AN INTEGRATED ASSESSMENT OF THE SUSTAINABILITY OF GREEN AND BUILT-UP ROOFS

Helen Muga[1], Amlan Mukherjee[2] and James Mihelcic[3]

ABSTRACT

There is growing demand to develop methods that integrate environmental and economic assessment of more sustainable technologies incorporated into commercial and residential buildings. In this paper, we incorporate economic and energy use data obtained for a green roof operating in the Midwest U.S. at latitude 42.94N into an integrated approach to estimate and compare the economic and environmental impacts of an intensive (or extensive) green roof with a built-up roof. The life cycle stages included in the analysis were material acquisition life stage which including the transportation effects from material extraction through manufacturing to the finished products, and the use and maintenance life stage of the building. Environmental impact analysis indicates that green roof emits three times more environmental pollutants than built-up roofs in the material acquisition life stage. However, in the use and maintenance life stage, built-up roof emits three times more pollutants than a green roof. Overall, when emissions from both material acquisition life stage and use and maintenance life stage are combined, the built-up roof contributes almost 3 times more (or 46% more) environmental emissions than green roof over a 45-year building life span. Furthermore the overall energy use, specifically energy involved in the transportation from material extraction through to the finished product indicate that green roof uses 2.5 times less energy than a built-up roof. An Economic Input and Output life cycle assessment (EIO-LCA) was used to estimate the environmental impacts. The economic impact over an assumed 45-year building life was determined using life cycle costing, taking into account Net Present Value (NPV) calculations. Life cycle costing results indicate that green roof costs approximately 50% less to maintain over a 45 year-building life than a built-up roof. A Monte Carlo simulation is also performed to account for any variability in cost data. In addition, the paper presents a method to quantify the value incentive that a decision-maker has in adopting green technology. Results from the study indicate that when a green roof is compared to the Midwest regional NPV of a built-up roof, we find that the cost to maintain it ($35 per square foot) lies well below the average regional NPV of $59 per square foot of a built-up roof.

KEYWORDS

sustainability, green roof, built-up roof, life cycle assessment, life cycle costing, net present value, Monte Carlo

INTRODUCTION

In 2000 alone, 17% of the total primary energy consumption in the U.S was from the commercial building sector (U.S. DOE, 2000). With increasing demands driven by population and affluence, by 2010 the energy consumption in building operations could increase current carbon emissions 12% over 1997 levels (Koomey, et al., 1998).

In addition to considerable energy consumption and waste production, buildings also contribute to degraded water quality associated with urban runoff (Mason, et al., 1999). Furthermore rapid runoff from roofs and other impervious surfaces can exacerbate flooding, increase erosion, and overwhelm combined sewer collection systems.

These adverse impacts have provided motivation to implement new designs and construction management strategies that contribute to a more sustainable built environment. Specifically, introduction of technology such as green roofs may enable a building

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[1] PhD Candidate, Department of Civil and Environmental Engineering, Michigan Tech. University, 1400 Townsend Dr., Houghton, MI 49931. Email: hemuga@mtu.edu.

[2] Assistant Professor, Department of Civil and Environmental Engineering, Michigan Tech. University, 1400 Townsend Dr., Houghton, MI 49931. Email: amukherj@mtu.edu.

[3] Professor, Department of Civil and Environmental Engineering, Michigan Tech. University, 1400 Townsend Dr., Houghton, MI 49931. Email: jm41@mtu.edu.

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to be more environmentally sustainable while creating a more aesthetically pleasing, attractive urban environment. For example, in some geographical areas built-up roofs can reach temperatures as high as 65°C, while a similar green roof would only reach 24°C in the summer (Guggemos, 2006). In such cases replacing a built-up roof by a vegetated green roof can reduce energy usage for cooling and contribute to lowering the urban heat island effect.

Green roofs have primarily been implemented as low impact technology for controlling storm water (Perry 2003, Akbari and Rose, 2001) and for aesthetic reasons (Dimoudi and Nikolopoulou, 2003; Wong et al., 2003a). Although green roofs seem to have numerous environmental and economic benefits, their direct energy savings and reduced environmental impacts associated with energy usage during the use and maintenance life stage remain largely unevaluated, especially in the U.S. The life cycle costs (LCC) of a green roof compared a built-up roof also remain largely unevaluated.

Life cycle costs under varying discount rates, interest rates, and energy costs are also important from a contractor's perspective when deciding what roof design to install. For example, a contractor may want to know if green roofs are more economically and environmentally preferable in the long term than built-up roofs, or if built-up roofs are a superior design choice? One life cycle cost analysis (LCCA) evaluating extensive and intensive green roof systems against commercial roofs in Singapore found that although green roofs had a higher initial construction cost, their life cycle cost was greatly reduced over the building life (Wong et al., 2003b). This was primarily due to lower maintenance and replacement costs of the green roof. The LCCA took into consideration the initial construction costs as well at the maintenance and replacement costs of the different roof types. The study however, neglected the environmental effects associated with the different roof alternatives. A comparative environmental life cycle assessment (LCA) study of a built-up roof, an extensive green roof, and an intensive green roof found that the extensive and intensive green roofs had lower energy use because of lower thermal conductivity due to the growing medium (Kosareo and Ries, 2007). Relative performance of the three roof alternatives in terms of several environmental stressors (i.e., ozone layer depletion, acidification, eutrophication, and global warming impact) also suggested the extensive green roof performed better than the built-up roof, and that the intensive green roof performed better than the extensive green roof. That study however did not perform any economic analysis.

Saiz et al. (2006) on the other hand, performed a life cycle assessment on a standard and green roof for a residential building in Madrid. Their life cycle assessment focused the environmental impacts associated with energy use during the materials acquisition, use, and maintenance life stages. The environmental impacts were determined using the LCA tool called SimaPro (Goekoop and Oele, 2001). Their results indicated that replacing a common flat roof with a green roof reduced the environmental impacts over the roof's life span between 1.0 to 5.3%. The environmental impact categories studied were: abiotoc depletion, global warming, ozone layer depletion, human toxicity, photochemical oxidation, acidification, eutrophication, and ecotoxicity to freshwater, marine, and terrestrial life. Also annual energy savings was found to be just over 1%, with summer cooling load reduced by over 6%. The energy performance of both roof types was determined using the Environmental Performance-research (ESP-r) software (Clarke et al, 2002). An economic analysis was also not performed in this study.

Comparison studies of roof technologies have thus primarily analyzed the environmental impacts of alternative roofs and neglected the economic impacts, or analyzed the economic impacts and neglected the environmental component. Guggemos (2006) however went one step further by merging economic and environmental assessment methods to compare a built-up roof and an extensive green roof located in the western U.S. The analyses were performed on the material and energy used for each roof type during manufacturing, construction, use and maintenance, and end-of life stages. Cost data for materials, equipment and labor associated with all life stages of each roof were estimated from RS Means (2005), while the energy usage was obtained from a Department of Energy Survey (Energy Information Administration, 1995). The environmental impacts were determined using an Economic Input and Output-Life Cycle Assessment (EIO-LCA)

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(Hendrickson et al., 1998, 2006). It should be noted that although energy usage and cost data during the use and maintenance life stage was obtained, it was not included in the overall EIO-LCA analysis based on the assumption that the energy costs for both roof types are equal and therefore need not be included. There are differences in energy usage between a green roof and a built-up roof (Saiz 2006, Wong et al 2003c). Neglecting energy usage in the overall LCA greatly underestimates emission reduction associated with reduced energy use by green roofs compared to built-up roof. Economic costs were determined using LCCA. Specifically, the net present value of the total life cycle costs for the built-up roof and the green roof were determined at different rates of return. Guggemos (2006) further confirmed that green roofs seemed more environmentally and economically favorable over built-up roofs, over the total lifetime of the building. Although Guggemos (2006) sheds light on the benefits of green roofs, a comparative study that uses real energy data, specifically energy usage during the use life stage from green and built-up roofs in the U.S, and the inclusion of these data in a LCA would seem more plausible. Because of the high variability associated with economic costs, specifically maintenance costs, further analyses is also required to capture any variability in real economic data so the results are more readily transferable to other locations.

Accordingly, the objective of this study is to assess the environmental and economic impact of a built-up (a type of conventional roof) and green roof using an LCA and LCCA approach. An EIO-LCA (Hendrickson et al., 1998, 2006) is used to determine the environmental impacts associated with the material acquisition life stage (which includes the transportation effects from material extraction and creation or manufacturing through to the storage of the supplier's finished product), and the energy usage during use/maintenance life stage (which includes the consumer's use of the product and its maintenance over its life time) of the two different roofs. We focus on these two life stages because they are reported to contribute the majority of environmental impacts over a building's lifetime compared to the environmental impacts associated with the construction and end-of life stages (Junnila and Horvath, 2003). The emissions used as primary environmental stressors include sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter (PM_{10}), and carbon dioxide (CO_2) emissions. Other measures of environmental effects such as wastes, embodied energy, and water pollution have not been taken into account.

An LCCA approach using Net Present Value (NPV) is used to determine the economic impacts over the lifetime of the two roof types. Specifically, the costs involved with material acquisition, construction/installation, and use/maintenance stages are considered in the calculation of NPV due to their significant contribution to assessing economic and environmental impact. The data used in this study, specifically the energy use and economic data, were obtained from a green roof contractor in the Midwest region of U.S at latitude 42.94N and elevation of 748 feet. For the conventional roof, we used energy cost and usage data for different US geographic regions from the Department of Energy records.

Given the inherent variability in energy usage and cost data, and interest and discount rates (critical to the NPV calculation) due to regional climates and national economic trends, a Monte Carlo simulation was used. Hence, the methods in this paper are general and applicable to different climate zones. This study also conducts a sensitivity analysis of the life cycle costs under varying discount rates, interest rates, and energy costs. This analysis is important from a contractor's perspective when comparing long-term returns on investment between alternative roof systems.

The integrated approach presented in this paper to analyzing the economic and environmental impact of a process, service or activity will assist decision-makers in evaluating and selecting the most appropriate roof alternative. The economic benefits from life cycle energy savings will help building contractors to quantify the value addition to their decisions when they adopt green technologies such as green roofs over conventional roof systems. For example, a contractor's decision to adopt a green roof will be driven by immediate and long-term economic incentives. Higher adoption rates will in turn, lead to lower life cycle emissions and reduce the environmental impacts of the infrastructure. Given long-term variability of energy prices, interest and discount rates, establishing a framework to analyze value can be a

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challenge. A critical contribution of this paper is that along with an analysis of economic and environmental impacts, it also presents a method to quantify the value incentive that a decision-maker has in adopting green technology. It is the decision to adopt or not to adopt that will eventually lead to reduction of environmental impacts.

LIFE CYCLE ASSESSMENT (LCA)

The sustainability of the roof systems can be assessed through different assessment tools such as economic analysis and life cycle assessment (LCA). For this study a LCA and life cycle cost analysis (LCCA) are used to determine the environmental and economic impacts, respectively.

LCA is an analytical tool that aims to estimate the environmental impacts over the different life stages of a product, process or activity. It is a well-recognized method for assessing the long-term environmental impacts of a process, product or activity, in this case different roofing systems. It has been used in various environmental assessment studies including assessment of residential homes (Keoelian et al., 2001; Peuportier, 2001), structural systems (Cole, 1999), commercial buildings (Junnila and Horvath, 2003) and evaluation of retrofitting versus building (Dong et al., 2005). None of these studies used an integrated assessment involving LCA and LCCA to compare the environmental and economic impacts of a built-up roof and a green roof.

The activities involved in the construction and end-of life stage or demolition and landfill stages were not included in the LCA, because they contribute relatively small environmental emissions over the life cycle of the building. A study by Junnila and Horvath (2003) reported that the construction life stage accounted for only 2% in climate change emissions (e.g. CO_2, CH_4) and 6% in eutrophication emissions (e.g. nitrates) over the building life. The demolition of the building accounted for only 1% and 5% of the contributions to climate change and eutrophication emissions. Therefore, the omission of the environmental impacts associated with the construction and demolition life stage is not expected to significantly affect the final results.

There are three main steps in an LCA: 1) inventory analysis, 2) impact analysis, and 3) improvement analysis (ANSI/ISO, 1997). The inventory step is an accounting procedure whereby resource and energy requirements as well as product waste, and emission outputs during the different life cycle stages of a product, process or activity are identified, quantified and tabulated. The different life cycle stages or stages include: 1) material extraction or acquisition, 2) manufacturing, 3) construction, 4) operation and maintenance, and 5) refurbishment/demolition. The impact analysis step puts the results of the inventory analysis into further perspective through classification, characterization and valuation steps. The associated impacts to human health and the environment are determined in this step. The improvement analysis is a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout the whole life cycle of the product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements, such as changes in product, process, and activity design, raw material use, industrial processing, consumer use, and waste management (ANSI/ISO, 1997).

The environmental impacts can be determined quantitatively by collecting data over a period. The challenges of this approach are that it requires considerable resources, and time. If this approach is taken the uncertainty in the data available and lack of data presents a limited conclusion to the sustainability of a process, product or activity that in turn impacts decision-making. Software tools such as SimaPro and Economic Input and Output-Life Cycle Assessment (EIO-LCA), can instead be used to quantify for the environmental impacts. For this study, the EIO-LCA method developed at Carnegie Mellon University (Hendrickson et al., 1998, 2006) was used. The model defines the scope and number of environmental effects quantified in this study. It contains templates and data libraries that estimate the economic contribution, resource requirements and environmental emissions for a particular product, process, or activity. The data is from the U.S. Department of Commerce's commodity-by-commodity input-output matrix augmented by various resource use, waste, and emission factors. The model attempts to capture all the requirements to produce a product, service, or activity, only for the life cycle stages of extraction/mining, transportation, and

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manufacturing. Disposal impacts of products are not accounted for in the EIO-LCA model, and have to be determined independently.

Life Cycle Cost Analysis (LCCA)

Life cycle costing is a technique that uses economic principles to compare the value of competing alternative product, process or activities across its life cycle (Kirk and Dell'isolla 1995, ASTM 1999). It incorporates initial and discounted future costs over the life cycle of the alternative activities and attempts to identify the best value or the lowest cost over time (Kirk and Dell'isolla, 1995). The application of life cycle costing in this study allows us to compare the value of competing roof design by factoring in their energy usage through the use life stage. This provides us an integrated platform to estimate both economic and environmental impacts.

RESEARCH METHODOLOGY

This study was performed on a green roof and a built-up roof in the Midwest region of the U.S. Commercial buildings in the Midwest region represent 27% of all U.S. commercial buildings (U.S. DOE, 2008). Built-up roofs represent 22% of all commercial roofs in the U.S, shingle roofs (not wood) 30%, synthetic or rubber roofs 10%, and concrete 1% (U.S. DOE, 2008). The methods described in the study can be extended to any other type of conventional roof system. Green roofs on the other hand, are an emerging technology in the U.S. Hence, data on the number of commercial buildings fitted with greens roofs and energy usage in these buildings are scarce and unavailable, making a Monte Carlo simulation or sensitivity analysis difficult. This is not the case for our conventional built-up roof.

The research was conducted in two parts. The first part involved a LCA to quantify the environmental effects in the, 1) extraction/acquisition and manufacturing life stage, and 2) use and maintenance life stage of the two different roofing systems. The second portion involved a LCCA to determine the economic impacts of the two different roofing alternatives.

Life Cycle Assessment (LCA)

The EIO-LCA model was used to calculate the environmental effects of the extraction/material acquisition and manufacturing life stage, and the use and maintenance life stage (CMU, 2007). The environmental effects/indicators of interest to this study were emissions of built-up air pollutants (sulfur dioxide, carbon monoxide, nitrogen oxide, and particulate matter) and greenhouse gases (carbon dioxide, methane, nitrogen dioxide, and chlorofluorocarbon), as well as energy requirements.

The analysis was performed on a benchmark commercial building (refer to Guggemos, 2006) that has a roof area of 1,445 m^2, and a building life of 45 years. It was assumed that all the structural elements of the building were the same for both the built-up roof and green roof (extensive roof). Due to an extensive roof's relatively low weight, demand (limited soil depth between 5 and 15 cm), they are suitable for large roofs and may safely be used on existing structures (Johnston and Newton, 1995). This is based on the assumption that the structural components of a built-up roof are designed to take additional loads. Hence, if a built-up roof is to be converted to a green roof, the additional load of the vegetation/garden would not be substantially different. This assumption only takes into account the additional load of 5 to 15 cm of soil, grasses and small plants. The thickness of the soil layer and other additional loads such as snow loads can have significant implications in the construction of the building and roof support system. However, this assumption is being made, because the structural analysis of the roof systems, while important, it is not directly related to the present study, and hence has not been considered.

The major difference between the two roof systems is the material requirements used in the initial construction life stage, and the use and maintenance life stage. These requirements and subsequent environmental impacts were used as comparison in this study. The previous study (Guggemos, 2006) used the following assumptions to compare the environmental impacts of the different roof systems. The built-up roof would be replaced every 15 years (after year 15 and year 30). A building life of 45 years is assumed. At the end of the building's 45-year life the roof would be demolished and land-filled. The study also assumed that the green roof would require that the vegetation be fertilized biannually, and that it would be demolished at the end of the

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TABLE 1. Initial material quantities and costs for a built-up roof used in EIO-LCA

Material	Quantity (m^2)	Cost (1997$)	Sectors	SIC Code
Insulation, polystyrene	2,890	18,420	Polystyrene foam product manufacturing	32614
Base felt, 30 lb	1,445	980	Broadwoven fabric mills	31321
Felt, 3 plies, 15 lb	1,445	1,400	Broadwoven fabric mills	31321
Asphalt	2,890	4,200	Asphalt shingle and coating materials manufacturing	324122
Gravel aggregate, 4 lb/sf	1,445	740	Sand, gravel, clay and refractory mining	21232
Total Material Cost		25,740		

Source: Guggemos, 2006.

TABLE 2. Initial material quantities and costs for a green roof used in EIO-LCA

Material	Quantity (m^2)	Cost (1997$)	Sector	SIC Code
Roofing Membrane, EPDM	1,445	10,700	Synthetic rubber manufacturing	325212
Root Barrier, CSPE	1,445	16,700	Synthetic rubber manufacturing	325212
Insulation, polystyrene	1,445	10,200	Polystyrene foam product manufacturing	32614
Drainage layer, polyethelene	1,445	220	Plastic material and resin manufacturing	325211
Filter fabric, polypropylene	1,445	350	Fiber, yarn and thread mills	31322
Soil, 0.15 m deep	1,445	4,600	Truck transportation	484
Grass seeds	1,445	200	Truck transportation	484
Plants	6,687 each	1,320	Truck transportation	484
Total Material Cost		44,300		

Source: Guggemos, 2006.

45-year building life. For this study we have used the same assumptions as Guggemos (2006). In addition, we added an assumption that there would be re-planting of the green roof every 15 years.

The material and energy inputs into the two different roof systems were identified and quantified. These material requirements and their respective costs are listed in Tables 1–5, for the two life cycle stages studied. Table 1 indicates the material requirement for the initial construction of a built-up roof and Table 2 for the green roof. The initial material acquisition requirements for the green roof seem to be more than the built-up roof. These materials are predominantly petroleum based and used for insulation, waterproofing membrane, root barrier, and filter fabric. The petroleum-based products tend to be energy-intensive to manufacture, and should consequently contribute significantly to the environmental emissions. Tables 3 and 4 show the respective material and energy requirements during use and maintenance life stage for both roof types for a 45 year building life. It should be noted that maintenance for a built-up roof as assumed occurs every 15 years, while that of a green roof occurs

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TABLE 3. Material quantities, energy, and costs during use and maintenance of a built-up roof over the building life used in EIO-LCA.

Material and Energy use	Quantity (m^2)	Cost (1997$)	Sector	SIC Code
Base felt, 30 lb	1,445	1,720	Broadwoven fabric mills	31321
Felt, 3 plies, 15 lb	1,445	2,400	Broadwoven fabric mills	31321
Asphalt	2,890	7,300	Asphalt shingle and coating materials manufacturing	324122
Gravel aggregate, 4 lb/sf	1,445	1,300	Sand, gravel, clay and refractory mining	21232
Material Placement	1,445			
Labor	1,445	14,800	Maintenance & repair of nonresidential building	23332
Equipment	1,445	5,200	Machinery & equipment rental and leasing	53241
Transport	1,445	16,300	Truck transportation	484
Electricity	1,445	760,000	Power generation & supply	22111
Natural Gas	1,445	293,000	Oil & gas extraction	21111
Total Material Cost		1,100,000		

Source: Guggemos, 2006; Bazzani and Associates, 2006; Means, 2006.

TABLE 4. Material quantities, energy, and costs during use and maintenance of a green roof over the building life used in EIO-LCA.

Material and Energy use	Quantity (m^2)	Cost (1997$)	Sector	SIC Code
Fertilizer	1,445	2,000	Nitrogenous fertilizer manufacturing	325311
Grass seeds	1,445	270	Truck transportation	484
Plants	1,445	1,730	Truck transportation	484
Transportation	1,445	830	Truck transportation	484
Electricity	1,445	280,300	Power generation & supply	22111
Natural Gas	1,445	150,000	Oil & gas extraction	21111
Total Material Cost		435,130		

Source: Guggemos, 2006; Bazzani and Associates, 2006; Means, 2006.

biannually (fertilizing) and at every 15 years (replanting). The materials requirements for each maintenance interval have been accounted for in Tables 3 and 4. Energy use during the 45-year building life for both roof types has also been accounted for in Tables 3 and 4. Annual and total energy requirements and respective costs over the building life of both roof types are shown in Tables 5 and 6. These energy and maintenance requirements are used to determine the environmental impacts over the 45-year building life.

The materials and energy usage at each use and maintenance life stage of the two alternative roofs varied. A previous study (Guggemos, 2006) used the following assumptions to determine the economic and environmental impact of the two roof

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TABLE 5. Annual energy consumption and cost during use and maintenance phase of a 1,445 m^2 built-up and green roof.

Use	Energy Use (kWh) Built-up Roof	Cost 2006 $/yr Built-up Roof	Energy Use (kWh) Green Roof	Cost 2006 $/yr Green Roof
Natural gas (heating)	261,740	10,400	109,400	4,400
Electricity (cooling)	248,900	22,000	92,000	8,140
Total	510,640	32,400	201,400	12,540

TABLE 6. Total energy consumption and costs during use and maintenance phase over a 45-year life span of a built-up roof and green roof (1,445m^2)

Use	Total Energy Use (kWh) Built-up Roof	Total Cost (2006 $) Built Roof	Total Energy Use (kWh) Green Roof	Total Cost (2006 $) Green Roof
Natural Gas (heating)	11,780,000	382,000	4,920,000	195,000
Electricity (cooling)	11,200,000	990,100	4,140,000	366,000
Total	22,980,000	1,372,100	9,060,000	561,000

types. The use and maintenance life stage was assumed to be a function of roof replacement materials, transportation of these materials to the building site, material placement at the building site (including labor and equipment use), and electricity and natural gas use. The built-up roof was assumed to be replaced every 15 years, with the new roof being placed on top of the existing roof, hence no demolition of existing materials was required. The replacement materials used included all the components used in the original roof except the insulation (see Table 3). As per Guggemos (2006) study, the green roof required minimal care with a biannual application of fertilizer, labor (for watering and weeding the turf and provide replacement if necessary) and a truck used for delivery, shown in Table 4. We have assumed the same assumption as Guggemos (2006). We have also considered the costs of re-planting of grass seeds at the end of every 15 years (Kirk and Dell'isola, 1995), variations in electricity and natural gas costs ($/kWh and $/ccf, respectively), and building usage (kWh/sf and ccf/sf for electricity and natural gas, respectively) across different regions of U.S. These variations would greatly affect the economic impacts, particularly the cost in maintaining both roof types and subsequent environmental emissions. We have not considered maintenance costs of new roofing materials and maintenance crew required to replace a worn out membrane in the event of a leakage.

Annual energy use was obtained from a green roof contractor in Grand Rapids, Michigan. For a built-up roof 16 kWh/sf was used for electricity and 0.572 ccf/sf for natural gas. For a green roof 5.91 kWh/sf was used for electricity and 0.24 ccf/sf for natural gas. These annual and total energy consumptions over the building life, along with associated costs, are listed in Tables 5 and 6 for both roof types. The use and maintenance life stage was the most obvious difference between the two roof alternatives, in terms of costs and environmental effects over the building's 45-year life. Transportation and material placement costs for the built-up roof were estimated using RS Means Cost Data (2006). The costs have been corrected to 1997 dollars because the most recent data in the EIO-LCA model is in 1997 dollars.

The EIO-LCA tool (Hendrickson et al., 1998, 2006) was used to compare the resources/material inputs and environmental outputs of the built-up roof and green roof. It was used to determine the environmental burdens of the materials in the extraction to manufacturing life stages, including effects from transportation. These materials were used in the initial roof construction and also in the use and maintenance life stage (Tables 1–4). Environmental

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impacts from energy production used during the use and maintenance life stage were also calculated using EIO-LCA (Tables 5 and 6). Both roof types were estimated in this analysis by using commodity groups in the 519 × 519 input-output matrix. The sectors (Standard Industrial Classification or SIC code) that were selected from the EIO-LCA model for the materials and energy are provided in Tables 1–4. The costs shown in Tables 1–4 were modified to 1997 dollars, as the most recent data set in the EIO-LCA model is in 1997 dollars (Hendrickson et al., 1997). These 1997 costs were then used in the EIO-LCA model to estimate emissions.

It should be noted that this study only included one built-up roof and one green roof system in one region of the United States. Other scenarios may produce different results based on the roof design and size, materials used, construction equipment requirements, maintenance requirements depending on the region's climate, and regional energy sources. Furthermore, the focus of this paper is to present a methodology that allows the assessment of environmental and economic impacts of two different roofing systems rather than specific results.

Life Cycle Cost Analysis

The Life Cycle Cost Analysis was conducted by calculating and comparing the net present values (NPV) of the design alternatives. All relevant costs for particular design, system, component or material were estimated and costs were adjusted for inflation and the discount rate in the economy (U.S. Department of Commerce, 1980).

The discount rate is used to reduce the future expected expenditures to present day terms. It should reflect historical economic trends over long periods. Historically, discount rates over an extended period have been 3 to 4 percent, but a range of 4 to 8 percent is more common (Kerr and Ryan, 1987). For this study, a discount rate of 5 percent was used. The other variable used in calculating the NPV is the inflation rate, 3 percent. This is the annual compound rate of increase in the cost of maintenance.

The costs for the initial material acquisition life stage and the use and maintenance life stage were obtained from Guggemos (2006). Other equipment, labor and transportation costs were obtained from RS Means (2006). Usage data for electricity and natural gas for a built-up roof and a green roof were, obtained from a contractor in Grand Rapids, Michigan (2006). The costs for energy and gas use were obtained from U.S. Department of Energy (2007a and 2007b).

An interest of this research was to determine whether the progressive costs in the use and maintenance life stage of a built-up and a green roof differed over the 45-year building life. The unit costs for each of the initial construction and maintenance plans had to be calculated before calculating the Net Present Value (NPV) to determine if there were any notable differences between the two alternative roof systems.

Table 7 lists unit prices in dollars per square feet ($/sf) for the initial material acquisition, installation, replacement/maintenance and energy (electricity and gas) for built-up and green roof systems.

TABLE 7. Unit costs of built-up roof and green roof used to calculate the Net Present Value (NPV)

Material & Energy Use	Built-up Roof Unit Costs ($/sf) ($/m^2) (2006 $)	Green Roof Unit Costs ($/sf) ($/m^2) (2006 $)
Initial Material costs	2.20 (22.50)	3.60 (38.80)
Installation costs	2.30 (24.80)	3.90 (41.72)
Replacement costs (materials)	0.60 (6.30)	0 (0)
Replacement costs (labor & equipment)	1.70 (18.20)	0.01 (0.10)
Re-planting	—	0.10 (1.40)
Electricity costs	1.40 (15.20)	0.50 (5.60)
Gas usage costs	0.60 (5.90)	0.30 (3.00)

Source: Guggemos, 2006; Bazzani and Associates, 2006; Means, 2006.

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(These costs are the same as in Tables 1 and 2, adjusted to the 2006 dollar). Once all the unit prices were gathered, costs were estimated for the initial construction and each subsequent use and maintenance costs at intervals of 15 years for the built-up roof and yearly for the green roof. Energy use for the roof systems was estimated annually. Re-planting of the green roof was assumed to occur at intervals of 15 years. An inflation rate of 3% was used to estimate future costs and an average discount rate of 5% with a standard deviation of 0.05% was used to calculate the Net Present Value (NPV) as follows:

$$NPV = IC + NPV = IC + \sum_{k=1}^{n} MC_k \frac{(1+i)^k}{(1+r)^k} \quad (1)$$

In Equation 1, IC is the initial construction cost, including costs of construction operations and materials used in the design sections. MC_k is the maintenance cost in the year k, i is the rate of inflation, r is the discount rate and n is the life time studied. It should be noted that the unit costs are dependent on availability of local materials and market conditions. (Note discussion on sensitivity of analysis to prices is in a later section).

Monte Carlo Analysis

The NPV calculation involves energy usage, energy prices, interest and inflation rates that are inherently variable. A Monte Carlo simulation was performed to account for the variability in each of these factors and assess the sensitivity of our analysis to variations in price, and changes in national economic trends. The simulation was used in the calculation of NPV for the built-up roof system using readily available U.S. national energy usage data (kWh/sf and ccf/sf: Table 8,) and cost data ($/kWh for electricity and $/ccf for natural gas: Table 9). The NPV for the green roof was calculated only from the case study data as there is no readily available resource of green roof energy performance data. Based on the maximum, minimum and average and standard deviations calculated from the data the energy prices and usage were sampled from a normal distribution. The interest rates were also sampled from a normal distribution with mean inflation rate of 3%, discount rate of 5% and standard deviation of 0.05% each.

The regions described in Tables 8 and 9 include Northeast (New England, Middle Atlantic), Midwest (East North Central, West North Central), South (South Atlantic, East South Central, West

TABLE 8. Electricity and natural gas usage in each U.S region

	Electricity usage, kWh/sf			Natural gas usage, ccf/sf		
Region	**Minimum**	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
Northeast	13.00	14.60	15.80	0.32	0.40	0.44
Midwest	13.50	15.50	18.00	0.40	0.42	0.45
South	16.60	17.70	19.10	0.30	0.30	0.40
West	13.50	13.90	14.10	0.30	0.33	0.40

Source: DOE, 2007a.

TABLE 9. Electricity and natural gas costs for built-up roof in each U.S region

	Electricity costs, 2006 $/kWh			Natural Gas, 2006 $/ccf		
Region	**Minimum**	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
Northeast	0.12	0.14	0.15	1.30	1.40	1.50
Midwest	0.07	0.08	0.10	1.10	1.10	1.14
South	0.07	0.08	0.10	1.01	1.20	1.40
West	0.08	0.12	0.12	1.00	1.06	1.10

Source: DOE, 2007b; DOE, 2007c.

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South Central), and West (Mountain, Pacific) (U.S.DOE, 2007a, 2007b, 2007c). The NPV values developed from our study were then compared to these regional and national distributions.

RESULTS

EIO-LCA Results

This section compares the resource inputs and environmental outputs for the two different roof systems over the 45-year building life.

Tables 10 and 11, show the environmental emissions and energy (from material acquisition life stage and, use and maintenance life stage) for a 1,445 m^2 built-up roof and green roof, respectively. The environmental effects of the material acquisition and manufacturing life stage included the effects of the respective supply chains. The transportation effects from material extraction and creation through the storage of the supplier's finished product were included in this stage. The total environmental impacts for the green roof in the material acquisition and

TABLE 10. Environmental impacts for a built-up roof over a 45 year building lifetime

Environmental Impact Indicator	Units	Material/ Manufacturing Phase	Use/Maintenance Phase	Total
Sulfur dioxide	ton-SO_2	0.10	43.00	43.10
Carbon monoxide	ton-CO	0.30	8.20	8.50
Nitrogen oxide	ton-NO_x	0.10	20.50	20.60
Particulate Matter	ton-PM_{10}	0.01	1.20	1.20
Global Warming Potential	ton-CO_2 equiv.	27.00	8,600	8,627
Carbon dioxide	ton-CO_2 equiv.	21.50	7860	7881
Methane	ton-CO_2 equiv.	2.90	630	632.90
Nitrogen dioxide	ton-CO_2 equiv.	1.90	7.40	9.30
CFCs	ton-CO_2 equiv.	0.50	101	101.50
Total Emissions	**ton**	**27.60**	**8,675**	**8,700**

TABLE 11. Environmental impacts for a green roof over a 45 year building lifetime

Environmental Impact Indicator	Units	Material/ Manufacturing Phase	Use/Maintenance Phase	Total
Sulfur dioxide	ton-SO_2	0.10	15.70	15.80
Carbon monoxide	ton-CO	1.00	2.60	3.60
Nitrogen oxide	ton-NO_x	0.10	7.60	7.70
Particulate Matter	ton-PM_{10}	0.01	0.40	0.40
Global Warming Potential	ton-CO_2 equiv.	71.3	3,212	3,283.30
Carbon dioxide	ton-CO_2 equiv.	62.1	2,914	2976.10
Methane	ton-CO_2 equiv.	6.00	247.2	253.20
Nitrogen dioxide	ton-CO_2 equiv.	2.40	14.10	16.50
CFCs	ton-CO_2 equiv.	0.80	37.50	38.30
Total Emissions	**ton**	**72.80**	**3,240**	**3,312**

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manufacturing life stage (see Table 11), is 45% more than for the built-up roof. This is in close agreement with the Guggemos (2006) study where total environmental impacts for the green roof are 43% more than the built-up roof. These observations are due to the energy-intensive processes required to manufacture the petroleum-based materials that are used in the green roof. The manufacture of roof barrier followed by roof membrane (composed of chlorosulfonated polyethylene, CSPE) contributed the most to these emissions (25 tons). In the use and maintenance life stage, the higher energy consumption of a built-up roof (see Table 10) contributes more environmental emissions than the green roof with lower energy consumption. The total environmental impacts for the built-up roof in the use and maintenance life stage, is 46% more than the green roof. This is contrary to findings by Guggemos (2006), where the total environmental impacts for both roof types during the use and maintenance life stage are almost equal. A major reason for this contradiction is that the Guggemos study had assumed energy usage for both roof types to be equal, and hence did not include in the LCA. In our study we had observed differences in energy usage and cost data for both roof types, which was included our LCA. Overall, when emissions from both material acquisition and manufacturing life stage and use and maintenance life stage are combined, the built-up roof contributes almost 46% more environmental emissions than green roof over a 45-year building life span. This finding is contrary to Guggemos (2006) where the

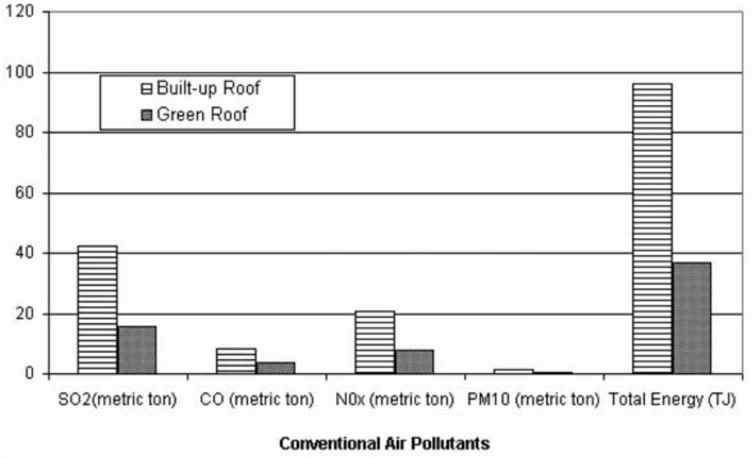

FIGURE 1. Net emissions of built-up air pollutants and energy during material acquisition phase and use and maintenance phase of built-up roof and green roof (per 1,445 m^2 roof area).

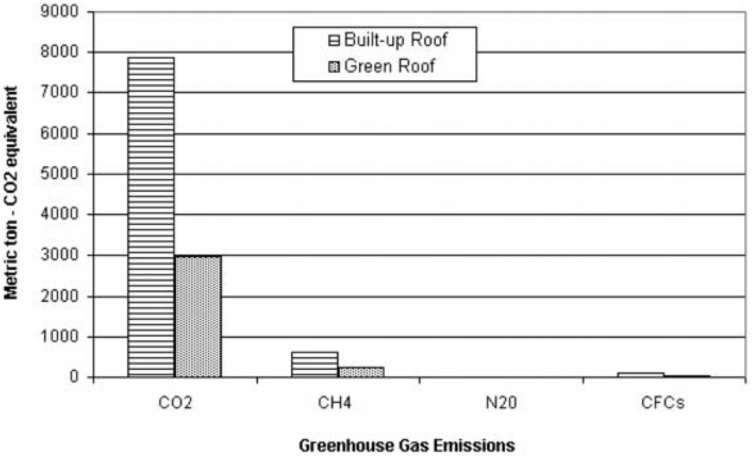

FIGURE 2. Net greenhouse gas emissions (global warming potential) during material acquisition phase and use and maintenance phase of built roof and green roof (per 1,445 m^2 roof area).

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green roof contributes 35% more emissions than the built-up roof. As pointed out, a major reason for this is the lack of inclusion of energy usage data during the use and maintenance life stage for both roof types in the LCA, based on the assumption that energy usage for both roof types is equal.

Figures 1 and 2 further show the net emissions (emissions from the two life stages combined) for specific air pollutants and greenhouse gases, respectively, for the two roof alternatives studied (details were presented in Tables 10 and 11). The primary environmental emissions (on a mass basis) for both roof types are carbon dioxide, followed by methane. Carbon dioxide accounts for 99% and 96% of the net emissions for the built-up roof and green roof, respectively. The embodied energy that is involved in the material acquisition life stage and the use and maintenance life stage indicate that built-up roof has 61% more embodied energy than the green roof. The result is contradictory to Guggemos (2006) where green roof has 40% more embodied energy than built-up roof. This is due to the lack of inclusion of energy use into the use and maintenance life stage LCA.

As can be seen from Tables 10 and 11, and from Figure 3, the highest environmental impacts are associated with the use stage. This stage accounts for more than 80% of the total environmental impact in all categories for the built-up roof and more than 72% for the green roof. Within the use stage, the

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FIGURE 3A. Relative contribution of the different phases on a built-up roof's environmental impacts over a 45-year life span.

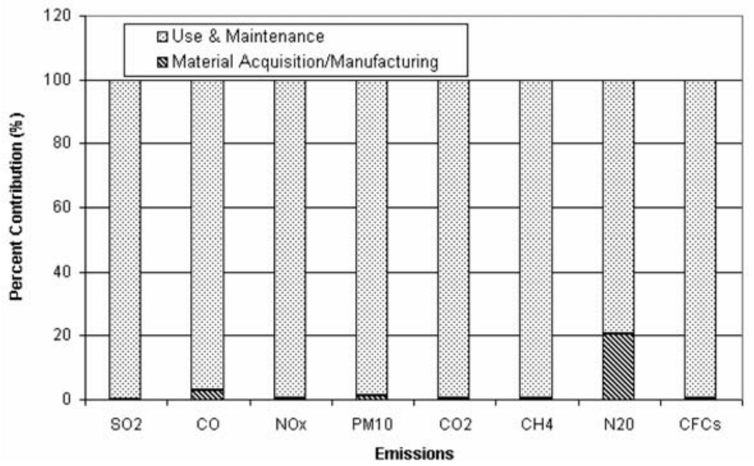
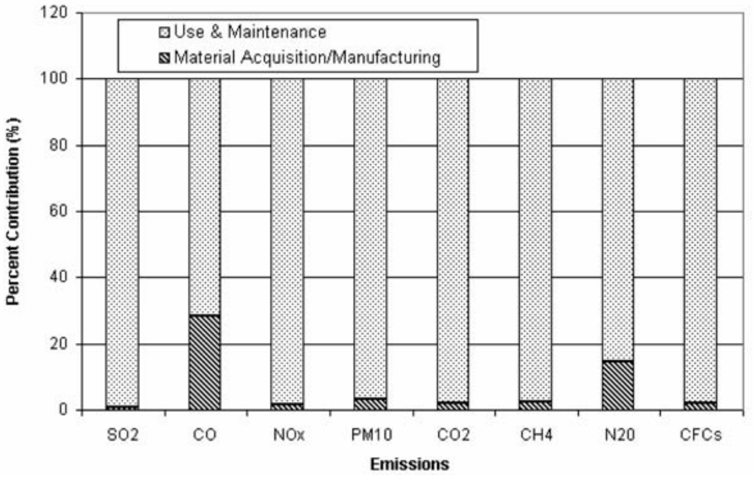


FIGURE 3B. Relative contribution of the different phases on a green roof's environmental impact over a 45-year life span.



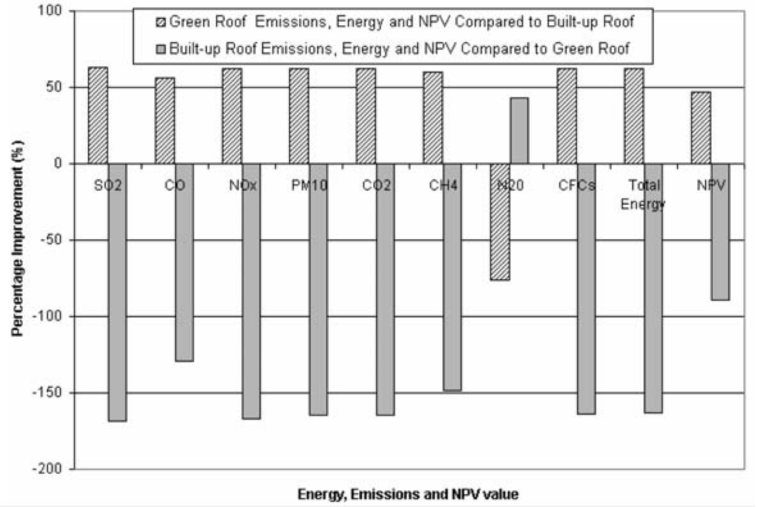


FIGURE 4. Improvements in emissions, energy, and NPV values when both roof types are compared to each other. These percentage improvements are for both initial material acquisition phase, and use and maintenance phase.

main environmental impact in all categories was from electricity use, which is used for space heating, cooling, lighting, and outlets. This was followed by the use of natural gas for heating the building and hot water.

A further interest is to determine what the improvements would be if a green roof is used in place of a built-up roof and vice versa. For example, would emissions associated with built-up roof be reduced by if a green roof is used instead of a built-up roof. Or how much economics savings would result if a green roof is used instead of a built-up roof. Figure 4 shows percentage improvements in emissions, energy usage and NPV values when both roof types are compared to each other. These percentage improvements are for both initial material acquisition life stage and the use and maintenance life stage. As can be seen from Figure 4, when a equivalent green roof substituted for a built-up roof, the net emissions are reduced and energy use improved by over 50%. On the other hand, when a built-up roof is substituted for an equivalent green roof, negative net emissions and energy use result. In terms of economic impacts, a green roof results in a positive NPV value when compared to a built-up roof, while a negative NPV value results when a built-up roof is compared to a NPV value. In other words, a green roof user will save money and, reduce environmental emissions and energy use when they use a green roof over of a built-up roof.

Table 12 and 13 show the reduction or savings in emissions that would occur annually and over the building life span of 45 years when a green roof is used over a built-up roof. These emission reductions are primarily from reductions in energy consumption, particularly electricity and natural gas. Table 13 shows that a green roof uses almost 43% less energy than a built-up roof over the entire building life. The energy reduction also results in savings in energy costs. An annual reduction of 120 tons of total environmental emissions can be realized if green roof is used. Over the 45-year building life, these reductions can be as much as 5,405 tons. Emission reduction may even be greater if energy conversation strategies such as energy efficient lighting are included. Results suggest that the roofing technology impacts the environment. The results further show that the green roof system is environmentally superior to the built-up roof over the building life; however it has greater environmental emissions in the initial material acquisition and manufacturing life stage.

Results from this study indicate that a saving of more then 50% in annual energy consumption (Table 6) may be realized when using a green roof over a built-up roof. Energy savings however, may vary from region to region, with the individual building characteristics (size, use, number of stories and roof/attic design), the different levels and type of insulation used, the thickness of soil used (if a

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TABLE 12. Annual energy, cost and emission savings or reduction during use and maintenance phase from using a green roof (1,445 m^2 area).

Use	Energy savings (kWh)	Cost Savings (2006 $)	Total Emissions Savings (tons)
Heating from natural gas	152,340	5,990	7.10
Cooling from electricity	156,980	13,900	113
Total	309,320	19,890	120.10

TABLE 13. Energy, cost and emission reduction during use and maintenance phase when using a green roof over a 45-year building life span (1,445 m^2).

Use	Energy Savings (kWh)	Cost Savings (2006 $)	Emission Savings (tons)
Natural gas (heating)	6,900,000	272,000	324
Electricity (cooling)	7,063,000	625,000	5,082
Total	13,963,000	897,000	5,406

green roof is used), and whether other energy saving technologies, such as efficient lighting are also used or not. An un-insulated green roof on a commercial building in Northern California has the potential to reduce its annual heating/cooling energy demand by 30% compared to a conventional roof with dark membrane as insulation (R-18) (Wark and Wark, 2003).

The soil depth and plant used on a green roof also have the ability to act as insulation, and thus reduce heating and cooling energy demands. For example, a five-story commercial building that uses a green roof with soil thickness of 0.10–0.90 cm can save 1–15% of annual energy consumption (Wong et al., 2003c). Strategically placing plants on the roof-top of a building can reduce the building surface temperature by as much as 20°C, and savings in cooling energy by as much as 80% (Meier, 2000). A major factor in energy savings when using green roofs is the reduced indoor air temperatures, which often translates to lower cooling energy. Decreasing indoor temperature by 0.5°C may result in up to 8% reduction in cooling energy (Dunnett and Kingsbury, 2004). Green roofs have the potential to reduce indoor temperatures by 3 to 4°C when outdoor temperatures are between 25°C and 30°C (Peck et al., 1999). Such cooling energy savings are significant during the summer months and also warmer regions of the U.S. such as the West Coast and Mountain regions.

Energy savings can also be realized by the different types and level of insulation used. Insulating a building roof with polystyrene and rock wool can result in heating energy savings of 40% and 35%, respectively (Mohsen and Akash, 2001). In warmer climates/summer period, a concrete roof with an insulation thickness of 0.095 cm polyurethane and aluminum has the potential to reduce cooling energy by as much as 74%, while an insulation thickness of 0.195 cm polyurethane and aluminum can reduce cooling energy by as much as 79% (Alvarado and Martinez, 2008). Increasing the insulation thickness can also result in a reduction in heat losses and heating energy requirements, especially during cooler months.

The critical conclusion from LCA is that green roof's lower energy consumption resulting in savings in user costs, lower maintenance costs and lower emissions over the life time of a green roof that offset the high material and initial construction costs, making green roof a viable technology.

Life Cycle Costing Results

The NPV calculated is $66.90/sf for built-up roofs and $35.30/sf for green roofs. Figure 5 shows progressive costs of the built-up roof and green roof or

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TABLE 14. Regional NPV values for the different regions in the U.S.

Region	Minimum NPV 2006 $/sf	Average NPV 2006 $/sf	Maximum NPV 2006 $/sf
Northeast	66	82	105
Midwest	43	60	70
South	51	60	81
West	43	73	54

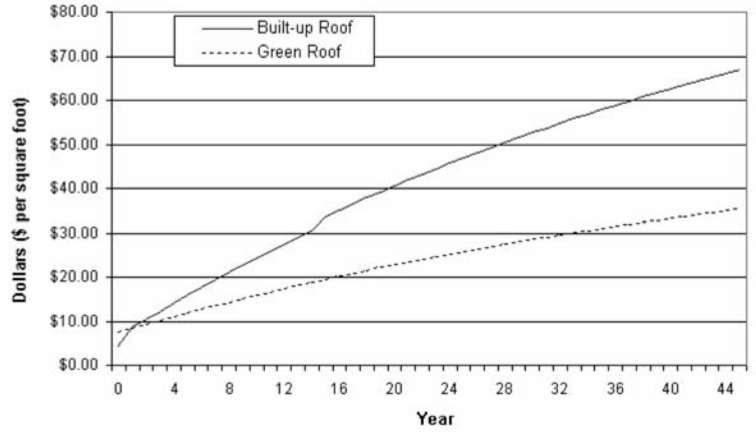

FIGURE 5. Progressive costs of built-up roof and green roof over the entire building life.

the general trend of the NPV over the analysis period of 45 years. The NPV has been presented on a yearly basis to illustrate the progressive costs over the building life. These costs were calculated using the costs per square foot of roof area as expressed in Table 5 and using Equation 1. The results indicate that both green roof and built-up roof have high initial maintenance costs. However, over the life cycle studied, the green roof has approximately half the maintenance costs compared to the built-up roof. The higher initial construction costs of the green roof over the built-up roof can be attributed to the initial material requirement, which are primarily petroleum-based and driven by market costs.

Monte Carlo Analysis Results

In order to account for the variability of the usage, prices and interest rates in the NPV calculation, a Monte Carlo simulation was performed for the built-up roof system using normally distributed samples of cost and interest variables (described in a previous section) based on data described in Tables 8 and 9. The simulation yielded probability distributions of NPV for built-up roof systems. Figure 6 shows the combined national NPV distribution from the different regions of the U.S. Regional NPV distributions are shown in Figures 7a–d. The regional probability distributions of NPV can be closely approximated to normal distributions. The national NPV distribution has two distinct humps, reflecting the large regional variability due to weather. Nationally the NPV value for a built-up roof (over a 45 year

FIGURE 6. Combined national NPV distribution across the United States.

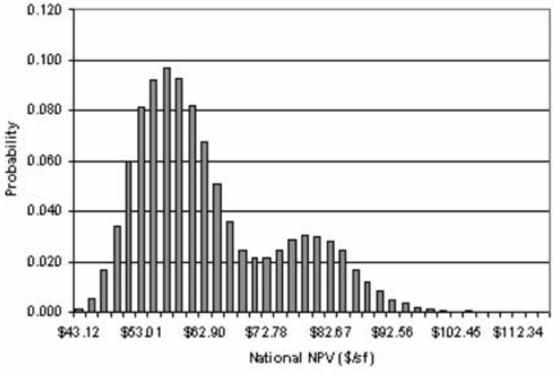

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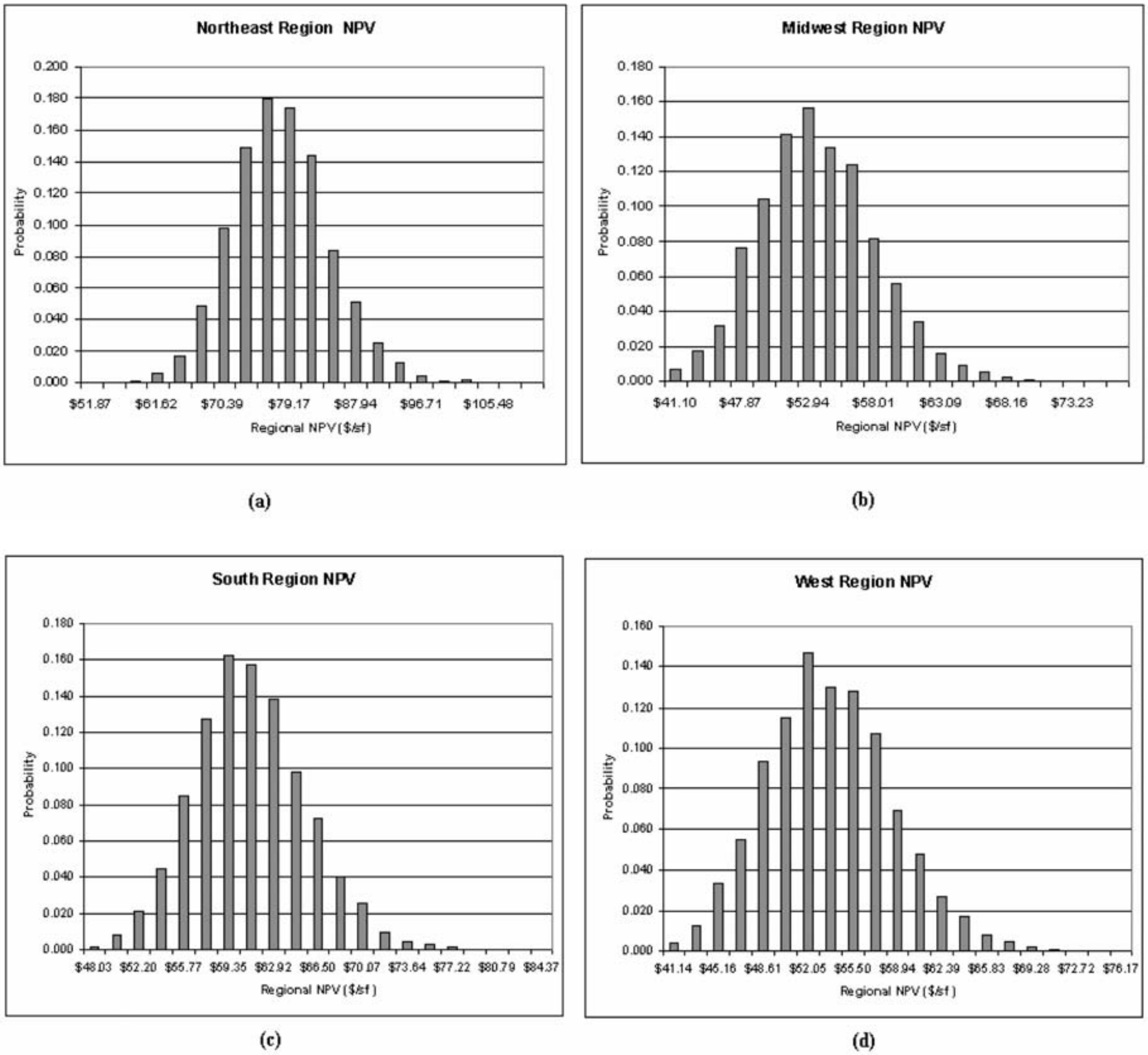
FIGURE 7. NPV distributions across the different regions of the U.S. a) Northeast regional NPV distribution, b) Midwest regional NPV distribution, c) South regional NPV distribution, and d) West regional NPV distribution.



building life) in the U.S can range from as low as $43 per square foot to as high as $103 per square with an average of around $57.40 per square feet.

The minimum, average, and maximum NPV values for each region are also shown in Table 14. When the NPV values from our study, $66.90/sf for built-up roof and $35.30/sf are compared to the regional NPV values, we find that they fall in the range of the Midwest regional NPV distribution (Figure 7b). These results indicate that a green roof costs almost 50% less to maintain over a 45-year building life then an average built-up roof (in the Midwest region).

The critical conclusion from the life cycle cost analysis (LCCA) is that green roof seems to be an ideal roofing system in terms of environmental and economic performance.

NPV Sensitivity Analysis. A sensitivity analysis was conducted to estimate the sensitivity of our NPV analysis to variations in discount rate, interest

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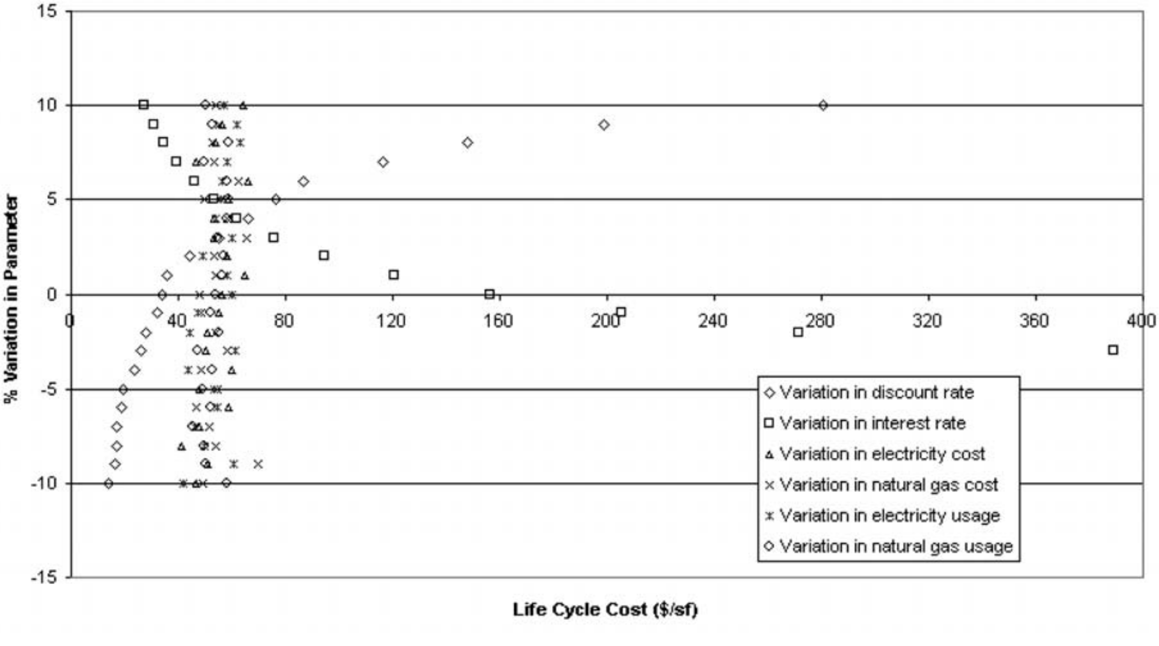
rate, electricity and natural gas cost, and electricity and natural gas usage. Figure 8 indicates that there are large variations in the life cycle cost when the discount rate and interest rate are varied from ±10%. When the discount rate is varied between ±10%, the life cycle cost ranges from $15/sf to $280/sf. A 72% increase in life cycle cost is experienced when the discount rate is increased by 5%. Likewise, when the interest rate is varied between ±10%, the life cycle cost ranges anywhere from $30/sf to greater than $400/sf. A 48% decrease in life cycle cost is experienced when the interest rate is increased by 5%. These large variations indicate that the life cycle costs are highly sensitive to variations in discount rate and interest rate.

Variations in electricity and natural gas costs, and electricity and natural gas usage, on the other hand do not exhibit large fluctuations in the life cycle costs. These parameters are not sensitive to such variations. They are stable between a certain range. For example, electricity costs fluctuate between $40/sf and $60/sf, while natural gas cost fluctuates between $45/sf and $75/sf. A 5% increase in electricity cost results in a life cycle cost that ranges between –9 and 15%. Likewise, a 5% increase in natural gas cost results in a life cycle cost that varies between –15 and 10%.

Value Analysis. Within the context of the design-bid-build delivery system in the construction industry, we present a way to analyze enhancements in economic value to stakeholders such as contractors when they decide to adopt alternative green technology such as green roofs. In this analysis, we have used the design-bid-build delivery system. The design-build-operate delivery system was selected because it provides an integrated platform to consider value enhancements through the life of the infrastructure instead of limiting it to the immediacy of the construction process (Dahl et al. 2005). However, given the predominance of the design-bid-build delivery system in practice, we have developed this discussion so it can be extended to the design-build-operate system. Specifically, the role of the contractor is considered in the decision-making process and the value associated with their decisions.

In the given context, we consider the decision scenario in which the contractor is bidding on a

FIGURE 8. Variation in life cycle cost with variation in discount rate, interest rate, electricity cost, natural gas cost, electricity usage, and natural gas usage.



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construction of a publicly financed commercial building job and is considering the relative advantages of choosing between two alternative designs: the built-up roof discussed in this paper and the green roof. It is assumed that the following will drive the contractor's decision-making process:

- The contractor uses the NPV to conduct a value analysis because the scope of the design-build-operate delivery system encompasses the entire life cycle of the facility, and the NPV, reflects long-term savings and reduced maintenance costs due to differences in energy performance
- When bidding a job, the lowest responsible bidder is most likely to win the job.
- A higher contingency in the bid increases the bid price and makes it less competitive, even though it provides the contractor a higher margin of error and improves their chances of completing the job successfully, and/or making a profit.
- The mean of the (u) regional and national NPV distributions for the roofing part of the job was considered to be typical bid price, and was used to benchmark the contractor's bid price. (Note we are limiting our analysis to the roofing component of the job. This is reasonable, as the goal is to compare value derived from alternative roofing systems). The contractor's goal is to maximize the value of the bid.

We define the expected value of a decision as its' consequence, weighted by the probability of the bid being successful. The probability of success is further defined as the probability of winning the bid (p) multiplied by the probability of completing the job successfully. The probability distribution of the regional NPVs arrived at through the Monte Carlo simulation was used to establish the probability of successfully completing the job. The area under the curve (A) up to the bid price (x) is the probability of completing the job successfully for an NPV of at most x. The consequence of the decision is defined as the difference between the price the contractor intends to bid (x) and the expected bid price (u). A profit is made when the consequence results in a positive value (i.e. $x - u > 0$). A loss is made when the consequence results in a negative value (i.e. $x - u < 0$). Hence, the equation for Expected Value (EV) is as follows:

$$\begin{aligned}\text{EV} &= \text{probability of success multiplied by the consequence} \\ &= p\,A\,[x - \text{u}] \qquad (2)\end{aligned}$$

The value of p will reflect various external market factors not relevant to this discussion, and for the sake of this discussion we will consider it only symbolically and in relation to the other analysis components. As the value of $[x - u]$ increases (for $[x - u] > 0$) the value of p decreases, and the value of A increases. This reflects the trend that a higher bid price increases a contractor's probability of completing the job successfully (A) and increases the expected profit ($[x - u]$), even though it makes the bid less competitive and therefore reduces the probability of the contractor winning the job (p). Hence, the contractor faces the challenge of maximizing the value of his bid while fulfilling the conflicting requirements of developing a competitive bid that can be successfully completed with a profit margin. Figure 9a and 9b illustrate the situations where the bid price (x) is less than and more than the expected bid price (u) (i.e. $x - u < 0$ and $x - u > 0$) respectively. In each case, as the value of (x) increases the value of (A) increases reflecting the described trend, while the probability of winning the job (p) goes down.

Hence, for different values of x, the quantities $A.[x - u]$ and p vary inversely. Contractors can significantly improve the value of their bid if they can control the inverse variation between the quantities $A[x - u]$ and p, i.e., if they can develop a low and competitive bid price without compromising on their profit or their ability to successfully deliver.

We contend that the introduction of a new technology can reduce the average NPV cost, u, thus increasing the quantity $A.[x - u]$ while holding the individual quantities, p, x and A constant. As an example we investigate the alternative use of green roof technology, instead of built-up roofing technology as studied here. It can provide an alternative that will reduce the value of u and free the decision-maker from the inverse variation dilemma.

Our estimates illustrate that using the NPV distribution for the Midwest region (Figure 7b), the value of u, is approximately \$53/sf. In our case study, the bid price (x) is \$66.90/sf ($[x - u]$ = \$13.90/sf) when using a built-up roof and \$35.30/sf when the alternative green roof technology is used. Introduc-

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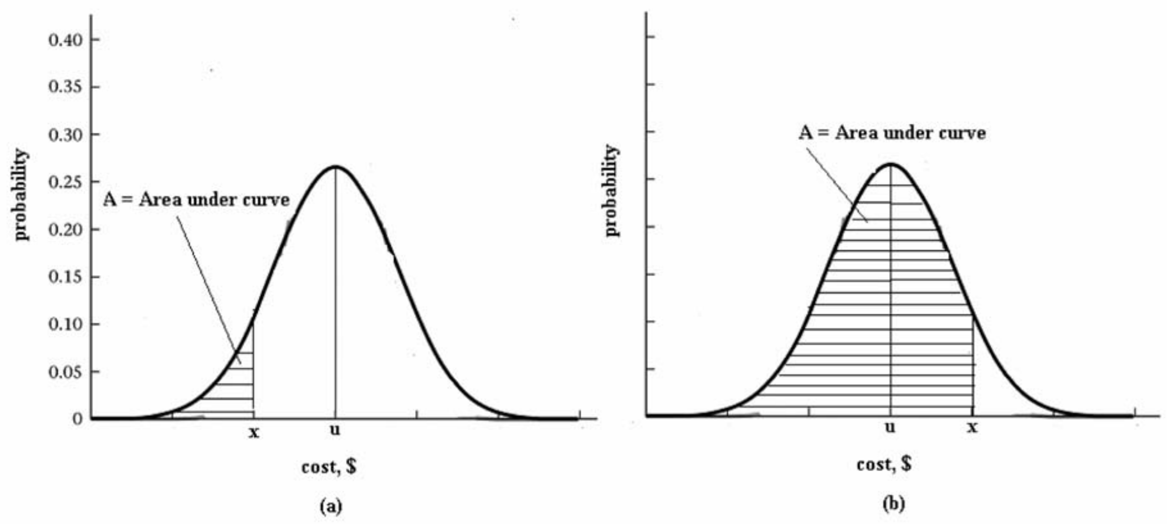
FIGURE 9. (a) Bidding at the lowest cost (*x*) results in a high probability of winning the job and a lower probability of completing the job successfully, while, (b) Bidding at the highest cost (*x*) results in a high probability of completing the job successfully but at the same time a lower probability of winning the job.



tion of green roof technology in this case provides the contractor with a bid that is significantly more competitive as the expected NPV of the roof is ($35.30/sf) is significantly less than the value of the expected bid price of approximately $53. The contractor has a margin of $17.70/sf (= $53 – $35.30) to assign to contingency or improve his net profit margin without making his bid uncompetitive. Compared to the built-up roof bid, by introducing the new green roof technology, any bid they made above the price of $35.30/sf and below the price of $53/sf, will provide a better probability of winning the job and a comparably improved probability of completing the job successfully. This can be quantitatively expressed as the net improvement in value due to the improved technology as follows: For the same values of x, A, and p, the contractor has a value improvement of:

$$p\,A.[x-53]-p\,A.[x-35.30]=pA.[x-17.7]\ \text{per sf.}$$

The purpose of this analysis is to show how a contractor can make a bid significantly more competitive, environmentally friendly and hope to make a higher profit by introducing green roof technology in traditional markets where built-up roofing technologies hold sway.

DISCUSSION/CONCLUSIONS

The primary focus of this paper was to use an integrated assessment of life cycle assessment (LCA) and life cycle costing analysis (LCCA) to investigate the environmental and economic impacts of two different roof systems; a built-up and a green roof. The paper focused costs, energy use, and environmental emissions throughout the life cycle of the two roof systems studied (from material acquisition and manufacturing life stage through the use and maintenance life stage). Given the inherent variability in energy usage patterns and cost due to variation in regional climatic conditions, and variability in interest and discount rates due to changes in economic trends, we used a Monte Carlo simulation and analyzed the sensitivity of our conclusions. Finally, the study also presented a method to quantify the long term value addition or incentive that construction industry stakeholders can expect when they decide to adopt a green technology such as a green roof.

The results from this study tend to support claims from other studies that green roof systems are environmentally and economically viable. It can aid designers and engineers in the construction and building industry in deciding the most appropriate roofing systems for a building. This study indicates

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there is tremendous reduction in energy (43% energy savings), costs, and emissions when using a green roof, and therefore seem to be a more preferable option, particularly for urban areas than built-up roof, over the building lifetime.

Results from the Monte Carlo simulation indicate that a green roof costs almost 50% less to maintain over a 45-year building life then an average built-up roof (in the Midwest region). Results from the sensitivity analysis indicate that the life cycle costs are highly sensitive to variations in interest rate and the discount rate. These life cycle costs are however less sensitive to variations in electricity and natural gas costs and usage.

When it comes to preparing a competitive bid to design, build and operate, the value analysis provides a method that a contractor can use to decide if by introducing a green technology they can enhance the long-term and immediate value of their bid, while keeping them competitive in the market and reducing long-term environmental impacts. Our analysis shows, that the introduction of green roof technology can allow the contractor to significantly add value to the bid and be competitive.

Only two life stages of the LCA: material acquisition and manufacturing and use and maintenance were analyzed. These two stages have more environmental emissions than other life cycle stages (Saiz, 2006; Junnila and Horvath, 2003). This study further supports the claim that the use and maintenance stage contributes the most to environmental emissions. When considering cost saving measures for roofing systems, a long term horizon should be used that includes construction and usage costs. This encourages design choices that emphasize improved energy usage and performance, while increasing the economic value of constructing and maintaining the system.

There are several limitations in this study. Firstly, only two stages were analyzed. A complete assessment of the other life cycle stages would strengthen the case of the green roof on both cost and environmental performance. Green roofs do not come with a 100% guarantee of lasting 45 years without problems. Leaks may develop over the building life and hence the roof membranes may need to be replaced. Although this study does not include green roof membrane replacement, it should be considered in future studies. Its inclusion may have an impact on the life cycle costs and NPV value of green roofs over the building life. Potential energy savings associated with different types of and level of insulation for alternative conventional roof systems have not been considered in detail, and thus should be included in future work. Potential savings in urban storm water reduction (i.e. reduction in storm water treatment fees) have not been included in this study, and could be included in future studies. Different results may also be produced depending on the roof designs, a region's climate that may affect maintenance requirements and the different energy sources used. However, it is likely that the regional and national NPV distributions that have been developed from department of energy data will be useful in accounting for such variations.

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