   | Centrifugal chiller: Seasonal COP, 5.5              |           |         |
| **Climate zone**     | Zone 7B  | Zone 4    | Zone 5  |
| **Wall U value (W/m²-K)** | 0.210 | 0.315     | 0.278   |
| **Roof U value (W/m²-K)** | 0.162 | 0.227     | 0.183   |
| **Windows U value (W/m²-K)** | 2.2    | 2.4       | 2.2     |
| **Window-to-wall ratio (%)** | 0.27   | 0.4       | 0.4     |
| **Total horizontal solar radiation (kWh/m²/yr)** | 1,380   | 1,230     | 1,320   |

*Overall heat transfer coefficient.

m² = square meters; W/m²-K = watt per square meter Kelvin; kWh/m²/yr = kilowatt-hour per square meter per year; LDPE = low-density polyethylene; Cal = Calgary; Van = Vancouver; Tor = Toronto; N/A = not applicable; PV = photovoltaic(s); BOS = balance of system; COP = coefficient of performance.

Installation of the existing gray roof are outside the scope of this study, increased longevity of the existing roof membrane resulting from smaller temperature fluctuations of white roofs is not accounted for in this analysis.

**Photovoltaic Roof**

The solar panel array is designed similar to Myrans (2009). The tilt angle is chosen as 50° with an array azimuth of 0° south. Row separation is 2.5 meters (m) to avoid shading among panels under winter low-sun-elevation conditions (17°), resulting in 345 polycrystalline PV panels (15 rows x 25 panels) with a total area of 433 m². A 16% efficiency is assumed, which is at the high end of the efficiency spectrum, but is chosen for consistency with the PV module in Stoppato (2008).

The materials and manufacturing of the PV module are based on the SimaPro polycrystalline PV panel product (see the Supporting Information on the Web). The panels are transported by freighter from China to Vancouver and then by train to Calgary and Toronto. For the materials and manufacturing of the balance of system (BOS) components, data are obtained from Mason and colleagues (2006), taking into account the embodied energy and GWP. No data were found for other impact categories.

The PV panels are assumed to have a life of 25 years, common in many studies (Branker et al. 2011), so the PV array will be replaced once during the LCA time frame.

**Use Phase**

**Building Energy Simulation Model**

Building energy use is assessed using EnergyPlus 8.1 (US DOE 2013). EnergyPlus is selected as the modeling tool because it accounts for the optical properties of roof surfaces in the building energy balance (i.e., solar absorptance and thermal emittance), features the green roof model developed by Sailor (2008), and has a model for roof-mounted PV.

Building geometry is defined according to the specifications of the “large office” archetype (Government of Canada 2011). The floor plan is 36.6 m x 36.6 m (1,338 m²), and floor-to-floor height is 3.8 m. Envelope characteristics are adapted to the three study locations as per the requirements in the prescriptive compliance path in NECB 2011 (CCBFC 2011), resulting in a different building model for each location.

It must be noted that buildings that meet the requirements in NECB 2011 are expected to provide, on average, 26% energy savings relative to the 1997 version of the Model National Energy Code for Buildings (Caneta Research Inc. 2011). The energy benefits and associated environmental impacts resulting from the sustainable rooftop technologies would change if applied on a lower-performing baseline study building.

The baseline gray roof is assumed to have a 0.9 thermal absorptance and a 0.1 solar reflectance. The white roof is assumed to have a 0.9 thermal absorptance and a 0.65 solar reflectance. Roof properties correspond to “standard gray” and “standard white” low-sloped roofing materials (aged properties).
in Levinson (2009). Optical properties of gray roofs are used both in the baseline case and the roof-mounted PV case.

The building model of the roof-mounted PV case includes shading surfaces on the roof to account for the shading effect of the PV panels on the roof membrane. PV electricity production was computed with EnergyPlus, assuming 16% efficiency for the PV panels and 89% for the inverter (Stoppato 2008). Additional losses, such as in cables or accumulation of dust, are not accounted for in this study.

The green roof case was simulated using the EcoRoof model by Sailor (2008) in combination with the weather files (Government of Canada 2014; US DOE 2011). Further details on the building modeling assumptions may be found in the Supporting Information on the Web.

**Electricity- and Natural-Gas–Saving Benefits**

The energy savings or expenditures caused by each retrofit during the use phase results in offset or adverse environmental impacts for each region. The electricity generation profile for each province, represented in SimaPro using the ecoinvent database (SCLCI 2014), is used to assess the impacts caused from changes in cooling loads. A natural gas industrial furnace, also represented in the SimaPro/eco2invent database, was used to assess the impacts caused from changes in heating loads. Infrastructure impacts, such as changes in the electricity generation and distribution infrastructure resulting from variations in electricity demand with the rooftop technologies, are excluded from these calculations.

**Air and Stormwater of Green Roof**

This study uses the results from a case study completed by the Toronto and Region Conservation Authority (TRCA) (TRCA 2006) to quantify the air and stormwater environmental impacts associated with green roofs. It is assumed that both the 2006 TRCA green roof and the green roofs chosen for this LCA will perform similarly given that both are extensive, have similar growing medium thickness (TRCA is 14 cm and this LCA assumes 15 cm), and operate in cold climates. Green roof performance is dependent upon climate and roof composition, although the actual performance in Calgary, Vancouver, and Toronto will not be exactly the same as TRCA (2006); however, using their results provide insight into the approximate impacts and relative contribution of a green roof’s influence on air quality and stormwater runoff. As research and development progresses and a greater understanding of the performance of green roofs is obtained, future LCAs can improve upon these results to be climate and site specific.

TRCA (2006) monitored runoff volume and the precipitation event mean concentration of an extensive green roof and control roof in order to calculate the volume-weighted mean concentration of each roof. To obtain the loading per functional unit, the concentration is multiplied by the roof area, 50 years, and the runoff volume, which is obtained from each city using the Weather Office of Environment Canada’s (WOEC’s) Climate Normal for annual precipitation (WOEC 2012).

The findings of two U.S. Department of Agriculture Forest Service’s Urban Forest Effects models completed in Toronto (Currie and Bass 2008) and Washington (Casey Trees Endowment Fund and Limno-Tech Inc 2005) are used to estimate air pollution reduction. It is assumed that the volume of pollutants removed is applicable to approximate the green roofs in this LCA; however, it is acknowledged that air-quality improvements are driven by local pollution concentrations, meteorological data, and plant-specific removal rates. The average results from the two studies of particulate matter, sulfur dioxide (SO₂), nitric oxide, carbon monoxide, and ozone reductions are applied to the green roofs. This study does not account for CO₂ reductions resulting from photosynthesis during the use phase because CO₂ is released when vegetation undergoes decomposition.

**Results**

Table 3 summarizes the life cycle impact of a white roof, green roof, and roof-mounted PV array, relative to a conventional gray roof, in Calgary, Vancouver, and Toronto. Results are shown as “impact reductions”; therefore, positive and negative reductions imply beneficial and adverse environmental impacts, respectively, compared to a gray roof. The addition of any one of the rooftop technologies will add to environmental impacts of the system; therefore, upstream impacts are always negative. Impact reductions of PV are 1 to 3 orders of magnitude higher than those of white and green roofs in all impact categories in the three cities. Aquatic eco-toxicity, terrestrial eco-toxicity, global warming (GW), and nonrenewable energy are the impact categories with the largest variations. Overall, the three cities show consistent results. The final net result for some impact categories (i.e., whether a technology results in a net benefit or a net adverse impact, relative to the baseline, in a given category) differs in Calgary, compared to Vancouver and Toronto, owing to the dominant role of coal in the Alberta electricity generation system; namely, impact categories of respiratory inorganics, aquatic eco-toxicity, and aquatic eutrophication for green roofs and carcinogens and noncarcinogens for white roofs. Respiratory organics and respiratory inorganics are the categories that see the smallest impact with PV.

The green roof’s influence on stormwater and air quality is essentially negligible under the conditions modeled in this study. The relative contribution of all impact categories, except aquatic eutrophication and aquatic eco-toxicity, were less than 1%. The largest contribution occurs in Vancouver, owing to higher precipitation, with a relative contribution of approximately 9% and 11% for aquatic eutrophication and aquatic eco-toxicity, respectively. In Calgary and Toronto, all relative contributions are below 3%. Green roofs reduce aquatic eco-toxicity by decreasing the pollutant load of metals and polycyclic aromatic hydrocarbons. These contaminants are observed in runoff from the control roof in the TRCA (2006) study caused by the roof material (shingles and tar). Nitrogen and phospho-
Table 3  Summary of results: Reductions on impacts relative to a conventional gray roof

| Impact category              | Unit               | White roof | Green roof | PV     |
|-----------------------------|--------------------|------------|------------|--------|
| Carcinogens                 | kg C₂H₄Cl-eq.      | 2.1E+03    | 2.2E+03    | 4.8E+05|
| Noncarcinogens              | kg C₂H₄Cl-eq.      | 2.5E+02    | 6.8E+01    | 7.4E+04|
| Respiratory inorganics      | kg PM₉.₅-eq.       | −3.3E+01   | −6.5E+00   | 2.3E+03|
| Respiratory organics        | kg C₂H₄-eq.        | −2.2E+01   | 3.7E−01    | 4.2E+02|
| Aquatic eco-toxicity        | kg TEG water       | −1.7E+07   | −2.9E+05   | 2.9E+08|
| Terrestrial eco-toxicity    | kg TEG soil        | 5.8E+04    | −2.0E+05   | 4.2E+07|
| Terrestrial acid/nutri      | kg SO₄-eq.         | −4.9E+02   | −1.6E+02   | 4.8E+04|
| Aquatic acidification       | kg SO₄-eq.         | −1.8E+02   | −3.5E+01   | 2.4E+04|
| Aquatic eutrophication      | kg PO₄ P-lim       | −1.3E+01   | 2.2E+00    | 1.2E+03|
| Global warming              | kg CO₂-eq.         | −5.8E+04   | 3.4E+04    | 3.3E+06|
| Nonrenewable energy         | MJ primary         | −1.1E+06   | 6.9E+05    | 4.3E+07|

| Impact category              | Unit               | White roof | Green roof | PV     |
|-----------------------------|--------------------|------------|------------|--------|
| Carcinogens                 | kg C₂H₄Cl-eq.      | −6.6E+02   | 8.5E+02    | 7.0E+04|
| Noncarcinogens              | kg C₂H₄Cl-eq.      | −1.5E+02   | 2.0E+00    | 1.2E+04|
| Respiratory inorganics      | kg PM₉.₅-eq.       | −4.7E+01   | −1.7E+01   | 9.8E+01|
| Respiratory organics        | kg C₂H₄-eq.        | −2.4E+01   | −2.4E−00   | −3.9E+01|
| Aquatic eco-toxicity        | kg TEG water       | −1.8E+07   | 6.0E+04    | 8.3E+07|
| Terrestrial eco-toxicity    | kg TEG soil        | 1.0E+05    | −7.2E+03   | 2.1E+07|
| Terrestrial acid/nutri      | kg SO₄-eq.         | −7.7E+02   | −1.7E+02   | 4.3E+03|
| Aquatic acidification       | kg SO₄-eq.         | −3.3E+02   | −5.0E+01   | 1.7E+03|
| Aquatic eutrophication      | kg PO₄ P-lim       | −2.4E+01   | −6.7E−01   | 2.4E+01|
| Global warming              | kg CO₂-eq.         | −7.1E+04   | 1.5E+04    | 2.3E+05|
| Nonrenewable energy         | MJ primary         | −1.2E+06   | 2.9E+05    | 4.1E+06|

| Impact category              | Unit               | White roof | Green roof | PV     |
|-----------------------------|--------------------|------------|------------|--------|
| Carcinogens                 | kg C₂H₄Cl-eq.      | −9.7E+02   | 9.6E+02    | 7.8E+04|
| Noncarcinogens              | kg C₂H₄Cl-eq.      | −2.0E+02   | −1.8E+00   | 1.4E+04|
| Respiratory inorganics      | kg PM₉.₅-eq.       | −3.8E+01   | −4.3E+00   | 1.0E+03|
| Respiratory organics        | kg C₂H₄-eq.        | −2.5E+01   | −2.6E+00   | 2.0E+01|
| Aquatic eco-toxicity        | kg TEG water       | −1.7E+07   | 5.0E+05    | 1.7E+08|
| Terrestrial eco-toxicity    | kg TEG soil        | 8.2E+04    | −1.7E+04   | 2.7E+07|
| Terrestrial acid/nutri      | kg SO₄-eq.         | −5.9E+02   | −1.1E+02   | 2.3E+04|
| Aquatic acidification       | kg SO₄-eq.         | −2.8E+02   | −1.2E+01   | 1.0E+04|
| Aquatic eutrophication      | kg PO₄ P-lim       | −2.1E+01   | −1.3E−01   | 2.2E+02|
| Global warming              | kg CO₂-eq.         | −6.7E+04   | 1.3E+04    | 1.1E+06|
| Nonrenewable energy         | MJ primary         | −8.7E+05   | 5.4E+05    | 3.7E+07|

Note: PM₂.₅ is particulate matter smaller than 2.5 µm; acid/nutri = acidification/nitrification; kg = kilograms; C₂H₄Cl = vinyl chloride; eq. = equivalent; C₂H₄ = ethylene; TEG = triethylene glycol; SO₄ = sulfur dioxide; PO₄ = phosphate; CO₂ = carbon dioxide; MJ = megajoule; PV = photovoltaic(s); P-lim considers that phosphorus is the limited factor in water for nutrient enrichment.

Cubri et al., LCA of Rooftop Technologies in Cold Climates 255

rus can leach from fertilizers or compost used for vegetation growth; therefore, stormwater runoff adversely impacts aquatic eutrophication. TRCA (2006) recommends that the chemical and leachate properties of growing media should be considered during construction and phosphorus-rich fertilizers or excessive nutrient levels be avoided.

The relative contributions to environmental impacts in the use and upstream (manufacturing, transportation, and installation) phases for Toronto are shown in figure 2. PV performs best in all impact categories, with the lowest adverse upstream impacts and greatest beneficial impacts during the use phase. Green roofs perform better than white roofs in all impact categories, except terrestrial eco-toxicity. Given that this study assumes that the assessed rooftop technologies are retrofitted on an existing gray roof, there are no offsets from manufacturing, transportation, and installation of the gray roof included within the scope of this assessment. Therefore, upstream impact reductions are always negative. Use-phase impact reductions are positive in all cases, except for white roofs in impact categories of aquatic eutrophication, GW, and nonrenewable energy.
This is owing to the poor energy performance of white roofs in cold climates because they increase the heating load.

Figure 3 highlights greenhouse gas (GHG) emission reductions, which corresponds to impact category GW for white roofs (a), green roofs (b), and PV (c). The results focus on GHG emissions reductions because this impact category reflects interesting trade-offs between the impacts associated with heating and cooling energy use and electricity production, which are the most likely to influence investment decisions.

Variations in heating and cooling energy use strongly depend on climate. Calgary and Vancouver, the coldest and warmest cities in that order, show the largest variations in heating and cooling energy use, respectively. PV electricity generation varies depending on availability of solar radiation. Calgary and Vancouver are the cities with the highest and lowest PV generation, respectively. GHG emissions resulting from upstream activities are similar across each city.

The additional heating energy consumed as the result of white roof reflectance is larger than the cooling savings in terms of both final energy and GHG emissions reductions in the three studied locations. Upstream white roof impacts further decrease the potential to reduce GHG emissions with this technology. Cooling energy savings for white roofs in Vancouver (the city with the largest relative cooling loads) have little GHG emissions reduction impact owing to the low carbon intensity in British Columbia’s electricity generation mix consisting of approximately 92% hydro. The results (figure 3b) show that green roofs in each location provide reductions in both heating and cooling energy use. GHG emissions reductions in the use phase of green roofs, owing to decreased heating energy use, are larger than the adverse emissions in the upstream phases, resulting in a net positive impact in the three locations.

The beneficial impact of PV electricity production on GHG emissions reductions is 10 to 30 times larger than the impacts derived from the variations in cooling and heating energy use, as well as the upstream phases. The large variations in PV GHG emissions reductions are mainly a result of the differences in electricity carbon intensity across provinces.

**Sensitivity Analysis**

Electricity carbon intensity is the input that has the largest impact on GHG emissions results. There are variations in electricity use with white and green roofs resulting from their cooling load reduction. Figure 4 presents the sensitivity of the GHG emissions reductions in Toronto depending on the electricity grid carbon intensity, weather, envelope thermal resistance, and...
Figure 3  Heating, cooling, upstream energy savings and electricity production (kWh) and GHG emissions reductions (kg CO₂-eq) of (a) white roofs, (b) green roofs, and (c) roof-mounted PV. For example, white roofs in Calgary require approximately an additional 210,000 kWh of final heating energy use (natural gas) than conventional grey roofs and save approximately 49,000 kWh in cooling final energy use (electricity). PV electricity production not to scale. WR = white roof; GR = green roof; PV = photovoltaic; GWP = global warming potential; kWh = kilowatt-hours; kg CO₂-eq. = kilograms carbon dioxide equivalent.
**Figure 4** Sensitivity of global warming potential reductions in Toronto depending on the electricity grid carbon intensity, weather (Vancouver vs. Calgary), envelope thermal resistance (code requirements in Vancouver vs. Calgary), and the efficiency of the heating and cooling systems represented by boiler efficiency and chiller coefficient of performance (COP) for (a) white roofs, (b) green roofs, and (c) roof-mounted PV. For example, green roofs in Toronto reduce GWP by approximately 20,000 kg CO$_2$-eq compared to grey roofs. If the electricity grid carbon intensity is set to 0.0 kg CO$_2$-eq/kWh instead of setting it to Toronto’s electricity carbon intensity (approximately 0.3 kg CO$_2$-eq/kWh, the GWP reductions with green roofs drop to approximately 9,400 kg CO$_2$-eq). In contrast, if the electricity carbon intensity is set to 1.2 kg CO$_2$-eq/kWh, the GWP reductions with green roofs increase to approximately 52,000 kg CO$_2$-eq. “low” and “high” (black and white in the legend, respectively) refer to values used in the sensitivity analysis relative to Toronto. For example, testing sensitivity of GWP to building envelope, Calgary is “high” (white) because the envelope requirements in Calgary are higher than in Toronto, while the envelope requirements in Vancouver are “low” (black) relative to the requirements in Toronto. Elect Carbon Intens = electricity grid carbon intensity; Cal = Calgary; Van = Vancouver; PV = photovoltaics; kg CO$_2$-eq/kWh = kilograms carbon dioxide per kilowatt-hour; GWP = global warming potential.
the efficiency of the heating and cooling systems represented by boiler efficiency and chiller coefficient of performance (COP), respectively. See “building energy modeling details” in the supporting information on the Web.

GHG emissions reductions increase with increasing electricity carbon intensity across the three technologies. PV is particularly sensitive to electricity carbon intensity because its benefits are based on carbon-free electricity production, rather than on the impacts on building energy use. A zero carbon electricity grid intensity would result in net negative impacts of PV owing to the slight heating energy increase caused by shading and upstream impacts. However, a 100% renewable grid would also have negative impacts owing to the upstream activities. GHG impacts of white roofs remain negative even in the most carbon-intensive electricity generation mix.

Improvements in building envelope thermal performance (tested using Calgary’s code-compliant building) and boiler efficiency increase GHG emissions reductions for white roofs and PV, but reduce the benefits of green roofs. The impacts associated with a heating energy increase caused by white roofs and PV (i.e., shading) are reduced with increased insulation. On the other hand, the additional insulation provided by green roofs results in larger GHG emissions reductions on buildings with a lower insulation level, as well as a low efficiency boiler. It must be noted that this study is based on NECB 2011–compliant buildings, which requires a substantially higher level of insulation than previous versions of the code. It would be expected that most of the current building stock has lower insulation level and boiler efficiency than that required in the 2011 code. The benefits of green roofs would increase if applied on older buildings, whereas those of white roofs and PV would decrease.

Transportation of the green roof growing medium has a substantial impact on its GHG emissions reductions owing to its weight. Regardless, green roofs have net positive GHG emissions reductions even if materials are transported 1,000 kilometers (e.g., from Vancouver to Calgary).

Discussion and Future Work

The performance of white roofs in this study and those documented in the literature, which are typically studied in hot climates, suggest that performance is sensitive to climate conditions, which results in white roofs having a net adverse GHG emissions impact in the Canadian cities studied. A comprehensive study on white roof performance by Levinson and Akbari (2010) identified locations in northern U.S. cities where white roofs have a negative carbon reduction of up to –0.52 kg CO₂/m²/yr of conditioned roof area during the use phase. Using their functional unit, the use phase results for white roofs in this study have carbon reductions of –0.28, –0.48, and –0.41 kg CO₂/m²/yr for Calgary, Vancouver, and Toronto, respectively. This enforces Levinson and Akbari’s (2010) insight that white roofs may not be suitable for cold climate environments.

On a larger scale, the increase of surface albedo, a phenomenon that describes the ratio of reflected radiation to incident radiation, could be used as a means to reduce the urban heat-island effect (Taha 1997) and GW (Hamwey 2007). Susca (2012a, 2012b) proposes a method to include GW consequences of the albedo effect into LCAs by translating variations in surface albedo into kg CO₂-eq. The present article does not account for this effect, which could be explored in future work.

This study does not address cost-effectiveness of technologies. However, the outstanding environmental results of PV, relative to the alternative rooftop technologies, require a basic cost analysis. Competitiveness of solar PV as an electricity generation source has increased dramatically over the last decade. With the dominant role of China as a PV module producer (ECJRC 2011), the price of PV modules has dropped by 80% between 2008 and 2012 and is currently sitting below one U.S. dollar per peak watt (US$/Wp). Prices of installed PV systems, which include not only the PV modules, but also the inverter, balance of systems, engineering, installation, and financial costs, have also declined, but at a slower pace. The world-wide average price of a residential system as of June 2013 was US$1.97/Wp (ECJRC 2013), although higher prices in the order of US$4 to US$6/Wp are reported for North America (Black & Veatch 2012). The International Energy Agency (IEA) expects PV to achieve grid parity (i.e., to be competitive with electricity grid retail prices) by 2020 in many regions (IEA 2010). Assuming a 25-year period and a 5% discount rate, the cost of electricity production with the PV system would range from roughly US$0.10/kWh, assuming a US$2/Wp capital cost (ECJRC 2013), to $0.33/kWh, assuming a US$6/Wp capital cost (Black & Veatch 2012). Given the relatively small differential between PV electricity production cost and current electricity retail prices, roof-mounted PV could be easily cost-effective in a carbon tax scenario, particularly in carbon-intense provinces. Capital costs of green roofs are lower than those of PV in most cases (Wong et al. 2003a; Hong et al. 2012), but their cost-effectiveness in cold climates should be explored in future work.

This article assesses the life cycle performance of extensive green roofs because, as opposed to intensive green roofs, they require little or no maintenance and can be retrofitted on existing buildings without requiring structural changes. Environmental performance of intensive green roofs on new buildings would likely show larger benefits during the use phase, given that larger reductions of heating and cooling energy use are expected. However, the additional structural requirements would likely increase the upstream environmental impacts. This article accounts for the benefits of extensive green roofs that can be quantified with the impact categories listed in table 1. Other potential benefits of green roofs, such as sound insulation, aesthetics, or natural habitat creation, are not considered.

Conclusions

This study evaluates the environmental performance of white roofs, extensive green roofs, and roof-mounted solar PV as sustainable rooftop retrofits on a life cycle basis in cold climates.
Solar PV proves to be the highest-performing technology in all impact categories. Green roofs result in net positive impacts for most impact categories, including GHG emissions. White roofs have net negative impacts in most impact categories, including GHG emissions. The green roof’s influence on stormwater and air quality is essentially negligible under the conditions modeled in this study. The environmental benefits of PV technology are driven by its carbon-free electricity generation, resulting in benefits orders of magnitude higher than the alternative technologies and is therefore the preferred technology. Continuing declines in the cost of PV systems and/or a carbon tax could easily make PV cost-effective in many locations in Canada. Green roofs provide many environmental benefits and offer additional benefits, such as aesthetics and sound insulation, that are not included in this assessment. White roof environmental performance is poor because of the heating penalty caused by the additional heating energy requirement resulting from the high solar reflectance. Therefore, although white roofs have been proved to be a cost-effective solution to reduce carbon emissions in warmer environments, their use in Canada is discouraged.

The sensitivity analysis shows that although the relative benefits and negative impacts of the three technologies vary depending on location-specific parameters, particularly carbon intensity of the electricity grid, the above conclusions can be generalized for Canada and countries with similar climate conditions.

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References

Akbari, H., R. Levinson, and L. Rainer. 2005. Monitoring the energy-use effects of cool roofs on California commercial buildings. Energy and Buildings 37(10): 1007–1016.

Berggren, B., M. Hall, and M. Wall. 2013. LCE analysis of buildings—Taking the step towards net zero energy buildings. Energy and Buildings 62: 381–391.

Black & Veatch. 2012. Cost and performance data for power generation technologies. Golden, CO, USA: National Renewable Energy Laboratory (NREL).

Branker, K., M. J. M. Pathak, and J. M. Pearce. 2011. A review of solar photovoltaic levelized cost of electricity. Renewable and Sustainable Energy Reviews 15(9): 4470–4482.

Caneta Research Inc. 2011. Addendum to performance simulation of proposed changes to NECB relative to MNECB, ASHRAE 90.1 2007, and ASHRAE 90.1 2004. Mississauga, Ontario, Canada: Caneta Research Inc.

Casey Trees Endowment Fund and Limno-Tech Inc. 2005. Re-greening Washington, DC: A green roof vision based on quantifying stormwater and air quality benefits. www.greenroofs.org/resources/greenroofvisionfordc.pdf. Accessed 26 January 2015.

Castleton, H. F., V. Stovin, S. B. M. Beck, and J. B. Davison. 2010. Green roofs: Building energy savings and the potential for retrofit. Energy and Buildings 42: 1582–1591.

CCBFC (Canadian Commission on Building and Fire Codes). 2011. National Energy Code of Canada for Buildings 2011: Government of Canada. Ottawa, Ontario, Canada: National Research Council Canada.

Connelly, M. 2006. BCIT green roof research program, phase 1 summary of data analysis. http://commons.bcit.ca/greenroof/files/2012/01/cmbc_ethr_2006.pdf. Accessed 15 February 2015.

Currie, B. and B. Bass. 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosystems 11(4): 409–422.

de Wild-Scholten, M. 2011. Environmental profile of PV mass production: Globalization. In 26th European Photovoltaic Solar Energy Conference, 5–9 September, Hamburg, Germany.

Del Barrio, E. P. 1998. Analysis of the green roofs cooling potential in buildings. Energy and Buildings 27(2): 179–193.

ECJRC (European Commission Joint Research Center). 2011. PV status report 2011. Ispra, Italy: Institute for Energy and Transport, Renewable Energy Unit.

ECJRC (European Commission Joint Research Center). 2013. PV status report 2013. Ispra, Italy: Institute for Energy and Transport, Renewable Energy Unit.

Government of Canada. 2011. National model construction code documents—Adaptation guidelines for the National Energy Code of Canada for Buildings 2011. www.nationalcodes.nrc.gc.ca/eng/necb/necb_adaptation_guidelines.html. Accessed March 2014.

Government of Canada. 2014. Engineering climate datasets. Intensity-Duration-Frequency (IDF) files. Fredericton, New Brunswick, Canada: Environment Canada, National Inquiry Response Team.

Hamwey, R. 2007. Active amplification of the terrestrial albedo to mitigate climate change: An exploratory study. Mitigation and Adaptation Strategies for Global Change 12(4): 419–439.

Hong, T., J. Kim, and C. Koo. 2012. LCC and LCCO2 analysis of green roofs in elementary schools with energy saving measures. Energy and Buildings 45: 229–239.

IEA (International Energy Agency). 2010. Technology roadmap—Solar photovoltaic energy. Paris: International Energy Agency.

ISO (International Organization for Standardization). 2010. ISO 14024:2000. Environmental management—Life cycle assessment—Life cycle impact assessment. Geneva: International Organization for Standardization.

Jim, C. Y. and S. W. Tsang. 2011. Biophysical properties and thermal performance of an intensive green roof. Building and Environment 46(6): 1263–1274.

Jo, J. H., J. D. Carlson, J. S. Golden, and H. Bryan. 2010. An integrated empirical and modeling methodology for analyzing solar reflective roof technologies on commercial buildings. Building and Environment 45(2): 453–460.

Jolliet, O., M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebiter, and R. Rosenbaum. 2003. IMPACT 2002+: A new life cycle impact assessment methodology. The International Journal of Life Cycle Assessment 8(6): 324–330.

Levinson, R. 2009. Cool roof Q & A. Berkeley, CA, USA: Lawrence Berkeley National Laboratory.

Levinson, R. and H. Akbari. 2010. Potential benefits of cool roofs on commercial buildings: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. Energy Efficiency 3(1): 53–109.

Mason, J. E., V. M. Fthenakis, T. Hansen, and H. C. Kim. 2006. Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation. Progress in Photovoltaics: Research and Application 14(2): 179–190.
Mohareb, E. and C. Kennedy. 2012. Gross direct and embodied carbon sinks for urban inventories. *Journal of Industrial Ecology* 16(3): 302–316.

Müller, A., K. Wambach, and E. Alsema. 2005. Life cycle analysis of a solar module recycling process. Paper presented at 20th European Photovoltaic Solar Energy Conference, 6–10 June, Barcelona.

Myrans, K. 2009. Comparative energy and carbon assessment of three green technologies for a Toronto roof. Masters thesis, Graduate Department of Geography and Center for Environment, University of Toronto, Toronto, Ontario, Canada.

Niachou, A., K. Papakonstantinou, M. Santamouris, A. Tsangrassoulis, and G. Mihalakakou. 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings* 33(7): 719–729.

Oberdorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Kohler, K. K. Y. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: Ecological structures, functions, and services. *Biосience* 57(10): 823–833.

Peck, S., C. Callaghan, M. Kuhn, and B. Bass. 1999. Greenbacks from green roofs: Forging a new industry in Canada. Ottawa, Ontario, Canada: Canada Mortgage and Housing Corporation.

PRE Consultants. 2008. SimaPro LCA software. Amersfoort, the Netherlands: Pré Consultants.

Rowe, D. B. 2011. Green roofs as a means of pollution abatement. *Environmental Pollution* 159(8–9): 2100–2110.

Saadatian, O., K. Sopian, E. Salleh, C. H. Lim, S. Riffat, E. Saadatian, A. Toudeshki, and M. Y. Sulaiman. 2013. A review of energy aspects of green roofs. *Renewable and Sustainable Energy Reviews* 23: 155–168.

Sailor, D. J. 2008. A green roof model for building energy simulation programs. *Energy and Buildings* 40(8): 1466–1478.

Saiz, S., C. Kennedy, B. Brass, and K. Pressnail. 2006. Comparative life cycle assessment of standard and green roofs. *Environmental Science and Technology* 40(13): 4312–4316.

SCLCI (Swiss Center for Life Cycle Inventories). 2014. ecoinvent database. Dübendorf, Switzerland: Swiss Center for Life Cycle Inventories. www.ecoinvent.org/database/. Accessed March 2014.

Sherwani, A. F., J. A. Usmani, and Varun. 2010. Life cycle assessment of solar PV based electricity generation systems: A review. *Renewable and Sustainable Energy Reviews* 14(1): 540–544.

Stoppato, A. 2008. Life cycle assessment of photovoltaic electricity generation. *Energy* 33(2): 224–232.

Suehrcke, H., E. L. Peterson, and N. Selby. 2008. Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Buildings* 40(12): 2224–2235.

Susca, T. 2012a. Multiscale approach to life cycle assessment. *Journal of Industrial Ecology* 16(6): 951–962.

Susca, T. 2012b. Enhancement of life cycle assessment (LCA) methodology to include the effect of surface albedo on climate change: Comparing black and white roofs. *Environmental Pollution* 163: 48–54.

Symefa, A., M. Santamouris, and H. Akbari. 2007. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings* 39(11): 1167–1174.

Taha, H. 1997. Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings* 25(2): 99–103.

Tolderlund, L. 2010. Design guidelines and maintenance manual for green roofs in the semi-arid and arid west. Denver, CO: U.S. Environmental Protection Agency. www2.epa.gov/sites/production/files/documents/GreenRoofsSemiAridAridWest.pdf. Accessed 16 February 2015.

TRCA (The Toronto Region Conservation Authority). 2006. Evaluation of an extensive green roof. Toronto, Ontario, Canada: Toronto Region Conservation Authority.

US DOE (U.S. Department of Energy). 2011. EnergyPlus energy simulation software: Weather data. Washington, DC: U.S. Department of Energy. http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm. Accessed 2011.

US DOE (U.S. Department Of Energy). 2013. EnergyPlus energy simulation software. Washington, DC: U.S. Department of Energy. http://apps1.eere.energy.gov/buildings/energyplus/. Accessed July 2013.

USGBC (U.S. Green Building Council). 2010. The Leadership in Energy and Environmental Design (LEED). www.usgbc.org/DisplayPage.aspx?CategoryID=19. Accessed August 2009.

Urban, B. and K. Roth. 2010. Guidelines for selecting cool roofs. Washington, DC: U.S. Department of Energy, Building Technologies Program. www1.eere.energy.gov/buildings/energyplus/. Accessed 15 February 2015.

WOEC (Weather Office of Environment Canada). 2012. 1981–2010 Canadian climate normals and averages: Environment Canada. Fredericton, New Brunswick, Canada: Environment Canada, National Inquiry Response Team.

Wong, N. H., D. K. W. Cheong, H. Yan, J. Soh, C. L. Ong, and A. Sia. 2003b. The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and Buildings* 35(4): 353–364.

Wong, N. H., S. F. Tay, R. Wong, C. L. Ong, and A. Sia. 2003a. Life cycle cost analysis of rooftop gardens in Singapore. *Building and Environment* 38(3): 499–509.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This document provides information about the SimaPro products used for upstream impact assessment, building energy modeling details, further background information on green roofs, comparative LCAs, and results by phase.