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Exploring the Building Energy Impacts of Green Roof Design Decisions - A Modeling Study of Buildings in 4 Distinct Climates

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ABSTRACT: This study explores the complex and interacting physical mechanisms that lead to building energy use implications of green roof design decisions. The EnergyPlus building energy simulation program, complete with an integrated green roof simulation module, was used to analyze the effects of roof surface design on building energy consumption. Simulations were conducted for both black and white membrane control roofs and nine variations of green roofs. The investigation included a total of eight buildings - new office and new multi-family lodging buildings each in four cities representing diverse climatic conditions: Houston, Texas; New York City, New York; Phoenix, Arizona; and Portland, Oregon.

Building energy performance of green roofs was generally found to improve with increasing soil depth and vegetative density. Heating (natural gas) energy savings were greatest for the lodging buildings in the colder climates. Cooling energy (electricity) savings varied for the different building types and cities. In all cases a baseline green roof resulted in a heating energy cost savings compared to the conventional black membrane roof. In six of the eight buildings the white roof resulted in lower annual energy cost than the baseline green roof. However, a high vegetative cover green roof was found to outperform the white roof in six of the eight buildings.

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BACKGROUND

There is a growing interest in the relative building energy and environmental merits of green (vegetated) roofing in comparison to highly reflective “cool” roofs. Claims of the potential energy savings of green roofs range from virtually no impact (DeNardo 2003) to 15% annual electricity savings (Wong et al. 2003). In some cases a single author reports a spectrum of savings. For example, the modeling study of Niachou et al. (2001) found HVAC (Heating Ventilation and Air Conditioning) savings ranging from less than 2% up to about 48%. While Niachou clearly notes that the 48% savings was achieved for simplified simulations involving completely un-insulated roofing, there is a temptation among advocates of the technology to take the 48% number out of context. It is also not uncommon for researchers to report large reductions in roof heat flux associated with green roofing. For example, Theodosiou (2003) found that doubling the canopy leaf area index (from 3 to 6) could accomplish a 50% reduction in roof heat flux. These results can be misinterpreted as suggesting a comparable magnitude of HVAC energy savings (e.g., ignoring other contributors to HVAC load such as windows, walls, and internal gains). In fact, HVAC energy savings of up to 50% are commonly referenced in the soft literature and industry web sites and presentations. As suggested by Niachou’s work, ultimately, the energy savings of a green roof depends very much on the baseline used for comparison. For example, climate and roof insulation are both key parameters affecting the role of the roof in impacting building HVAC loads. Once the baseline for comparison is defined and articulated one can then explore how variations in green roof design affect building energy performance. Ultimately, the evaluation of any system requires quantitative estimates of a range of potential benefits. This is particularly true for green roofing where benefits may include reduction in storm water runoff, reduction of urban heat island magnitude, promotion of habitat, improvement of urban air quality, reduction of noise transmission into buildings, and reduction of building energy use.

This paper is only concerned with the building energy use implications of roof design. It examines the whole building energy impact of green roof design decisions, varying growing media depth and plant canopy density. To explore the role of climate, simulations were conducted for four U.S. cities in different climate zones. To explore the role of different building use categories, a prototype office and a prototype multi-unit residential building were modeled. As described below, all building energy simulations were for relatively new construction and two distinctly different conventional roofs (one dark and one white) were used as baselines for comparison.

METHODOLOGY

Simulation Program

The present study uses the green roof module introduced in the standard releases of EnergyPlus beginning in April 2007 (Sailor 2008). This module functions as an integral component of the simulation software, performing an energy balance on a vegetated rooftop within each time step. The green roof simulation module allows for control of various green roof related parameters such as leaf area index (LAI), which is the projected area of all leaves divided by the soil surface area. The module inputs also include plant height, soil depth, soil thermal properties, and stomatal resistance (a measure of the resistance of the plant stomata to moisture transport from the plant to the atmosphere). The green roof module accounts for long wave and short wave radiation incident on both soil and vegetative surfaces, evapotranspiration effects, one-dimensional conduction through and storage in the soil, and convection in the canopy—soil surface zone. It also allows for input of precipitation and irrigation schedules, tracking the resulting diurnal and seasonal variations in soil moisture. While the focus of this study is on the thermal effects of the green roof on the building, the green roof module implemented in EnergyPlus is capable of tracking stormwater runoff and sensible and latent heat fluxes from the roof (soil and plants) into the urban atmosphere (see for example (Scherba et al. 2011).

Methodology: Building Description

The department of energy has published fifteen "benchmark building" input files for public use (Torcellini et al. 2008) within the EnergyPlus simulation environment. Three vintages of benchmarks – new, pre 1980, and post 1980 – are available. For the purposes of this study the new benchmark buildings, which are based largely on the 2004 version of the ASHRAE 90.1 energy standard (ASHRAE 2004) were used to represent green roof energy implications for new construction.

Two of the building types from the DoE study were used in this analysis: the medium office building and the midrise apartment (lodging) building. According to the U.S. Department of Energy these two building types combined account for approximately 16% of building energy consumption in the U.S. (EIA 2003; EIA 2005). The office building consists of three floors, 4982 m^2 of conditioned space, 1660 m^2 of roof area, and a total of 15 thermal zones (four perimeter and one core zone per floor). The lodging building consists of four floors, 31 apartments, and an office space - totaling 2824 m^2 of conditioned area with a roof area of 744 m^2. Both building types have electric direct expansion (DX) cooling and natural gas heating. The office building is modeled with heating and cooling thermostat set points that are set-back at night when occupancy levels are low. The lodging building has constant (24 hours per day, 7 days a week) thermostat set points for both heating (21^{o}C) and cooling (24^{o}C). The different building types and corresponding thermostat schedules were chosen intentionally, in order to analyze the effect of the additional thermal mass of the green roof for the cases of full night time conditioning (lodging) and limited night time conditioning (office

The office and lodging buildings have different internal load schedules and energy use intensity, as well as different HVAC system types. A complete description of the DoE benchmark buildings can be found in the Department of Energy report (Torcellini et al. 2008). In each case the roof construction included metal decking, rigid insulation (0.125m thick, with conductivity of 0.049 W/mK) and a conventional roofing membrane with a default albedo (solar reflectance) of 0.30.

Simulations were conducted for the office and lodging prototypes for representative cities in four climate zones: Houston Texas; Phoenix Arizona; Portland Oregon, and New York City. The cities were chosen to represent a range of climatic conditions, while also being of some specific significance - due to their large populations, or in the case of Portland, a city with significant current and planned implementation of green roofs. It should be noted that climate-zone specific differences in building envelope and mechanical system components are accounted for within the benchmark building specifications. Energy simulation input files were created for each city by modifying the benchmark file for that city's climate zone with city specific information, including: site geographical information, recent (2008) utility rate schedules, and annual precipitation profiles. Simulations were carried out for each city using Typical Meteorological Year (TMY3) weather files that provide representative hourly weather for each geographic location (based on historical local airport weather data). Climatic information for the four cities is summarized in Table 1.

Table 1. Summary climate data for the four cities modeled.

City	Weather Station ID (WBAN #)	Annual HDD (deg C-day) Base 18°C	Annual CDD (deg C-day) Base18°C	Summer Conditions	Winter Conditions	ASHRAE Climate Zone
Houston	12960	1525	2893	Humid, Hot	Mild	2a
Phoenix	23183	1125	4189	Arid, Hot	Mild	2b
Portland	24229	4400	390	Arid, Mild	Moderately Cold	4c
New York City	94728	4754	1151	Humid, Moderate	Cold	4a

For the "conventional roof" simulations the outer roof layer of the benchmark building was left unchanged - a roofing membrane with a default solar reflectance (albedo) of 0.3. For the second case, - referred to as the "white roof" - the reflectivity of the roof membrane was changed to 0.65. A matrix of green roof cases was created for each building by changing the outer roofing layer to a green roof, and then varying the leaf area index (LAI) and the soil depth of that green roof. In all cases the green roof construction (consisting of soil and plants, but no drainage layer) was added directly above the conventional roofing membrane. A "baseline" green roof was defined to have a soil depth of 15 cm and a leaf area index (LAI) of 2. In all cases the green roof growing media was assigned the following thermal properties: conductivity of 0.4 W/m-K, specific heat of 1000 J/kg-K, and density of 500 kG/m^3. Green roof models were subjected to typical precipitation schedules representative of each location, but were not irrigated. Table 2 shows the nine green roof combinations simulated. While soil thermal conductivity does vary with moisture (e.g.(Sailor and Hagos 2011)), the green roof module available in EnergyPlus at the time of this research did not allow for moisture-dependent thermal properties.

Table 2. Definition of green roof cases.

	CASES								
	1	2	3	4	5	6	7	8	9
LAI	0.5	0.5	0.5	2.0	2.0	2.0	5.0	5.0	5.0
Soil Depth (cm)	5	15	30	5	15	30	5	15	30

RESULTS

The results are divided into subsections for ease of comparison. First, the role of building location, and hence, local climate is evaluated with respect to annual energy consumption for the buildings with the conventional roof. Second, the performance of the baseline green roof is compared to the conventional roof for each building in each city. The third subsection contains an analysis of the impacts of varying green roof parameters. Finally, a comparison is made between the green roofs and another common energy efficient roofing choice - highly reflective “white” roofs. Unless otherwise specified, all energy comparisons are presented on a per unit roof area basis.

Role of Building Location

Location is a key factor in affecting building energy use, and hence, the potential energy impacts of any change in roofing. While underlying climate – heating degree days (HDD) in winter and cooling degree days (CDD) in summer – helps to determine environmental loads on buildings, it is also important to note that construction and insulation requirements differ from one climate region to another. These climate zone specific differences in the ASHRAE standard are reflected in the DoE Benchmark buildings that formed the basis of this analysis.

Annual gas and electricity consumption for each baseline building in each of the four modeled cities is shown in Figure 1a. The corresponding annual gas and electricity cost for each building, based on the local utility rate schedules is shown in Figure 1b. All values are given on a per square meter of roof area basis.

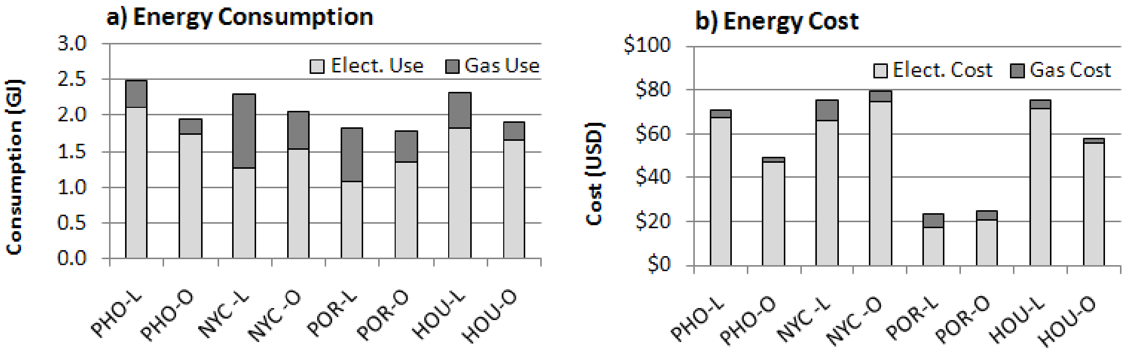

Figure 1. Annual gas and electricity consumption and cost for the conventional roof per square meter of roof area. Note: Office (O) and lodging (L) buildings have different roof-floor space ratios.

Both the office and lodging building use the least energy in the mild climate of Portland. The electricity use is especially low in Portland, as would be expected of a building in a climate with a relatively low mechanical cooling requirement (i.e. few cooling degree days). As would also be expected, the city with the most heating degree days (New York) shows the highest gas consumption. The gas consumption of the other cities follows in order of heating degree days. The low cost of electricity in Portland results in a particularly low annual energy cost for Portland.

The breakdown of energy consumption by end use for the lodging and office buildings in Phoenix and Portland is illustrated in Figures 2 and 3, respectively. In Phoenix the lodging building is dominated by cooling demand, whereas the office building is divided more evenly between cooling, plug loads, fans and lighting.

In contrast, the lodging building in Portland is dominated by energy use for domestic hot water (DHW) and plug loads. As was the case for Phoenix, plug loads, fans, and lighting are all important end uses for the office building in Portland, however, the relative importance of heating and cooling loads is reversed, reflecting the switch from a cooling-dominated climate in Phoenix to a heating dominated climate in Portland.

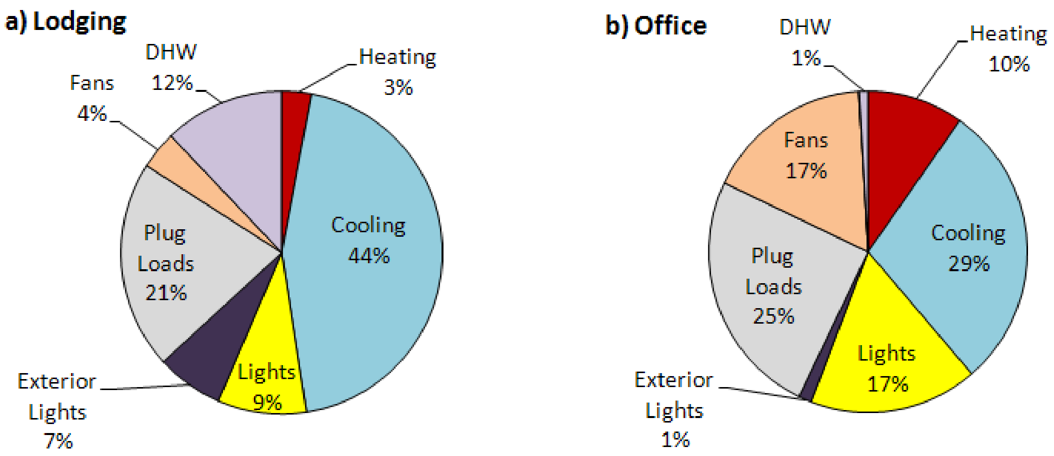

Figure 2. Percent energy consumption by end use for Phoenix lodging and office buildings (present study simulation results). Note: Office and lodging buildings have different roof-floor space ratios.

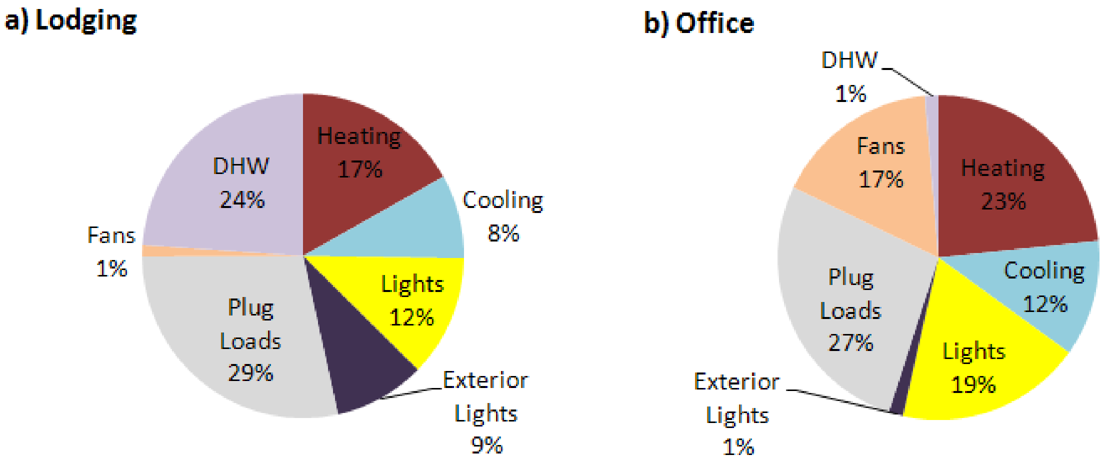

Figure 3. Percent energy consumption by end use for Portland lodging and office buildings (present study simulation results). Note: Office and lodging buildings have different roof-floor space ratios.

Energy Savings of the Baseline Green Roof compared to the Conventional Roof

In order to establish a starting point for evaluating the building energy performance of a green roof the baseline green roof (case 5 in Table 2) is compared here with the conventional (albedo=0.3) membrane roof. Figure 4 shows the gas and electricity energy and cost savings per unit roof area for the baseline green roof compared to the conventional membrane roof.

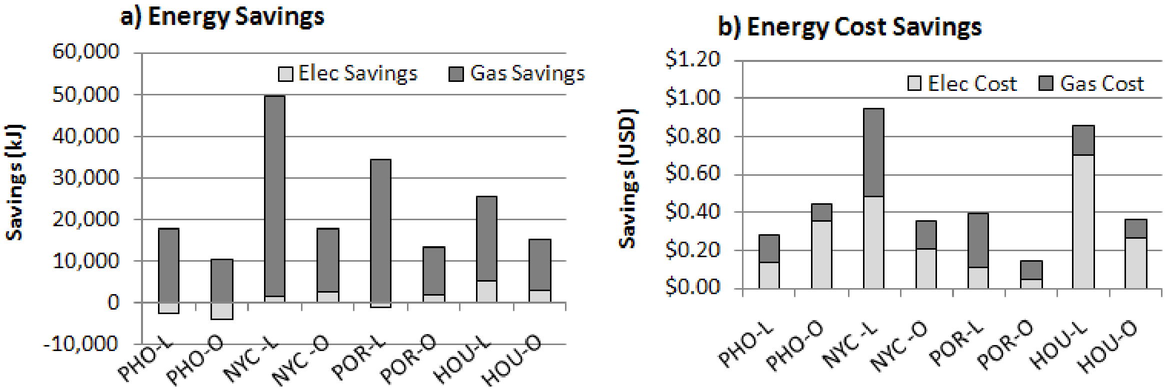

Figure 4. Electricity and gas savings of baseline green roof compared to conventional roof per square meter of roof area. Note: Office and lodging buildings have different roof-floor space ratios.

The baseline green roof is shown to reduce gas (heating) energy use for all buildings. The heating savings is a result of the increased insulation value and the thermal mass of the soil layer. The gas energy savings per unit roof area ranges from 10,500 kJ/m^2 for the Phoenix office building to 48,000 kJ/m^2 for the New York lodging building. As would be expected, the gas savings are highest in New York and Portland – the cities with the most heating degree days. The gas savings are higher for the lodging buildings, despite the fact that more heating energy is used in the office building. Several building differences could be responsible for this effect. Firstly, the lodging building has a constant heating thermostat set point, while the office building is allowed to cool off somewhat at night. The thermal mass of the green roof stores heat, allowing heat from the day to reduce the heating requirement of the lodging building at night and into the next morning. A second reason for the higher gas savings in the lodging building is that the heat load through the roof is relatively more important for the lodging building. As the office building heat load is more heavily dependent on ventilation air heating requirements and window heat loss (the office building also has a higher window to wall area ratio: office = 33%, lodging = 15%).

The baseline green roof saves electricity compared to the conventional roof in all cases, except for in Phoenix. The annual electricity savings of the green roof varies from a negative savings (increase in electricity consumption) of 4,016 kJ/m^2 for the Phoenix office building to a savings of 5,293 kJ/m^2 for the Houston lodging building. Even though the green roof has an electric energy penalty in Phoenix, it still produces an electricity cost savings. This is due to the reduced peak electricity use due to the green roof. The cost of electricity per kWh in the Phoenix rate schedule is dependent on peak demand as well as total consumption. Figure 5 shows the monthly reduction in peak demand of the Phoenix lodging building with a green roof. This figure also shows the monthly cost per kWh of electricity (cost includes monthly fees, energy and demand charges , this is commonly referred to as the "virtual electricity rate"). In May, September and October when the reduction in peak demand is high the virtual electricity rate with the green roof is noticeably lower than with the conventional roof.

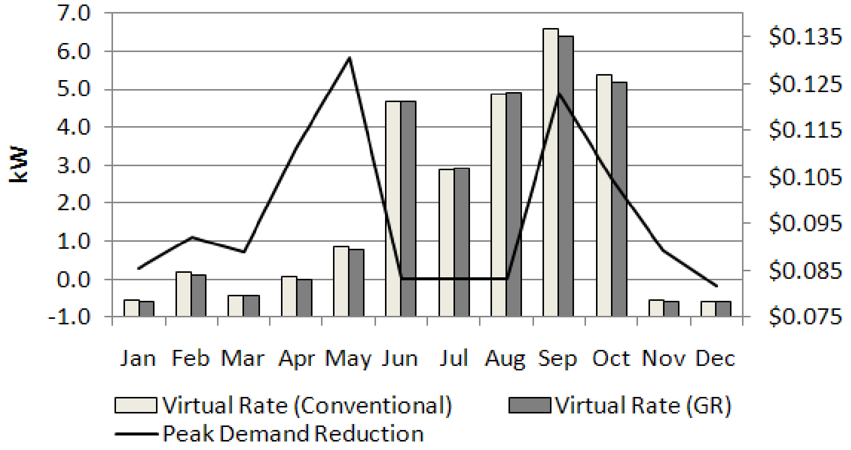

Figure 5. Monthly peak electricity demand reduction and virtual electricity rate for the Phoenix lodging building with the baseline green roof compared to conventional roof.

The electricity cost savings for all buildings is high relative to the gas cost savings when compared to the corresponding energy savings. This is due both to the higher cost of electricity per unit of energy, and the reduction of peak electricity use, which is typically billed at a higher rate. As reflected by the utility rate schedules, reducing peak demand is a top priority in many parts of the country, and should be considered in the valuation of performance of any energy conservation measure. This underscores the importance of using the applicable utility rate schedules in building energy simulation. Had a "virtual rate" (flat cost per kWh) been used, the green roof would show an electricity cost penalty instead of an electricity cost savings in Phoenix.

To explore the hourly variation in green roof impact, consider a snapshot of hourly energy use during the few days when the peak summer electricity loads occur for the Phoenix lodging building (July 15-17) and for the Portland lodging building (July 20-22). Figure 6a shows the hourly electricity consumption for the peak summer load for the Phoenix lodging building with the conventional roof and the baseline green roof. This figure also shows the hourly electricity savings of the green roof. Figure 6b shows the same information for the lodging building in Portland over several days around its peak summer energy use (peak occurs on July 21st).

The hourly electricity use for the Phoenix lodging building peaks on July 16th at 6pm. The lodging building with the green roof consumes more electricity at night due to the heat storing mass of the green roof. However, the green roof leads to less electricity use in the morning and evening - when building electricity use is high. In the middle of the day on both July 15th and 16th the electricity savings is zero. At these times the building is at maximum cooling with either roof. Since the building is at maximum cooling in either case, but the cooling load is higher for the building with the conventional roof, it follows that the internal space temperatures are slightly lower for the building with the green roof. For the annual simulation, the building with the conventional roof is unable to meet the cooling set point of every zone for a total of 196 hours. The number of hours for which the set point is not met drops by 16% to 164 hours per year for the building with the green roof.

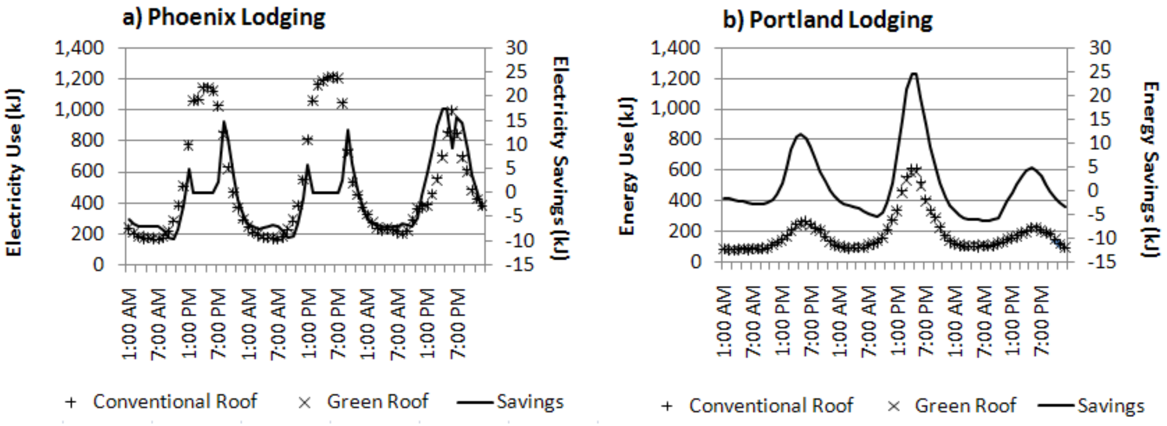

Figure 6. Hourly electricity consumption and savings of baseline greenroof compared to conventional roof during days of peak cooling demand for lodging buildings for Phoenix (July 15-17) and Portland (July 20-22).

The diurnal profile for the lodging electricity use and savings in Portland is similar to that of Phoenix, however the savings remains positive throughout the day. With both the conventional roof and the green roof, the lodging building is able to meet the cooling set point for every hour of the simulation.

The winter time natural gas use for the Phoenix lodging building peaks on February 10th. Figure 7a shows the hourly gas consumption for several days centered on this peak for both the Phoenix lodging building with the conventional roof and the baseline green roof. This figure also show the gas savings associated with the green roof. Figure 7b shows the same information for the lodging building in Portland, with a focus on the days around its peak gas use (Dec. 31).

For the coldest days in the Phoenix weather file (February 9-11) the lodging building gas use peaks at around 7am, and hits a minimum at around 4pm. Gas savings follows the same diurnal profile as consumption – peaking when usage peaks. There is actually a slight gas cost associated with the green roof during the day. The overnight savings, however, more than make up for the daytime penalty. The diurnal profile of gas use and savings follows the same pattern for the lodging building in Portland. Gas is not billed by time of day pricing, and peak demand is much less of a billing concern than it is for electricity.

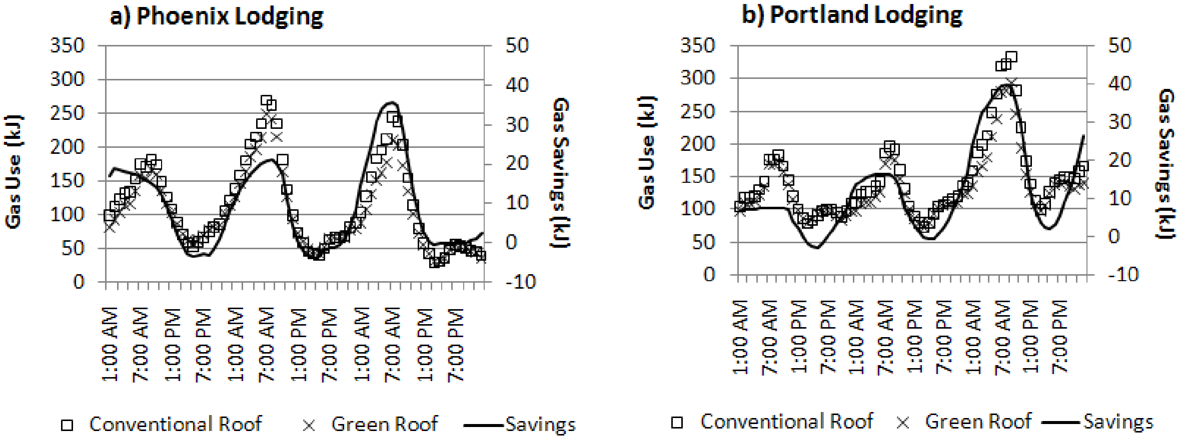

Figure 7. Hourly gas consumption and savings of baseline greenroof compared to conventional roof during days of peak heating demand for lodging buildings for Phoenix (Feb 9 - 11) and Portland (Dec. 30 – Jan 1).

Energy Savings Impact of Varying Green Roof Parameters

It should be noted that the energy analysis presented thus far focuses on one particular implementation of a green roof (LAI of 2 and a growing media soil depth of 15 cm). As these parameters vary, so too does the energy performance of the green roof. As noted earlier and summarized in Table 2, a total of 9 variations of green roofs were modeled for each building and city. In all cases only LAI and/or soil depth were varied. Figure 8 shows the gas and electricity savings associated with varying green roof soil depth for each of the buildings.

Increasing the soil depth of the green roof resulted in increased gas savings for all lodging buildings. Increasing the soil depth generally increases the gas savings of the office building however the increase is much less pronounced than it is for the lodging building. The gas savings are due to the added insulation value and thermal mass of the deeper soil. Increasing the soil depth also generally increases the electric energy savings of the green roof. In Phoenix, increasing the depth of the soil leads to an annual electric energy savings instead of cost. The added mass serves to even out the diurnal fluctuation of heat flux through the roof by smoothing out the night and day time peak temperatures of the surface adjacent to the conditioned space (i.e. the roof). Figure 9 shows the gas and electricity savings associated with varying leaf area index for each of the buildings.

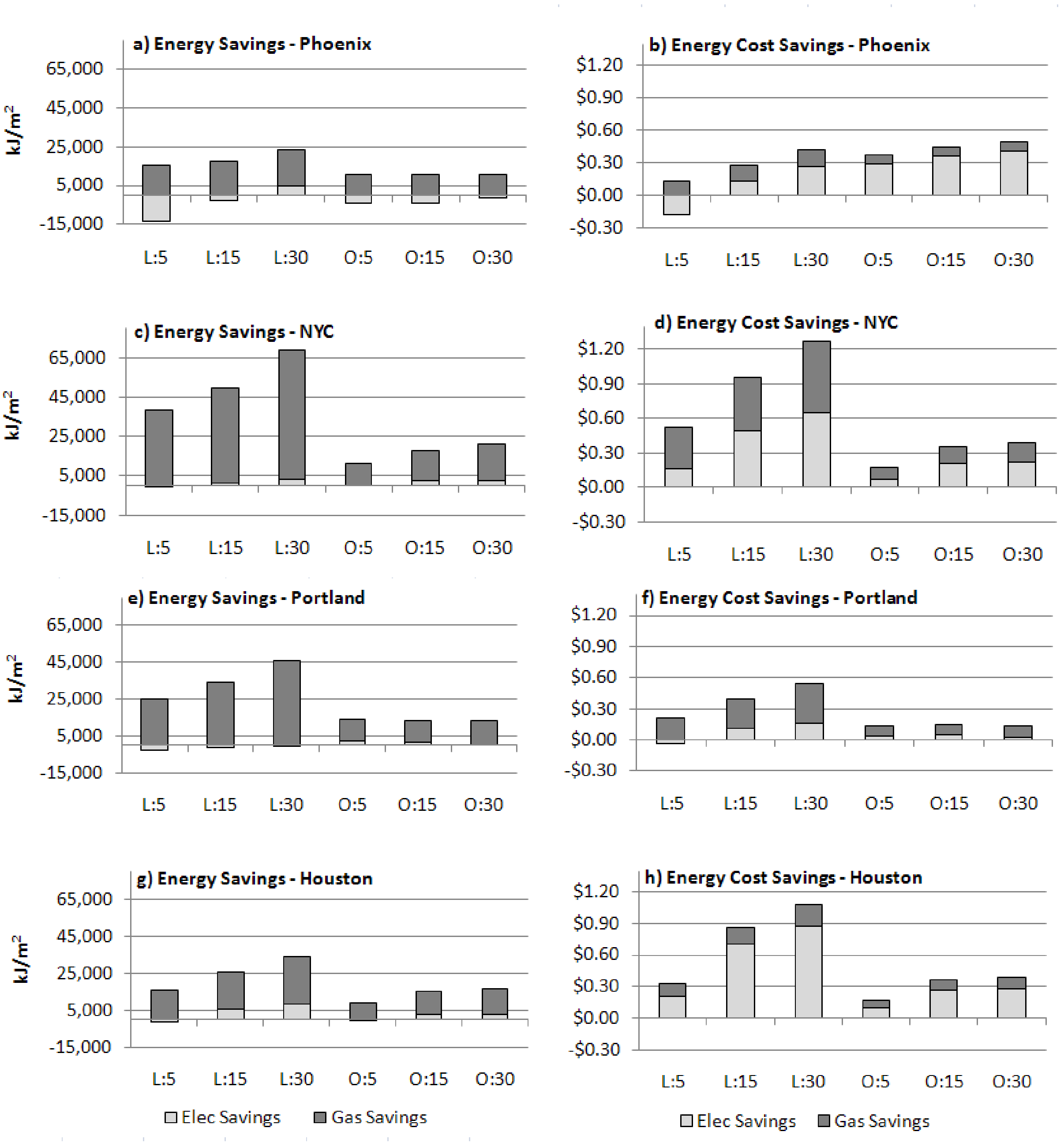

Figure 8. Annual energy and energy cost savings per square meter of roof for green roofs on lodging (L) and office (O) buildings with three different soil depths (5, 15, and 30 cm)compared to a conventional roof. Note: Office and lodging buildings have different roof-floor space ratios.

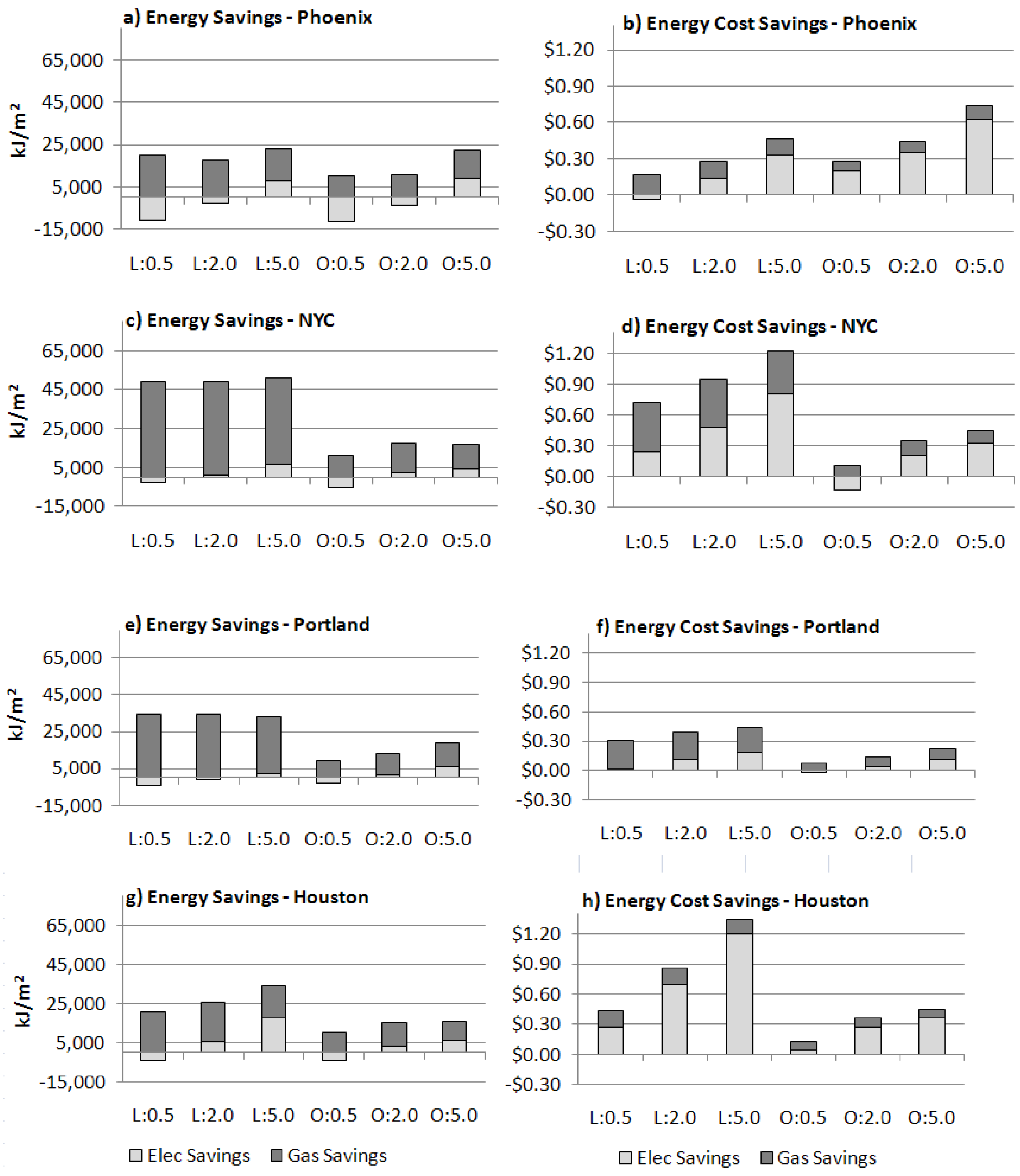

Figure 9. Annual energy and energy cost savings square meter of roof for green roofs on lodging (L) and office (O) buildings with three different levels of LAI (0.5, 2.0, and 5.0)compared to a conventional roof. Note: Office and lodging buildings have different roof-floor space ratios.

Increasing the leaf area index generally decreases gas energy savings. The decreased savings is due to two factors. Increasing the LAI increases the shading on the roof thereby reducing the solar heat gain to the space. Increasing the LAI also increases the transpiration cooling effect. It then follows that increasing the LAI increases the cooling energy savings in all cases for the same two reasons that it decreases the heating savings. The overall energy savings generally increases with increased LAI. The overall cost savings increases with LAI in all cases. On some buildings (e.g. Houston lodging) the savings increase associated with high levels of LAI is dramatic. The cost savings is again high relative to the energy savings due to the high cost of electricity and the reduction of peak load.

Green Roof and White Roof Comparison

Highly reflective roofs – commonly referred to as “white roofs” or “cool roofs” – are frequently installed as an energy saving alternative to conventional dark roofs. Roof reflectivity is regulated both by California energy code and by the LEED (Leadership in Energy and Environmental Design) certification program. In fact, through the ASHRAE 90.1 Appendix G modeling guidelines(ASHRAE 2007), LEED allows the modeling of white roofs as a means to demonstrate energy savings for one LEED credit point. For the present study, simulations were carried out in which the reflectivity of the roofing membrane of the conventional roof was adjusted to 0.65 (the value allowed under ASHRAE 90.1 Appendix G modeling guidelines for white roofs). Figure 10 shows the annual energy and energy cost savings of the baseline green roof as compared to a white roof for each building. Negative values represent a higher consumption/cost for the green roof than for the white roof.

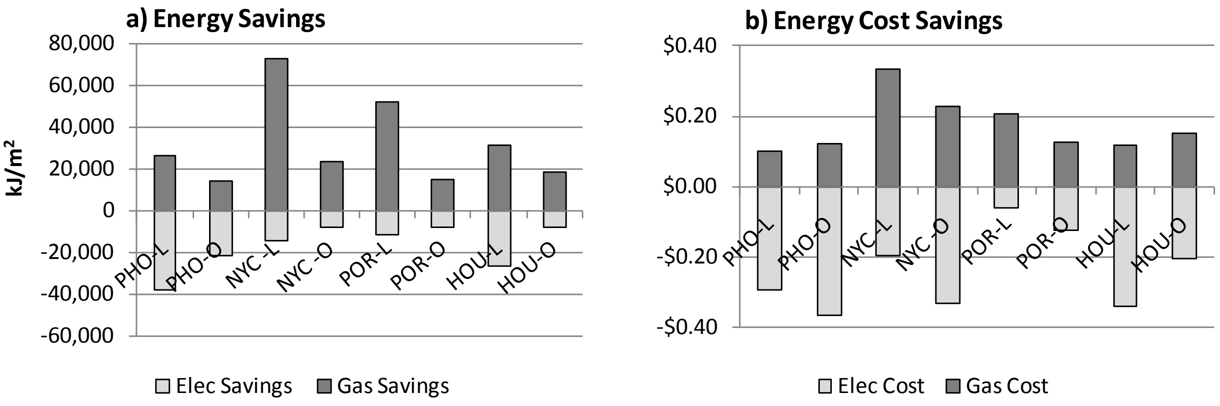

Figure 10. Annual energy and energy cost savings per unit roof area of the baseline greenroof compared to a highly reflective white roof. Note: Office and lodging buildings have different roof-floor space ratios.

In all cases the baseline green roof leads to more electricity consumption (cooling energy) than the white roof and less gas consumption (heating energy). For the New York and Portland lodging buildings the net result is a cost savings for the green roof over the white roof, however in all other cases the white roof leads to a lower total energy cost. The lodging buildings in New York and Portland show a net savings because of the colder climates. For these cases the heating cost savings outweighs the cooling cost penalty of the green roof. The green roof performs better on the lodging buildings than on the office buildings in both Portland and New York, due to the reasons discussed previously.

The primary advantage of the white roof over the green roof is the decreased solar gain absorbed by the roof. The green roof which absorbs the least solar gain is the high LAI roof. Figure 11a shows the annual energy savings of the high LAI green roof over the white roof for each building. Figure 11b shows the annual energy cost savings of the high LAI green roof over the white roof for each building.

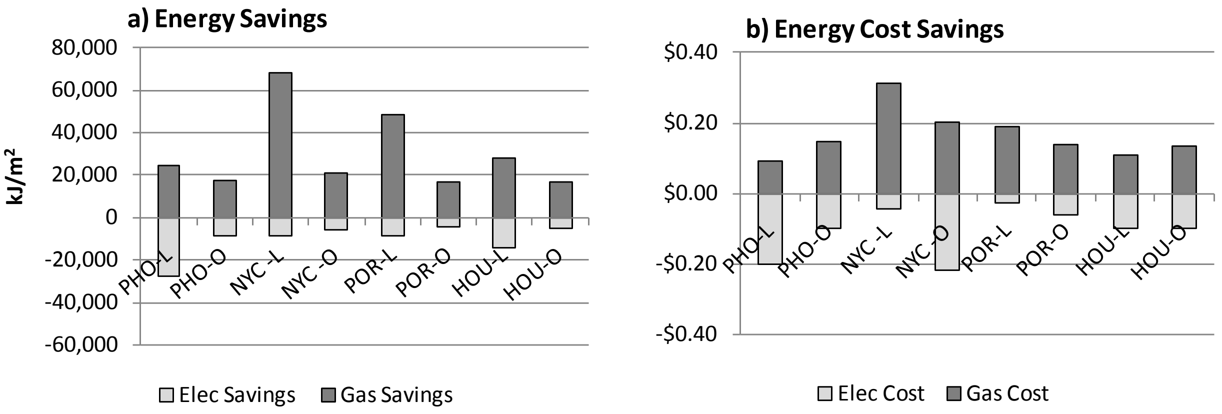

Figure 11. Annual energy and energy cost savings per unit roof area of the high LAI greenroof compared to a highly reflective white roof. Note: Office and lodging buildings have different roof-floor space ratios.

The high LAI green roof shows a gas savings and electricity penalty in comparison to the white roof for every building. The electricity penalty is however less than it was for the base green roof. The net energy cost savings is positive for all buildings except the Phoenix lodging and New York office buildings. The net cost savings is negative for the New York office building predominantly because of the particularly high utility rate for electricity (approximately 20 cents per kWh).

DISCUSSION AND CONCLUSIONS

For all modeled climates the baseline green roof showed an overall energy cost savings for both building types in comparison to the conventional roof. While it must be noted that electricity cost data used in this study will quickly become out of date, the results presented here will likely remain qualitatively useful unless structural changes in electricity pricing are implemented in the regions studied. Green roof cost savings generally increase with increased soil depth and increased Leaf Area Index (LAI). Heating savings is greatest for the lodging buildings in the colder climates. Electricity savings varied for the different building types and cities. In a few cases, the baseline green roof even shows an increase in electricity consumption compared to the conventional roof. However, in all cases the baseline green roof leads to an electricity cost savings. The discrepancy between increased electricity consumption and reduced electricity cost is a result of the reduced demand during more expensive peak hours with the green roof. The baseline green roof shows the highest savings for the New York lodging building. The annual cost savings is \$0.26/m^2 of conditioned building area and \$0.95/m^2 of roof area. In most cases the white roof leads to a lower annual energy cost than the baseline green roof. However, the high LAI green roof outperforms the white roof in most cases.

In summary, the impact of green roofs on building energy consumption can be thought of as having three facets – total energy use, peak electric loads, and total energy cost. From the standpoint of total energy use green roofs perform best in colder climates in buildings which require night time heating. Increasing soil depth will further increase the heating savings in these circumstances. For cooling dominated buildings, leaf area index is a more important parameter, as more dense vegetative cover helps to reduce cooling need. For buildings subject to high electricity cost, especially high peak electricity pricing, or demand pricing, the ability of the green roof to mitigate daytime peaks is especially valuable – both LAI (by reducing solar load) and soil depth (by increasing the insulation and thermal mass of the roof) contribute positively to the mitigation of peak electricity use.

The results presented in this paper are for relatively new construction with high levels of roof insulation. As illustrated in the work of (Kashiwagi and Moor 1993), the relative costs and benefits of energy conservation measures are quite sensitive to underlying building insulation characteristics. Thus, the relatively modest energy savings of the green or white roof systems relative to the control roof are not surprising. For retrofit applications of existing buildings the roof is generally less insulated and hence a more important contributor to HVAC loads. According to (Phelan et al. 2010), for example, the typical roof replacement starts from a baseline of approximately R-12.4 (RSI of 2.1 m^{2}K/W). While beyond the scope of the present work, it is clear that future studies should explore energy implications of green roofs for retrofit applications. Furthermore, the present study was limited to the situation of the non-irrigated roof. While this is generally the preferred implementation from a sustainability standpoint, there is no question that irrigation (perhaps using gray water) can greatly enhance the evaporative cooling aspects of green roofs.

Finally, it must also be noted that the energy performance of green roofs is only one aspect of their potential environmental benefits. Ultimately, this information must be integrated with estimates of other benefits to provide for a more comprehensive assessment of the life-cycle performance of green roof systems.

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