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Comparative Life Cycle Assessment of Standard and Green Roofs

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Life cycle assessment (LCA) is used to evaluate the benefits, primarily from reduced energy consumption, resulting from the addition of a green roof to an eight story residential building in Madrid. Building energy use is simulated and a bottom-up LCA is conducted assuming a 50 year building life. The key property of a green roof is its low solar absorptance, which causes lower surface temperature, thereby reducing the heat flux through the roof. Savings in annual energy use are just over 1%, but summer cooling load is reduced by over 6% and reductions in peak hour cooling load in the upper floors reach 25%. By replacing the common flat roof with a green roof, environmental impacts are reduced by between 1.0 and 5.3%. Similar reductions might be achieved by using a white roof with additional insulation for winter, but more substantial reductions are achieved if common use of green roofs leads to reductions in the urban heat island.

Introduction

Green roofs are among several technologies for developing more environmentally sustainable buildings and creating visually attractive urban environments. Recent high profile green roof projects in North America, for example, include those for Chicago City Hall, Henry Ford's Rouge automobile plant, and the new War Museum in Ottawa. Green roofs have been more common in central Europe and are now being constructed on buildings around the world.

There are several potential benefits provided by the inclusion of greenery in cities through the implementation of green roofs, although many of these remain unevaluated. Wong (1) sees green roofs as an "ecological solution to the concrete jungle in cities". Besides providing visual enhancement and improving air quality, green roofs may minimize the energy consumption of buildings by reducing the summer daytime temperature of roof surfaces. Direct shading, evaporative cooling, and photosynthesis allow plants to control surface temperatures and the microclimate around buildings. The reduction in the roof temperature may also reduce long-wave radiation emitted by the building surface, thus contributing to the reduction of the urban heat island in cities. In addition, green roofs may retain runoff water before it is released into the sewer system and with widespread adoption reduce the risk of flooding and contamination of local streams and rivers. Green roofs also

protect the underlying roof membrane, thus extending its lifespan, and providing a potential habitat for urban dwellers of all species (2). Thus, the widespread implementation of green roofs might have the potential to address multiple urban environmental issues by integrating the natural cooling, air filtering, and water retention properties of vegetation in city buildings (3–6).

Environmental life cycle assessment (LCA) is a suitable method for assessing the long-term environmental impacts of a technology such as a green roof. LCA is a well recognized method for assessing environmental impacts in the building sector; previous studies include assessments of commercial buildings (7), residential homes (8, 9), university buildings (10), structural systems (11), and evaluation of retrofitting versus rebuilding (12). None of these previous studies have considered how the building's life cycle impacts might be reduced with the addition of a green roof.

This study evaluates the life cycle environmental impacts of a multi-story residential building, including the addition of a green roof. The approach has two steps. First, LCA of the building with a common flat roof is undertaken in order to establish benchmarks for the environmental indicators. Then, the changes to the life cycle impacts are determined for the addition of a green roof to the building.

The impacts investigated are primarily those due to the change in energy use of the building. The solar absorptance of the roof is found to be an important factor, which is investigated further by including a painted white roof in the analysis. The impacts of vegetation on improving air quality and reducing stormwater runoff are not fully evaluated in this study. Two further potential benefits are, however, considered as part of a sensitivity analysis: the impacts of using stored water from the green roof for a gray water system; and the potential energy savings that might result from a reduced urban heat island, assuming that green roofs were prevalent throughout the city.

Method

The reference building is an eight story residential building (designed by S.S.) located in downtown Madrid, Spain. It has 34 dwelling units, a commercial space in the ground level and two levels of underground parking. The total living area is 3381 m², the footprint is 677 m², and the occupant intensity is 22 m²/person. The building is supported by a reinforced concrete structure and the façade consists of brick and aluminum-framed double-glazed windows. It is capped by a flat roof which is protected by gray gravel following the actual roof design practices in Madrid. The total surface of the building envelope is 3925 m² distributed as follows: windows 12%, external wall 71%, and roof 17%. Natural gas is the primary heating fuel, with electricity being used for space cooling. The building is representative of current multi-unit residential construction in Madrid.

The thermal performance of the building is studied for the climate of Madrid, located at N 40° 23', W 004° 1', with an elevation of 602 m above sea level. The climate data have been provided by the Spanish meteorological services. The annual number of heating degree days in Madrid is 1341. The average summer and winter temperatures are 19.4 and 9.7 °C, respectively. The annual precipitation is 436 mm and the relative humidity is 57%. The average wind speed is 5 m/s, mainly from the south. In this study, the following hourly data from a typical year (2003) were used: dry bulb temperature, direct sun radiation, diffuse sun radiation, relative humidity, and wind speed.

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TABLE 1. Thermal and Optical Properties of the Roof Materials under Dry Conditions

roof type	conductance (W/m ² °C)	thermal capacity (kJ/°C)	solar absorptance
common flat roof (BFR)	0.59	479	0.8
white roof (BWR)	0.59	479	0.4
green roof (BGR)	0.42	519	0.37

Two alternatives to a Madrid-standard gray gravel flat roof (BFR) are considered in the main analysis: a green roof (BGR) and a reflective white roof (BWR). The common flat roof is made of “filtron tiles” composed of 4 cm extruded polystyrene insulation protected by a layer of gray gravel. The tiles are set on a PVC membrane which is adhered to the structural deck of the roof. The white roof has the same composition, but with a reflective paint coating on the external surface. The flat roof and white roof have the same thermal conductance, but differ in optical properties (Table 1). The gray gravel exterior surface on the flat roof is assumed to have an absorptance value of 0.8 (13). The reflective external coating in the white roof has an absorptance value equal to 0.4 (14). The green roof is an extensive system, meaning that it is lightweight and does not permit use as an amenity space for the building’s tenants. As with the common flat roof, it includes filtron tiles set on a PVC membrane. A glass fiber filter layer is set on the filtron tiles, above which is 9 cm of soil substrate and the vegetation layer.

A combination of plant species including *Sedum sempervivum* (Sedum), *Opuntia aciculata* (Cactus), and *Larrea divaricata* (Desert shrub) is typically used in extensive green roof installations in this climate, covering the roof in both winter and summer. These are succulent plants characterized by their light green color and thick fleshy stems or leaves. These species have high resistance to drought and low maintenance requirements. A typical absorptance coefficient for succulent plants of 0.5 (15) was adjusted to account for energy consumed by evapotranspiration of 20% (16) and photosynthesis of 5% to give an equivalent solar absorptance of 0.37. The lower absorptance of the plants leads to lower roof temperatures.

The green roof has other minor impacts. The leaves and branches of the vegetation layer cause a reduction in the wind speed on the soil surface, creating an almost still layer of air. The reduction in convective heat transfer between the air and the roof surface is, however, considered to be negligible (17, 18). Reported values for the conductivity of the vegetation layer range from 0.06 to 0.2 W/m² °C (19, 20), but the thermal resistance of the vegetation layer is small relative to the soil layer. The thermal conductivity of the pine bark and compost (10%) soil layer was assumed to vary with moisture content, with a maximum value of 1.08 W/m² °C at a saturated moisture content of 85% (21). The overall conductance of the green roof is thus lower than the common flat roof (Table 1).

The energy performance of the building was simulated using the Environmental Systems Performance-research (ESP-r) software (22, 23). ESP-r is a finite element based integrated modeling package for the simulation of the thermal, visual, and acoustic performance of buildings. To simulate the indoor performance of the building, it has been divided into sixteen “zones” based on floor levels (Figure 1). An average occupancy was assumed to be 2 persons per apartment, with a typical heat load of 100 W per person (24). Artificial light averaging 200 W/dwelling is provided by incandescent lamps. To quantify the total inner loads in the building, the default “use profiles” given by ESP-r have been used for water, lighting, and outlets.

The model was validated through analysis of summer peak temperatures and heat fluxes using data for the hottest day

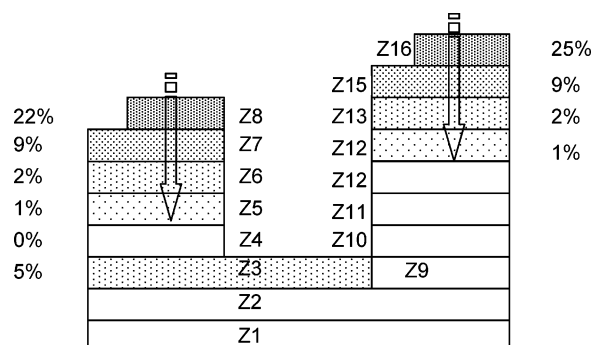


FIGURE 1. Peak cooling energy reductions achieved in the zones of the building with addition of a green roof.

in 2003. The key property of a green roof is its low solar absorptance, which results in a lower surface temperature, thereby reducing the heat flux through the roof. The peak hour temperature for the BFR is 65 °C, but only 35 °C and 42 °C for the BGR and the BWR, respectively. The peak temperature for the green roof compared favorably with the peak value of 39 °C reported for an experimental green roof in Madrid, which has the same thermal properties as that in the model. Modeled variations in surface temperatures over the hottest day also compared well with the experimental data (25). The difference in surface temperature of approximately 30 °C between common roofs and the green roof is also consistent with studies in Greece and Singapore (1, 18).

Environmental LCA was conducted for the whole building and then with changing each roof option, assuming a 50 year building life. A “bottom-up” approach was taken using the Sima Pro life cycle inventory software (26). Sima Pro is a Life Cycle Inventory (LCI) modeling tool, which enables users to construct and evaluate products and systems, in this case using Spanish production data. Three stages of the life cycle were considered: material production and transportation; building operation; and building maintenance. The construction phase and the end-of-life phase were not included in this study due to a lack of available data. Comparable studies, however, indicate that these phases amount to a relatively small contribution over the whole life cycle of the building. For example, Junnila and Horvath (7) reported both that the construction phase accounted for only 2% in the climate change category and that its maximum contribution was 6% in the eutrophication category. Building demolition accounts for only 1% and 5% of the contributions to the climate change and eutrophication categories, which is smaller than the contributions of construction and use. Consequently, the omission of the construction and the demolition phase is not expected to significantly affect the final results.

The amounts of materials used in the construction have been obtained from the project specifications and data provided by the construction company SOGIM S.A.U. The material masses and component lifespans, ranging from 10 to 50 years, are given in Table S1 in the Supporting Information. The changes to material content in replacing the common flat roof with a green roof are relatively minor. Following typical practices, local plants and substrate are

TABLE 2. Annual Energy Consumption for the Building with Common Flat Roof (BFR) and Reductions for Green Roof (BGR) and White Roof (BWR)

	BFR energy consumption	% change	
		BGR	BWR
heating (kWh) from natural gas	240,800	-0.12	+0.7
cooling (kWh) from electricity	90,200	-6.2	-4.0
lighting (kWh) from electricity	31,800	0	0
outlets (kWh) from electricity	66,100	0	0
hot water (kWh) from natural gas	71,000	0	0
total (kWh)	500,000	-1.2	-0.4

used for the green roof (27). The main change to the roof is the replacement of 78 t of gravel with 49 t of porous concrete.

Annual energy consumption in the building's heating and cooling system was calculated using ESP-r, configured for residential buildings under Spanish regulations NBE CT-79 (28). The energy source for heating and hot water systems is natural gas. Lighting, cooling, and outlets use electricity, which in Spain is generated from coal (31%), lignite (10%), oil (9%), uranium (35%), hydropower (13%), and natural gas (2%), according to Sima Pro.

A check was made to see that the building performance was structurally adequate for the different types of roof. With spans of 4–6 m, the structure of the roof is a reinforced concrete slab with hollow concrete blocks to reduce its weight. The governing criterion for the slab design is deflection. According to the Spanish structural design regulations EHE-98 (29) the slab thickness of 30 cm allows it to bear a load of 100 kN/m². The design load is calculated to be 79 kN/m² for the common flat roof and 81 kN/m² for the green roof. Thus, the installation of the green roof does not have an

impact on the roof structure and the roof deck is the same in the three cases studied. Furthermore, the columns of the structure are not affected, since the minimum size required according to the Spanish regulations (250 × 250 mm) is larger than that needed to support the load imposed by the green roof.

Results

LCA of Reference Building with Common Flat Roof. Energy consumption gives rise to a significant component of environmental impacts in the use phase of the building's life cycle. The total annual energy consumption for the reference building was 500 000 kWh, of which 240 800 kWh was for space heating and 90 200 kWh was for cooling (Table 2). This energy consumption is not uniform within the building; zones with a higher fraction of exterior have higher energy consumption. The levels of cooling energy consumed per m² in the upper zones Z8 and Z16 are, respectively, 72% and 38% higher than the average across the building (40 kWh/m²).

For the reference building, the LCA shows that the highest environmental impacts are associated with the use phase (Figure 2; Table 3). This phase accounts for more than 50% of the total environmental impact in all categories analyzed, and is especially high for abiotic depletion, acidification, terrestrial ecotoxicity, and eutrophication categories. For these categories, the use phase accounts for 71–83% of the total environmental impacts.

Within the use phase, the main environmental impact in all categories is from the subsystems which use electricity as an energy source (e.g., outlets, cooling, lighting). Of these the cooling subsystem is the most important, accounting for more than 30% in all the impact categories, except human toxicity and global warming potential. In those categories, it accounts for 20%. The heating subsystem, fed with natural

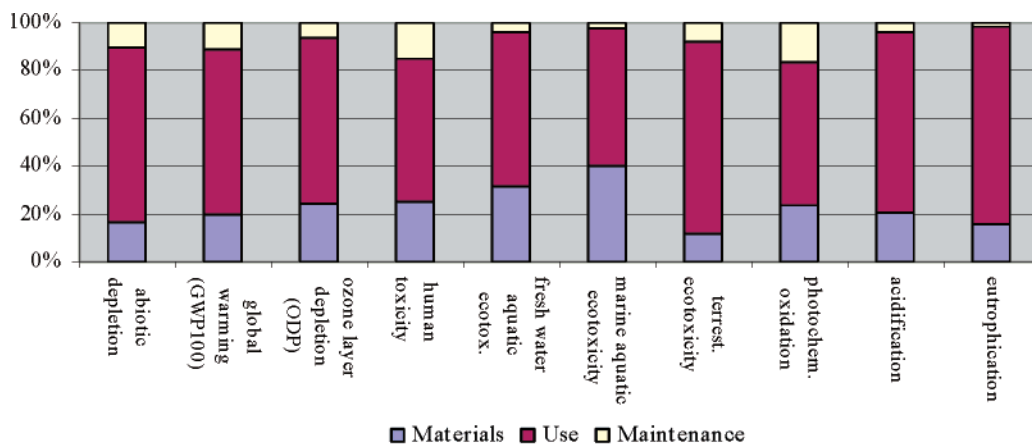


FIGURE 2. Relative contribution of stages on the reference building's environmental impacts over a 50 year life span (with common flat roof).

TABLE 3. Environmental Impacts for the Building with Common Flat Roof (BFR) over a 50-year Building Life Span

impact category	impact indicator	materials phase	use phase	maintenance phase	total
abiotic depletion	ton Sb equiv.	18.4	73.6	11.4	103
global warming (GWP100)	ton CO ₂ equiv.	2,900	8,970	1,630	13,500
ozone layer depletion (ODP)	kg CFC-11 equiv.	0.32	0.88	0.08	1.28
human toxicity	ton 1,4-DB equiv.	950	2,180	574	3,700
photochemical oxidation	ton C ₂ H ₂	0.72	1.71	0.49	2.92
acidification	ton SO ₂ equiv.	12.4	43.7	2.57	58.6
eutrophication	ton PO ₄ equiv.	0.42	2.19	0.04	2.65
freshwater aquatic ecotoxicity	ton 1,4-DB equiv.	75.4	152.5	10	238
marine aquatic ecotoxicity	10 ³ ton 1,4-DB equiv.	3,630	5,190	181	9,000
terrestrial ecotoxicity	ton 1,4-DB equiv.	3.85	23.65	2.44	29.9

TABLE 4. Changes in Environmental Impacts over a 50-year Building Life Span upon the Addition of a Green Roof (BGR)

impact category	impact indicator	Δ materials	Δ use	Δ maintenance	Δ total	% change total
abiotic depletion	ton Sb equiv.	0.02	-4.72	-0.50	-5.20	-5.0
global warming (GWP100)	ton CO ₂ equiv.	2.0	-101	-40.0	-139	-1.0
ozone layer depletion (ODP)	kg CFC-11 equiv.	0.00	-0.02	-0.01	-0.03	-2.4
human toxicity	ton 1,4-DB equiv.	1.00	-81.0	-15.0	-95.0	-2.6
photochemical oxidation	ton C ₂ H ₂	0.00	-0.06	-0.02	-0.08	-2.7
acidification	ton SO ₂ equiv.	0.00	-0.96	-0.29	-1.25	-2.1
eutrophication	ton PO ₄ equiv.	0.00	-0.13	-0.01	-0.14	-5.3
freshwater aquatic ecotoxicity	ton 1,4-DB equiv.	0.06	-6.00	-0.40	-6.34	-2.7
marine aquatic ecotoxicity	10 ³ ton 1,4-DB equiv.	0.00	-211	-4.00	-215	-2.4
terrestrial ecotoxicity	ton 1,4-DB equiv.	0.00	-0.35	-0.10	-0.45	-1.5

gas, has the largest relevant impact in abiotic depletion and global warming potential, accounting for 30% of the impacts in these categories. The contribution of the water subsystem in the human toxicity category is significant, accounting for 20%.

Broadly speaking, the materials phase accounts for about 20% of environmental impacts in most categories. This phase is most significant for marine aquatic ecotoxicity (40%) and freshwater ecotoxicity (30%). The embodied energy of the main components of the roof is higher than the most abundant materials in the buildings (e.g., PVC membrane 80 MJ/kg vs clay bricks 2.5 MJ/kg) (30); nevertheless, the contribution of the roof to the environmental burden of the materials phase is small as the roof accounts for only 1% of the total building mass.

Change in Life Cycle Impacts with Addition of Green Roof. The savings in annual energy consumption for the two alternate roofs are shown in Table 2. The reduction in annual energy use with the green roof is 1.2%. This is primarily due to summer cooling load reductions of over 6%, although the addition of a green roof provides energy savings in both warming and cooling seasons. In the winter, the additional thermal resistance of the soil layers more than compensates for the reduction in solar radiation due to the vegetation layer. In the summer, however, the reduction in solar radiation on the green roof is a significant benefit. For example, for the upper floors, the peak hour cooling load is reduced by as much as 25% relative to the common flat roof. This indicates the importance of the roof in relation to the energy consumption of the building, especially for cooling energy (Figure 1).

The importance of the optical properties of the surface can be seen in the results for the white roof: the cooling energy reduction of 4% is exclusively attributable to the reduction in the absorptance of the roof surface since the common roof (BFR) and the white roof (BWR) have the same roof conductance. The reduction of solar heat gains through the white roof, however, causes an increase in winter heating energy consumption under the BWR.

By substituting the common flat roof with the green roof, environmental impacts are reduced in all the categories by between 1.0 and 5.3% (Table 4). Most of the reductions are in the use-phase since the main effect of the green roof on the building is the reduction of the cooling energy consumed during its service life. The largest reductions are in the categories of abiotic depletion and eutrophication. The global warming potential is reduced by just 1%. The differences in reductions between impact categories are a reflection upon the extent to which impacts are associated with electricity for summer cooling versus natural gas for winter heating. For example, abiotic depletion is associated with mining of coal and lignite used for electricity generation, but not as much with natural gas production. Global warming is associated with both natural gas and the mix of technologies used for electricity generation (coal, oil, etc.), but since the addition of the green roof only significantly changes impacts

of the latter, the percentage change in global warming potential is seen to be small.

The change to the green roof also has a minor impact within the maintenance phase of the LCA. Of relevance is the expected increase in the life of the roof membrane from 10 to 40 years when it is covered by the soil substrate of the green roof (31). Use of the green roof alleviates production and transportation of roof materials, specifically PVC, which is a contributor to the environmental burden caused by the roof materials production.

Discussion

The reduction in energy consumption for space cooling is a significant factor in reducing life cycle environmental impacts of the residential building. Due to a lower absorption of solar radiation and lower thermal conductance, the addition of a green roof is estimated to reduce annual energy consumption by just over 1%. While such an energy saving might be considered small, it should be recognized that the green roof was added to just 16% of the building's exposed surface area. Greater energy reductions would be achieved with a larger roof-to-envelope ratio, such as with a low-rise building.

The results show that environmental impacts are reduced most significantly in categories associated primarily with electricity generation, but the size of these changes perhaps requires further consideration. One issue is whether it is appropriate to assess environmental impacts based on the average electricity mix, as done here, or by the marginal change in electricity generating impacts near peak production. The benefits of cooling by green roofs are particularly important at peak temperatures as shown in Figure 1. At peak demands it is likely that additional electricity is supplied by coal or natural gas generating stations, as opposed to nuclear plants, which typically provide base power. If this is the case, then the marginal environmental impacts of using green roofs would be higher than the 1–5% range found in this study.

It should also be recognized that the use of a white roof provides some of the cooling benefits that have been shown for the green roof. The reduction in cooling energy with the white roof is 65% of that with the green roof (Table 2), leading to changes in environmental impacts of the same order in categories dominated by electricity generation. Such a comparison is contingent on the values of solar absorptance (Table 1), i.e., the white roof is kept clean and the green roof maintains healthy green vegetation and contains sufficient water for evapotranspiration. Additional insulation would be required with the white roof in order to compensate for heat losses due to increased solar reflection in the winter.

Moreover, use of green roofs may preclude potential benefits from solar water heaters, passive solar heating, or daylighting. A future analysis that compares the overall environmental performance of such alternatives would be worthwhile.

To consider further potential benefits of green roofs, analysis of a green roof with capacity for water storage was also undertaken. The roof incorporated an additional air layer between the filtron tiles and the PVC membrane, formed by 10 cm high polyethylene spacers. Water stored in the cavity is used for maintenance of the vegetation layer and for feeding a gray water system. The load on the roof increased to 89 kN/m² due to the extra weight of the water, but this was still within the design capacity. Based on precipitation data for Madrid it was estimated that the gray water system could provide an annual water saving of 6420 m³, which was subtracted from the water budget in the life cycle of the building. With this additional layer to the green roof, reductions in environmental impacts of a further 0.2% to 2.0%, relative to the common flat roof, were obtained (Table S2). Such reductions are due to both the additional thermal resistance given by the air/water cavity layer and the water saving technology, although life-cycle impacts of additional piping for the gray water system were not evaluated.

A final analysis considered how the life cycle impacts might change if green roofs were commonly used on buildings throughout the city, leading to a reduction in the urban heat island. Studies in Toronto suggest that a 1 °C drop in temperatures would be obtained over one-third of the city if 50% of the buildings had green roofs and at least 3% of the green roofs were fully saturated (32, 33). Assuming that a similar effect might be obtained in Madrid, the building's summer cooling load (for temperatures over 23 °C) would be reduced by 33%, leading to reductions in life cycle impacts that are five times greater again than those shown in Table 4. Thus, the effects of green roofs when they reduce urban heat islands may be considerable and warrant further examination.

Acknowledgments

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Supporting Information Available

Table S1, mass of material inputs to primary construction and maintenance phases during 50 years service life of the building; Table S2, changes in environmental impacts relative to the building with common flat roof for additions of a green roof with gray water recycling and for a basic green roof with a 1 °C reduction in the urban heat island. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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