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COOLING ENERGY SAVING PERFORMANCE OF EXTERIOR GREENERY SYSTEM ON DEPARTMENT OF ENERGY REFERENCE BUILDINGS

A Thesis in

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by

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ABSTRACT

Exterior greenery system such as green roof and green wall can provide energy and environmental benefits to buildings. The objective of this paper is to quantify cooling energy savings by exterior greenery system on the building envelope. Three Department of Energy (DOE) reference buildings - medium office, hospital, and primary school - are simulated using a building energy modeling tool, EnergyPlus. Cooling energy consumption is estimated for six different exterior greenery system types, three built years and four climates. Heat transfer analysis is performed for both the original roof and green roof layers. Results show that energy saving by the greenery system is more significant in buildings with poorly insulated enclosure and buildings located in hot and dry climates. The results also suggest that latent heat transfer dominates the roof heat transfer process. Cooling energy saving is marginal in building with high internal load such as hospital. However, annual cooling energy saving by exterior greenery system can reach up to 20% for primary school, a single floor building in Phoenix.

Keywords: exterior greenery system, cooling energy saving, DOE reference buildings, EnergyPlus, latent heat

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Chapter 1

Introduction

Buildings have utilized green plants for centuries due to their various benefits such as energy saving, reducing heat islands effect, noise attenuation, aesthetics appeal, indoor air quality improvement, and stormwater management. Building green claddings can provide shading to reduce solar radiation into the building envelope during the summer. The greenery can function as thermal insulation to reduce conductive heat transfer through the roof and walls. During the winter, exterior greenery systems can reduce the wind speed upon the building surface. The reduction of the wind velocity lowers down the convective heat transfer rate. On microclimate, plant transpiration absorbs heat from the surroundings, which results in cooler building environment and even in large scale as urban environment. The process of the urbanization raises the concerns about urban heat island (UHI) effect. Wong et al. (2005) claimed that green areas in cities have the potential in mitigating urban heat island (UHI) effect. Veisten et al. (2011) found that exterior greenery systems are capable of attenuate noise. Green plants can improve indoor air quality and reduces indoor air volatile organic compounds pollution (Wood 2006). They add aesthetic appeal and property value. Furthermore, as stormwater runoff and urban flooding become a serious problem in big cities. Many researchers believe green roof can be an effective measure to manage stormwater. Berghage et al. (2009) stated rooftop garden can reduce 50% of the stormwater runoff from the roof through retention and evapotranspiration.

Several studies examined thermal performance of green roofs and green walls as well as their impacts on building energy consumption. Wong et al. (2003) claimed that rooftop garden can save 0.6-14.5% annual energy consumption of a five-floor commercial building. The peak space load saving could reach 17-79%. Sailor (2008) developed a green roof energy balance model in EnergyPlus and found that green roofs can save 2% electricity consumption annually for a two-floor office building in Chicago and Houston. Yaghoobian et al. (2015) developed a new green roof model and simulated single floor buildings in EnergyPlus and reported that green roofs can reduce by 32% of the daily surface radiation.

High rise buildings in big cities limit the effect of the roof gardens due to small roof areas compared to total floor areas. Also, building roofs are often occupied with equipment such as rooftop air conditioning units and cooling towers. Such limitations can be overcome by utilizing vertical greenery systems. Vertical greenery systems can be divided into two categories: 1) green façade and 2) living wall. The green façade has vegetation planted in the ground, mostly creeping plants growing directly on the exterior wall or on the supporting grid. For living wall systems, plants are grown in soil or substrates in the modular panels. The panels are supported on the surface of the wall. Various species of plants can be applied in the living wall systems, but the diversity also leads to more maintenance. Living wall needs less growing time and does less damage to the wall surface compared to green façade (Ottelé et al. 2011). However, living wall systems are more expensive and have longer pay back periods due to their high investment cost and maintenance fee (Perini et al. 2013).

Wong et al. (2010) installed eight vertical greenery systems (seven living walls, one green façade) in Singapore and compared their thermal impacts on the wall and surrounding temperature. They found there is a significant temperature reduction for the wall surface and surrounding air. Kontoleon et al. (2010) built a 10 m × 10 m × 3 m single floor thermal zone and used thermal-network model to calculate the thermal performance of the plant-covered wall (green façade). Results showed that plant-covered wall can reduce building cooling load significantly from 20.08% to 4.65% depending on different orientations in a northern region of Greece. Chen et al. (2013) conducted experiment and claimed the living wall systems are capable of reducing building exterior surface temperature, interior surface temperature, and interior space temperature. Plant types choice of green façade also influences the cooling potential (Cameron et al. 2014).

However, existing studies about exterior greenery systems focused on thermal impact of single roofs or walls (Cheng et al. 2010). Several studies used simplified buildings, such as a single floor thermal zone without windows, internal load, and mechanical systems (Kontoleon et al. 2010). The impact of exterior greenery system on the energy use of a full-scale standard building remains unknown. Also, few studies demonstrated how energy saving potential of exterior greenery systems varies with built year and building types. Although several studies did consider climate factor on greenery and simulated buildings in different cities, buildings in different climates follow various building codes, which should be considered when applying the same building into different climates. Furthermore, because the complex process of the plant and soil evapotranspiration as well as their intricate structure, few studies have described the heat transfer process of the greenery layers and their impact on the original walls.

To fill these research gaps, the objective of this study is 1) to quantify the cooling energy saving potential of the exterior greenery system on realistic and standard buildings considering building years, building types, various greenery systems, and climate condition; and 2) to analyze the heat transfer process of the exterior greenery systems and their impact on the buildings. This paper applies exterior greenery systems to the U.S. Department of Energy (DOE) reference buildings. The reference building models are established based on statistical parameterizations of building types and climates (Deru et al. 2011). There are 16 building types across 16 locations which represent approximately 70% of the commercial buildings in the United States with realistic building conditions. We study 108 simulation cases to evaluate how exterior green walls and green roofs influence cooling energy usage considering 1) building construction periods, 2) different types of exterior greenery systems, 3) building types and 4) climates. This study also conducted heat transfer analysis of the original wall layer and the exterior greenery system to give some insight into its cooling performance on the buildings.

Chapter 2

Method

2.1 Building models

Three Department of Energy reference buildings were chosen 1) medium office, 2) hospital, and 3) primary school (Figure 1). Office, education, and health care buildings are among the top five energy consuming categories by all commercial buildings in 2012 (U.S. EIA 2012). The primary concern of this study is medium office building, because office building accounts for a large proportion of energy consumption in commercial buildings. Hospital operated 24-7 hours with the largest internal load among buildings. It's energy utilization index (EUI) is around 3 times compared to medium office. Another difference is that hospitals use mass wall, a kind of wall with high thermal capacity (ASHRAE 2004). Primary school is a single floor building with the largest roof to floor area ratio and it may result in a higher portion of the enclosure heat gain in the total cooling load. HVAC system characteristics and geometry information of these three buildings can be found in Table 1 and Table 2.

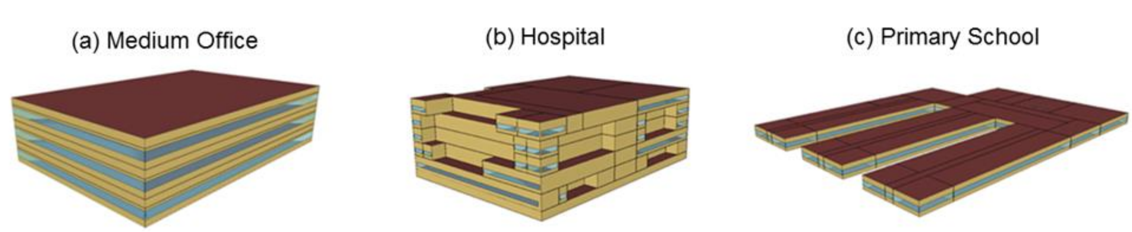


Figure 1. Department of Energy reference building model

For each building type, three construction periods are available to analyze, i.e., pre-1980 construction, post-1980 construction, and new construction. They share the same building geometry, area, and the same operation schedules. Buildings in different built years are varies in lighting level, HVAC systems and enclosure materials.

Table 1 HVAC Equipment Types (New Construction or Post-1980)

Building Type	Heating	Cooling	Air Distribution
Medium office	Furnace	PACU	MZ VAV
Primary School	Boiler	PACU	CAV
Hospital	Boiler	Chiller–water cooled	CAV and VAV

Table 2 Three Types of Buildings Information

Building Type	Floor Area, ft2 [m2]	Glazing Fraction
Medium Office	53628 [4982.2]	0.33
Primary School	73960 [6871.1]	0.35
Hospital	241351 [22422.2]	0.15

EnergyPlus was used in this study to perform the simulations of energy consumption. EnergyPlus is one of the most cutting edge building energy simulation software that is supported by DOE for analyzing the energy consumption of buildings. It is capable of simulating hourly energy use of a building on user specified internal loads, building construction, HVAC systems, schedule, and weather. DOE reference building models can be applied on this platform as building inputs. It is also able to calculate energy balance of greenery layer attached to the building envelope.

2.2 Plant models

Salior (2008) created green roof energy balance model that can be embedded in the EnergyPlus platform. The model can predict: latent heat flux (evapotranspiration), sensible heat flux (convection), short wave radiation, long wave radiation, and conduction heat flux into the soil and plant layer. Users can define growing media thermal properties and depth, and plant properties such as height and leaf area index.

Feng et al. (2013) utilized this model in Designbuilder, a graphical user interface of EnergyPlus, to simulate energy saving performance of green vegetation on a LEED certified building. Carlos (2015) applied this model to measure winter heating energy use on buildings with living wall system. The study also validated this model against the previous experiment and simulation results, which showed a good match.

The characteristic of plants and growing medium are shown in Table 3 and Table 4. After defining the thermal properties, we add these "green plant" layers on the exterior surface of the construction such as roofs or walls to create different envelope types. Because the soil layers are attached on the wall surface, the green wall in this study refers to living wall system.

Table 3 Thermal Properties of the Green Plant Layer

Height of Plants, ft [m]	Leaf Area Index	Leaf Reflectivity	Leaf Emissivity
0.66 [0.2]	2.5	0.22	0.95

Table 4 Thermal Properties of the Soil Layer

Soil Thickness, ft [m]	Conductivity of Dry Soil, Btu/h·ft·°F [W/m·K]	Density of Dry Soil, lb/ft³ [kg/m³]	Specific Heat of Dry Soil Btu/lb·°F [J/kg·K]
0.33 [0.1]	0.20 [0.35]	68.67 [1100]	0.287 [1200]

2.3 Simulation setup

Based on the building model and plant model described previously, a total of 27 simulation cases are shown in Table 5. Seven envelope types were considered: 1) a building with no plant (the baseline building model), 2) a building with green roof, 3) a building with south green wall, 4) a building with west green wall, 5) a building with both south and west green wall, 6) a building with whole green walls, 7) a building with green walls and green roof. These envelope types are achieved by modifying the wall condition of DOE reference building (baseline building), as shown in Table 5.

Table 5 Simulation Cases

Building Types	**Medium Office Building**			**Hospital**	**Primary School**
Built Years	**Pre-1980**	**Post-1980**	**New Construction**	**Pre-1980**	**Pre-1980**
Case 1 Baseline Building	√	√	√	√	√
Case 2 Building with Green Roof	√	√	√	√	√
Case 3 Building with South Green Wall	√	√		√	√
Case 4 Building with West Green Wall	√	√		√	√
Case 5 Building with South/West Green Wall	√	√			
Case 6 Building with Whole Green Wall	√	√	√	√	√
Case 7 Building with Whole Green Wall/Roof	√	√			

Climatic conditions play a crucial role in energy saving potential of exterior greenery systems. Four climate conditions were considered in this study: 1) Los Angeles, 2) Chicago, 3) Miami, and 4) Phoenix. Table 6 shows the temperature, humidity, and wind speed of these four cities. All 27 cases in Table 5 are simulated in these four cities, which yields a total of 108 cases. Briggs et al. (2003) classified climates in the U.S into 17 zones. Climate in Los Angeles is categorized as warm and dry. Chicago is cool and humid. Miami is defined as very hot and humid. Phoenix is hot and dry. We hypothesize cooling energy savings by greenery are higher in hot and dry climates such as Phoenix, considering that green plants have better shading and evapotranspiration effect in such climate. Shading can reduce solar radiation through the building; plants evapotranspiration can be translated into a cooling potential, which results in a cooler indoor environment. Also, researchers suggested that exterior greenery systems can reduce the wind speed upon the wall surface (Perini et al. 2011), which may affect cooling and heating energy consumption. But it is beyond the scope of this study.

Table 6 Climate Variables of Four Cities

City	Average Temperature, °F [°C]	Average Relative Humidity, %	Average Wind Speed, ft/s [m/s]
Los Angeles	61.99 [16.66]	69.98	11.74 [3.58]
Chicago	49.96 [9.98]	70.33	14.96 [4.56]
Miami	75.76 [24.31]	72.54	14.23 [4.34]
Phoenix	72.54 [22.52]	36.31	9.78 [2.98]

After generating all the 108 building simulation cases, we run the simulation in EnergyPlus and calculate the percent of annual cooling energy saving using eq 1.

$$S = (Q_o - Q_g)/Q_o \times 100\% \tag{1}$$

In eq 1, S = percent of annual cooling energy saving by adding the exterior greenery systems (%), Q_o = annual cooling energy consumption in baseline building model (GJ), Q_g = annual cooling energy consumption in building with exterior greenery systems (GJ).

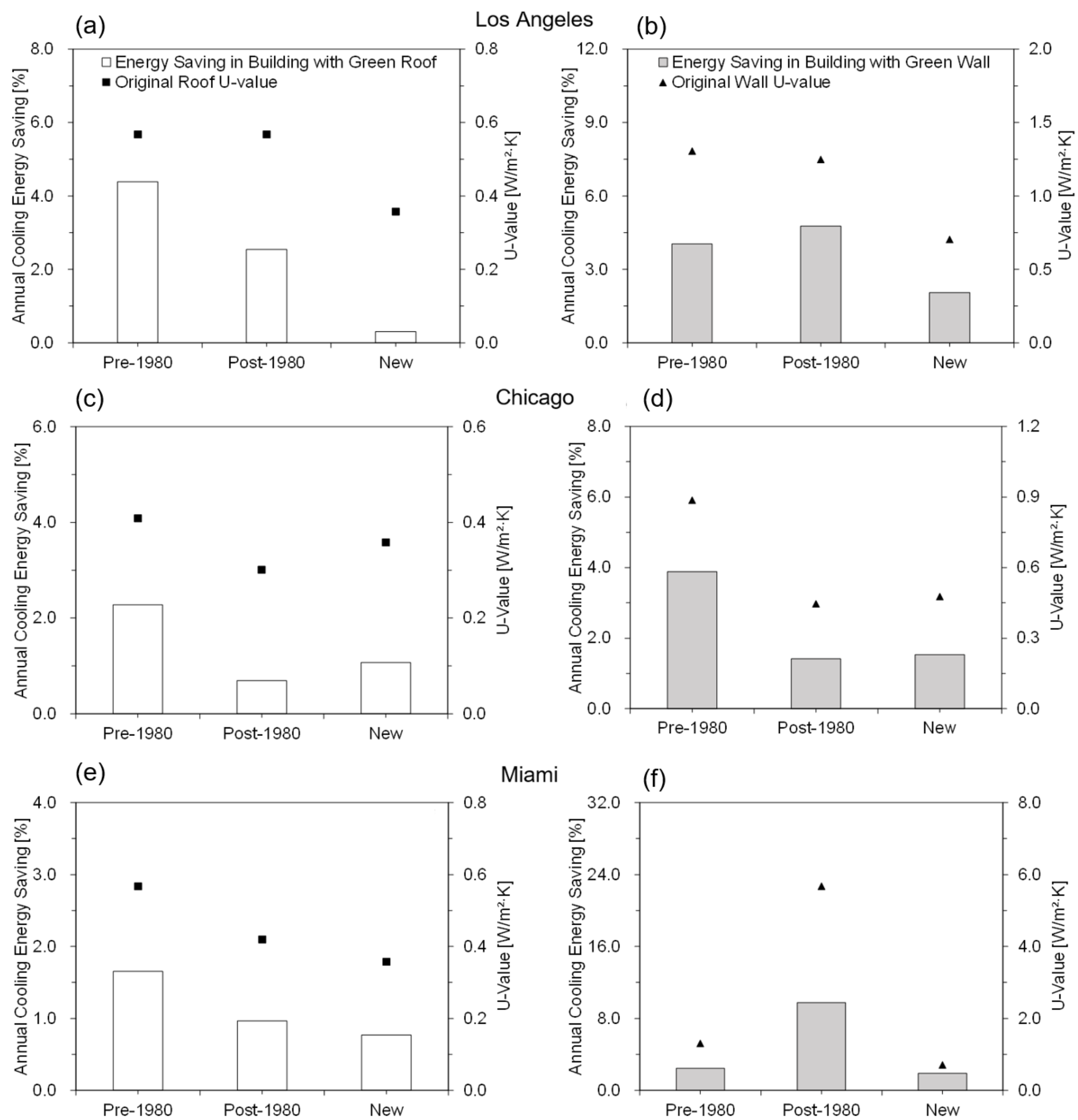
Chapter 3

Results and Discussion

This section is organized into four subsections. We present 1) cooling energy saving in buildings with three different built years; 2) effects of different exterior greenery systems on cooling energy use 3) heat transfer analysis of exterior greenery systems 4) effects of greenery systems on cooling energy use in the hospital and primary school.

3.1 Cooling energy saving in buildings with three different built years

Figure 2 shows annual cooling energy consumptions for medium office case 2 and case 6 compared to a baseline building model (case 1) and annual cooling energy savings in four cities due to greenery systems. It's evident that cooling energy saving varies with construction period. New construction buildings comply with the ASHRAE Standard 90.1 2014 requirements; the post-1980 buildings follow the ASHRAE Standard 90.1 1989. The pre-1980 models meet the requirement from previous studies (Deru et al. 2011). The standards and requirements differ in lighting schedules, mechanical systems, and insulation values. New construction buildings have a smaller lighting intensity (3.41 Btu/h·ft2 [10.76 W/m2]), compared to post-1980 and pre-1980 construction (5.35 Btu/h·ft2 [16.89 W/m2]). New construction and post-1980 share the same HVAC system (Table 1). Pre-1980 medium office building use constant volume air system instead of variable volume air system used in post-1980 and new construction. However, the most notable difference between them are the construction U-values. Construction U-values are the U-values of the envelope type 1 that are also shown in Figure 2. New and post-1980 construction U-values meet the Standard 90.1 2004 and 1989, respectively. The U-values of the pre-1980 construction are referred from Briggs et al. (1987).



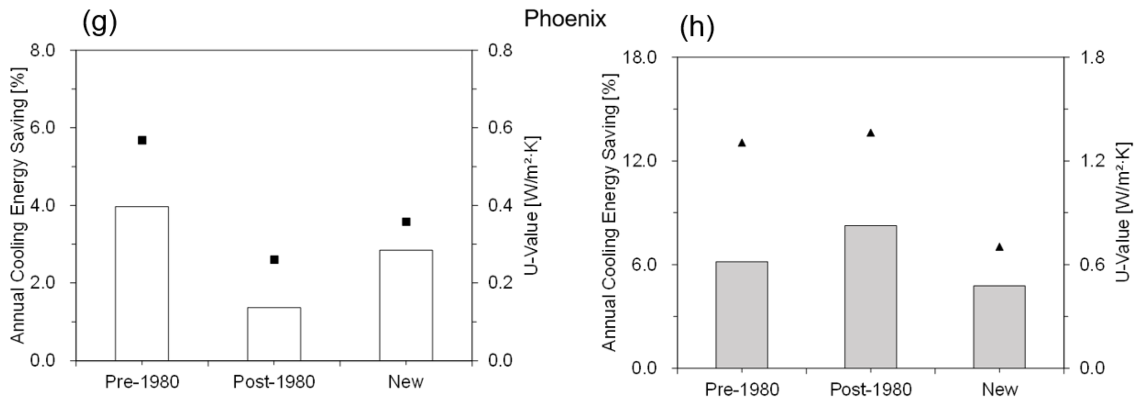


Figure 2. Medium office building annual cooling energy saving percent by green roof (figures on the left) or green wall (figures on the right) and baseline building roof U-values (figures on the left), and wall U-values (figures on the right). (a), (b) medium office in Los Angeles. (c), (d) medium office in Chicago. (e), (f) medium office in Miami. (g), (h) medium office in Phoenix.

Figure 2 shows the relationship between the wall and roof U-values with the annual cooling energy savings in four cities. In Figure 2 (c), (e), (g), green roof cooling energy savings decrease when roof U-values decrease. In Figure 2 (d), (f), (h), green wall cooling energy savings drop when wall U-values decrease. Medium office buildings in Chicago, Miami, and Phoenix reflect the similar correlations. For example, the post-1980 building in Miami green wall annual cooling energy saving increases compared to pre-1980 building because the wall U-value increases dramatically. However, Figure (a) (b) suggest that results in Los Angeles are slightly different. For example, in Figure 2 (a), the cooling saving decreases from pre-1980 to post-1980 while the original roof U-value remains the same. The reason will be discussed in the later sessions. In general, exterior greenery systems have a better cooling energy saving effect in old buildings with poor insulations which agrees with the findings of Yaghoobian et al. (2015).

3.2 Effects of different exterior greenery systems on cooling energy use

Results in Figure 2 suggest that it's more cost-effective to apply exterior greenery system in pre-1980 or post-1980 buildings because of their lower construction U-values. Consequently, we conduct further simulations (case 1 to case 7) only in pre-1980 and post-1980 medium office buildings. Exterior greenery systems are expensive both in initial cost and maintenance, and sometimes limited by façade design. Therefore, we applied green wall in south wall and west wall to find out how the wall orientation affects cooling energy savings. South facing wall has a stronger solar radiation depending on the different latitudes (Bradshaw, V., 2010). However, building designers sometimes avoid living wall on the south side because they prefer to put windows on south surfaces to maximize daylighting. West walls experience a serious solar radiation problem in some climates. During the summer, west surface receives highest incident solar radiation among other wall orientations in our four studied cities (Marion, W. et al. 1995). It can increase cooling energy consumption and the rooms facing west can have a higher indoor temperature in the afternoon.

Figure 3 (a) shows that pre-1980 buildings with plants in Phoenix have the largest energy savings. Buildings with green walls (case 6) in Phoenix can save about 6% cooling energy annually while 10% cooling energy can be saved with both green walls and a green roof (envelope type 7). In another warm and dry city, Los Angeles, 4% and 8% cooling energy is saved, respectively, for case 6 and case 7. In Figure 3 (b), Miami has the largest cooling saving in most cases due to its high original wall U-value, which is around 5 times more than the post-1980 office wall U-value in Phoenix. Yaghoobian et al. (2015) showed similar results by comparing the impact of the green roof on cooling load and found that buildings in Phoenix can have a better reduction by the greenery than in Baltimore.

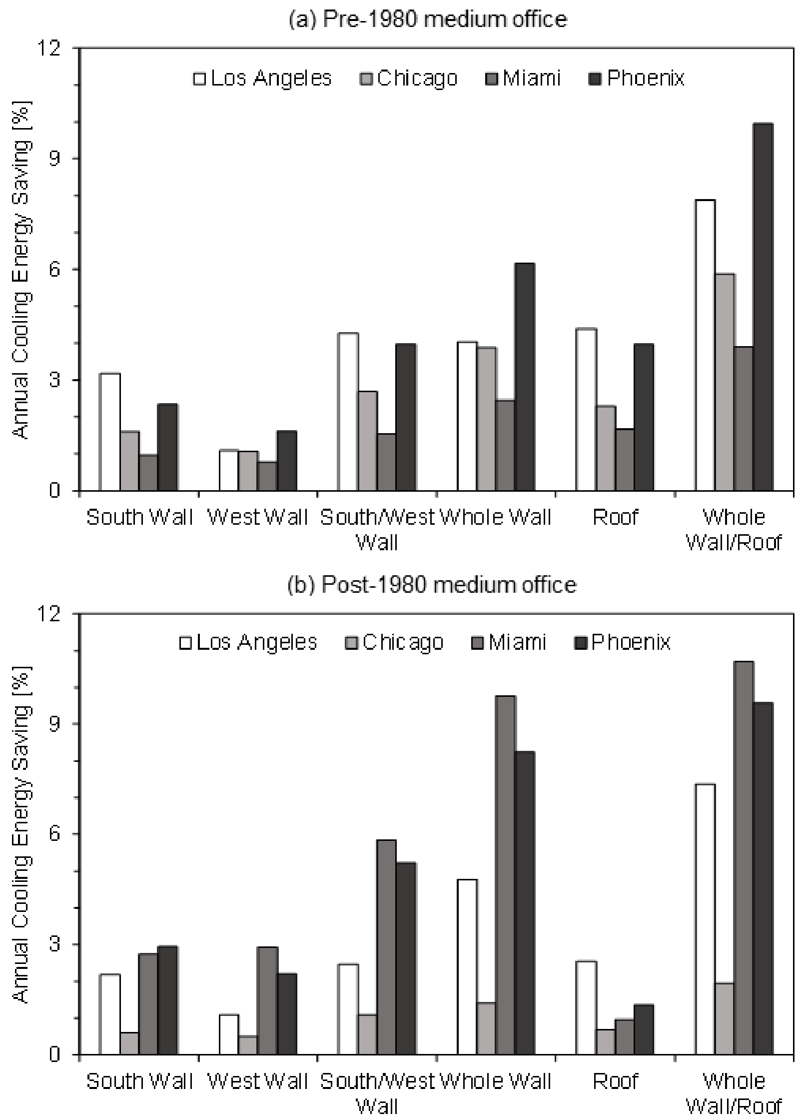


Figure 3. Annual cooling energy saving with different exterior greenery system types

According to Figure 3, south green wall generally has a better cooling reduction compared to west green wall. However, the areas of the south facing wall are bigger than west wall in medium office. The ratio of the south wall area to west wall area is around

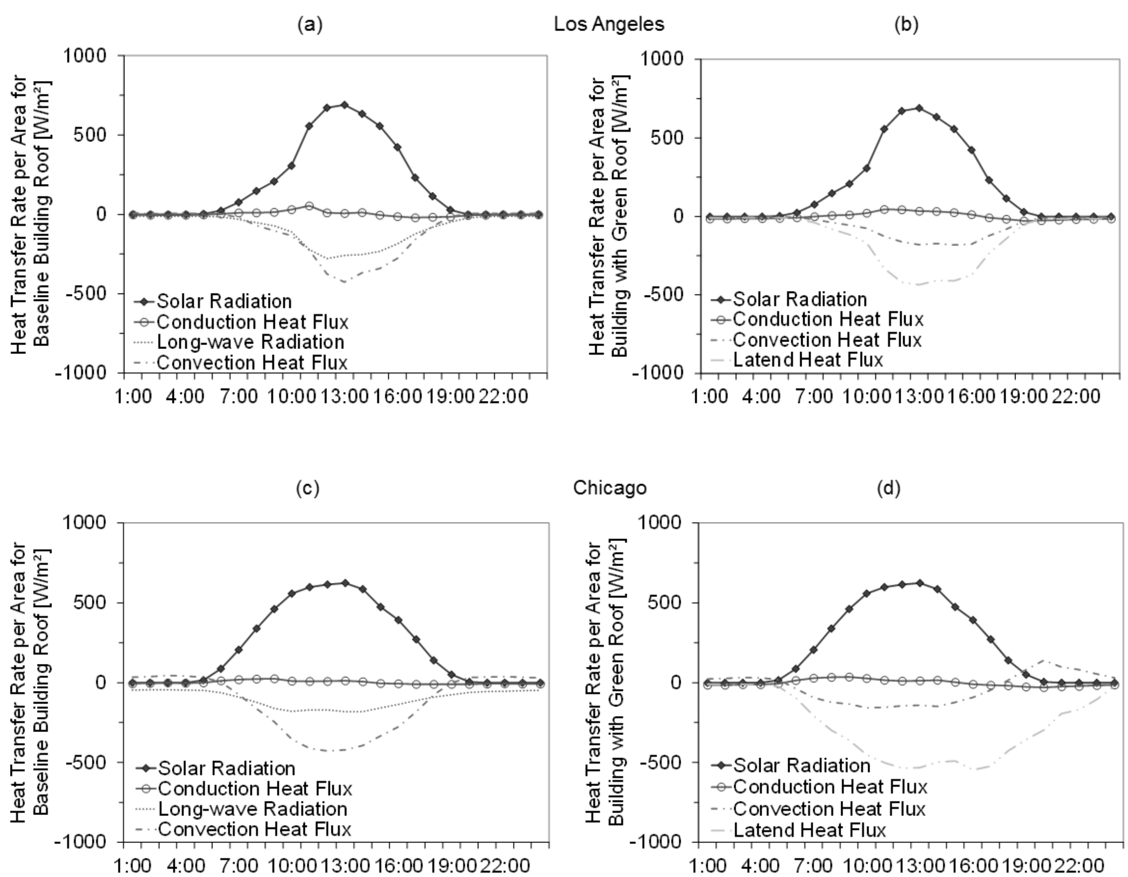
1.5. When adjusting the saving results with the wall area, we find that south and west living walls have a similar energy saving effect, except Los Angeles where the south green wall cooling energy saving is much higher than the saving by west green wall after the adjustment. When put both south and west green wall, the annual cooling energy saving is approximately the sum of the saving due to individual south and west green wall. Previous study shows that south green wall has much lower heat absorbance though the greenery due to its evapotranspiration effect (Jim et al. 2011). Another study proves that west-oriented wall has the most profound effect to lower down the building cooling load in Greece than other orientations (Kontoleon et al. 2010). These studies agree in that the vertical greenery systems can have a better cooling effect in south and west orientations.

Buildings with whole living walls (case 6) have a higher cooling energy saving than buildings with south and west living walls (case 5) except pre-1980 building in LA (Figure 3 (a)). In fact, cooling energy saving in case 6 decreases as opposed to buildings with south and west green walls. Monthly cooling energy data shows that in the winter cooling energy use increases after adding more living walls layers, but during the summer cooling energy use decreases. Pre-1980 medium office with whole living walls in Los Angeles consumes more cooling energy in the winter than the extra cooling energy saved in the summer. The reason is that during the winter, cooling is used to remove the internal heat due to internal load. Especially in Los Angeles where the temperature is warm in the winter, exterior greenery system may impede the heat exhaust from the buildings which increases the cooling energy because plants with soil can function as thermal insulation to trap unwanted heat. This also explains why in Figure 2 (1), (2), the relationship of the energy saving by greenery with construction U-values is slightly different from other cities. Stav et al. (2012) also found adding whole vertical green wall can have a smaller cooling saving than adding the living wall on one direction in Brisbane.

3.3 Heat transfer analysis of exterior greenery systems

Results in Figure 3 confirm that exterior greenery system can have a better cooling effect in hot and dry climate (Phoenix). To further prove that, we present Figure 4 to illustrate the roof heat transfer of pre-1980 medium office building in case 1 (baseline building) and case 2 (baseline building with green roof) on the summer solstice (June 21st). Figure 4 (a), c), (e), (g) show the convection, conduction, and radiation heat flux though the roof of case 1. Figure 4 (b), (d), (f), (h) indicate heat transfer through the same roof after adding green roof system (case 2). For conduction, radiation and convection, positive values suggest the heat is transferring from the outside into the thermal zones. We represented the long-wave radiation heat flux in the left figures. However, figures on the right only represent the solar shortwave heat gain because Energyplus is unable to output longwave radiation upon the exterior surface after adding the greenery layers. Convection heat flux in case 2 shows heat transfer between soil, foliage surface and surrounding air. The latent heat flux represents the evapotranspiration of plants and soil. It’s evident that plant evapotranspiration is the dominated force to balance the solar radiation and it helps to cool down the roof surface. Especially in Phoenix, the latent heat transfer rate is the highest among other three cities.

To get a better idea of the relationship of sensible and latent heat flux in the green roof systems, we calculated the heat flux during summer period (June – August). The results are shown in Figure 5. Plant evaporation effect is largest in Phoenix which is hot and dry. Followed by Los Angeles, which is a warm and dry city. Evapotranspiration is determined by four factors: solar radiation, air temperature, wind speed, and relative humility (Allen et al. 1998). Solar radiation as the key energy input in this process is the major factor to affect it. The average incident solar radiation upon the horizontal surface is largest during the summer in Phoenix compared to other three cities (Marion, W. et al. 1995). Results in Figure 5 also confirmed that cities with a higher solar radiation have a relatively higher latent heat transfer rate.



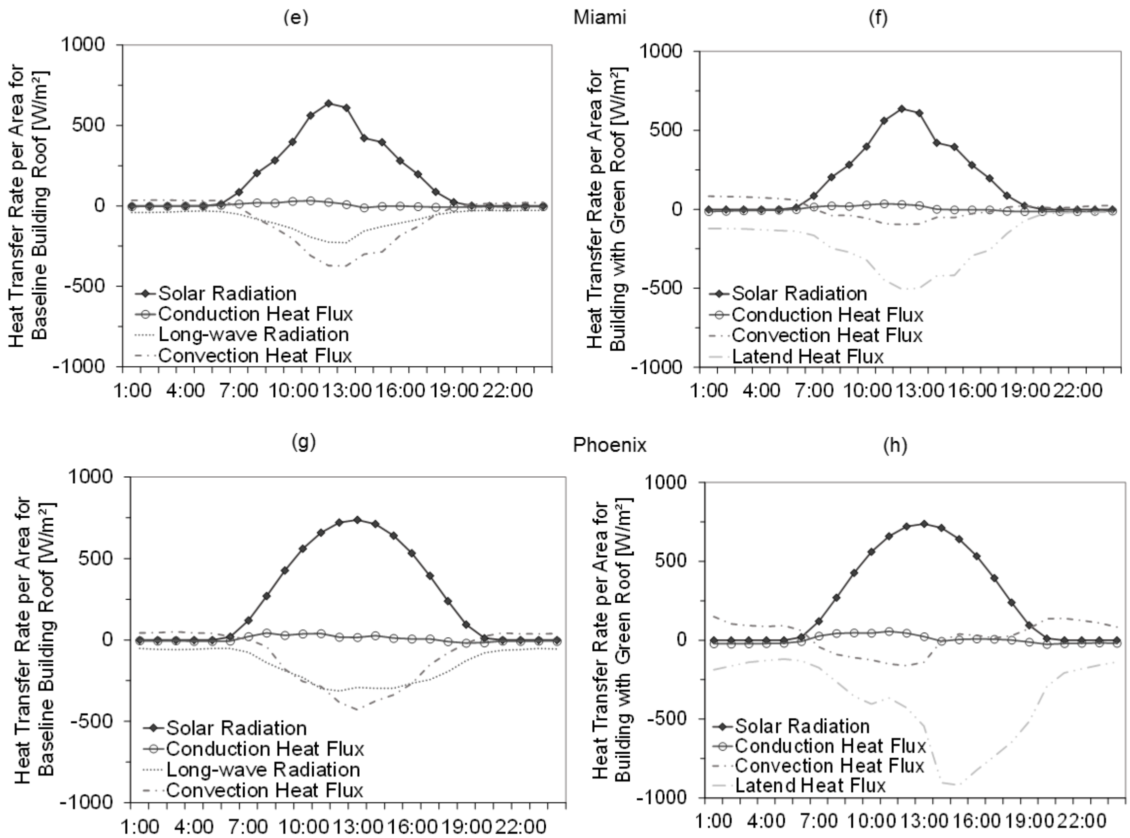


Figure 4. Heat transfer rate per area on roof of four climates on the summer solstice. Figures on the left represent case 1. Figures on the right represent case 2. (a), (b) are in Los Angeles. (c), (d) are in Chicago. (e), (f) are in Miami. (g), (h) are in Phoenix.

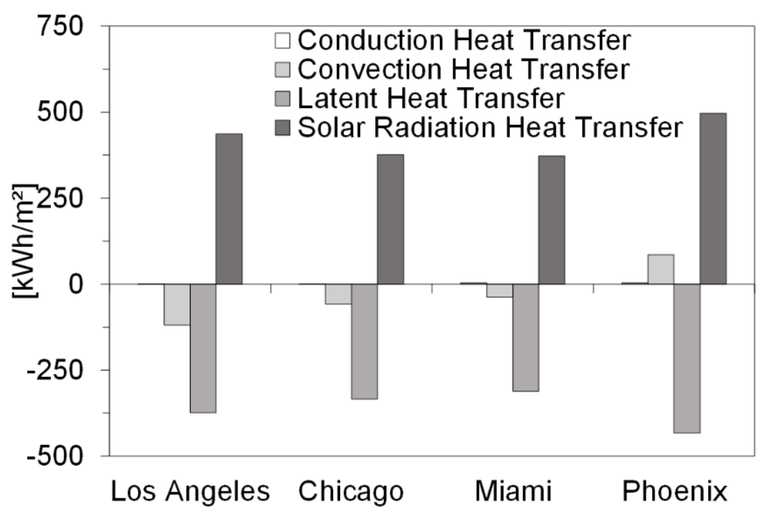


Figure 5. Pre-1980 medium office building (case 2) green roof heat gain during the summer period (June – August)

3.4 Effects of greenery systems on cooling energy use in the hospital and primary school

Case 1, case 2, and case 6 were applied in pre-1980 hospital and primary school. The cooling energy saving results (Figure 6) in hospital and primary school prove that greenery in Phoenix has a better cooling effect. The wall U-values of hospital in Los Angeles, Miami, and Phoenix are 0.230 Btu/h·ft²·°F [1.31 W/m2·K] and 0.156 Btu/h·ft²·°F [0.886 W/m2·K] in Chicago. The rood U-values in Los Angeles, Miami, and Phoenix are 0.10 Btu/h·ft²·°F [0.568 W/m2·K] and 0.072 Btu/h·ft²·°F [0.409 W/m2·K] in Chicago. Base on Figure 6 (a), Phoenix has the largest cooling saving percent around 1.5% both in case 2 and case 6. Los Angeles has 1.5% cooling energy saving annually when applying green roof. But it turns to negative saving when applying whole living wall system. Hospital cooling energy saving is marginal in all four cities. Cooling energy of case 6 in Los Angeles and Chicago even increase compared to baseline building. The reason is hospital is a very energy intensive building. Its floor area is around 5 times compared to medium office building (Table 2), with a lower glazing fraction, but its annual cooling energy use is about 15 times more than medium office in Los Angeles (Figure 9). Hospital has a huge equipment and people internal load, and it operates at night. Enclosure heat gain only takes a small portion in cooling energy use. For this type of buildings, sometimes the major task is to remove the heat from the inside to the outside. Exterior greenery system impedes this process and mass wall of the hospital makes this condition even worse. Because mass wall stores heat during the day time and tends to release the heat at night (Balatas 1996), but the greenery layer traps the heat and increases the cooling energy use. Previous experiment result suggested that during the night, wall surface covered by substrate tends to retain heat and has a higher temperature than the substrate surface (Wong et al. 2010), which validates our hypothesis.

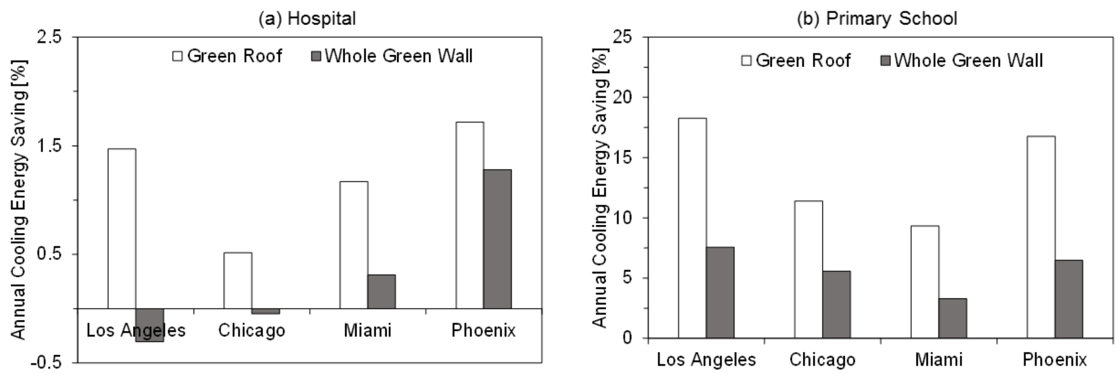
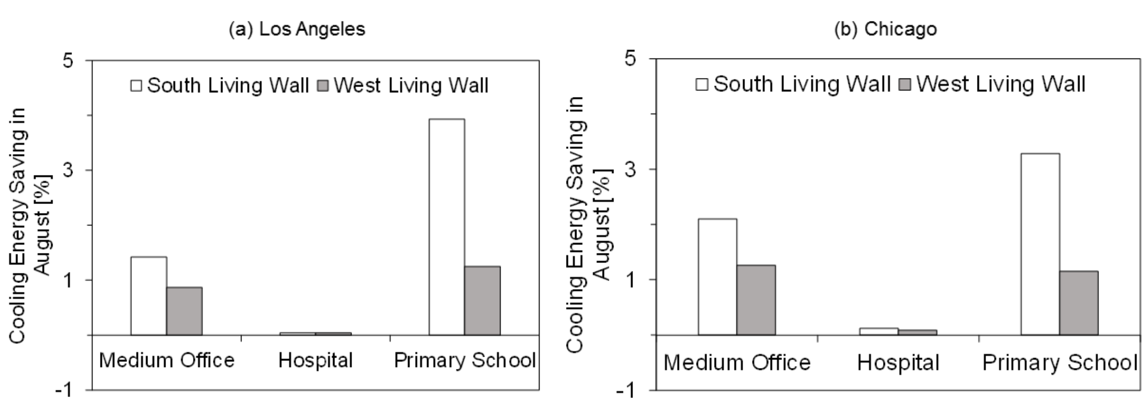


Figure 6. Exterior greenery system annual cooling energy saving in pre-1980 hospital and primary school

Figure 6 (b) shows the energy saving is large in primary school. Case 2 in Los Angeles and Phoenix has the similar saving around 18% annually. Primary school in case 6 has 7.5% annual saving in Los Angeles and Phoenix. Primary school is a single floor building which has the largest exterior area to floor area ratio. This translates into envelope heat gain in primary school accounts for a big fraction of the total cooling energy consumption.



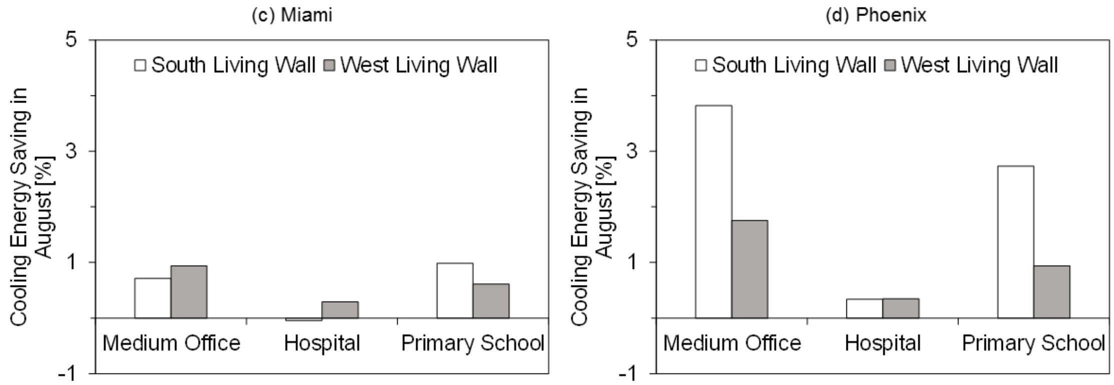


Figure 7. Cooling energy saving in August for medium office, hospital, and primary school

More comparison results are shown in Figure 7. Case 3 and case 4 are applied in pre-1980 medium office, hospital, and primary school. Figure 7 indicates the cooling energy saving in August by adding south or west living wall systems. The south wall area to west wall area ratio for hospital is 1.3 and 2.8 for primary school.

Primary schools still have a saving advantage among four cities, but cooling saving percent of medium office buildings in Miami and Phoenix is higher than primary school. However, medium office is a three-floor building which give it more space for living wall systems than primary school. The saving in hospital is marginal with south or west living wall systems.

Results in Figure 8 demonstrate why there is a saving difference between these three building types. Enclosure heat gain accounts for 4% in peak cooling period in medium office building. Hospital takes 0% enclosure heat gain but highest lighting and equipment heat gain around 80% combined. Primary school has a 32% enclosure heat gain which explains why exterior greenery systems have a significant saving compared with other building types. Previous study also found that small office building is more sensitive to the greenery in term of cooling energy saving than retail store, an energy-intensive building (Yaghoobian et al. 2015).

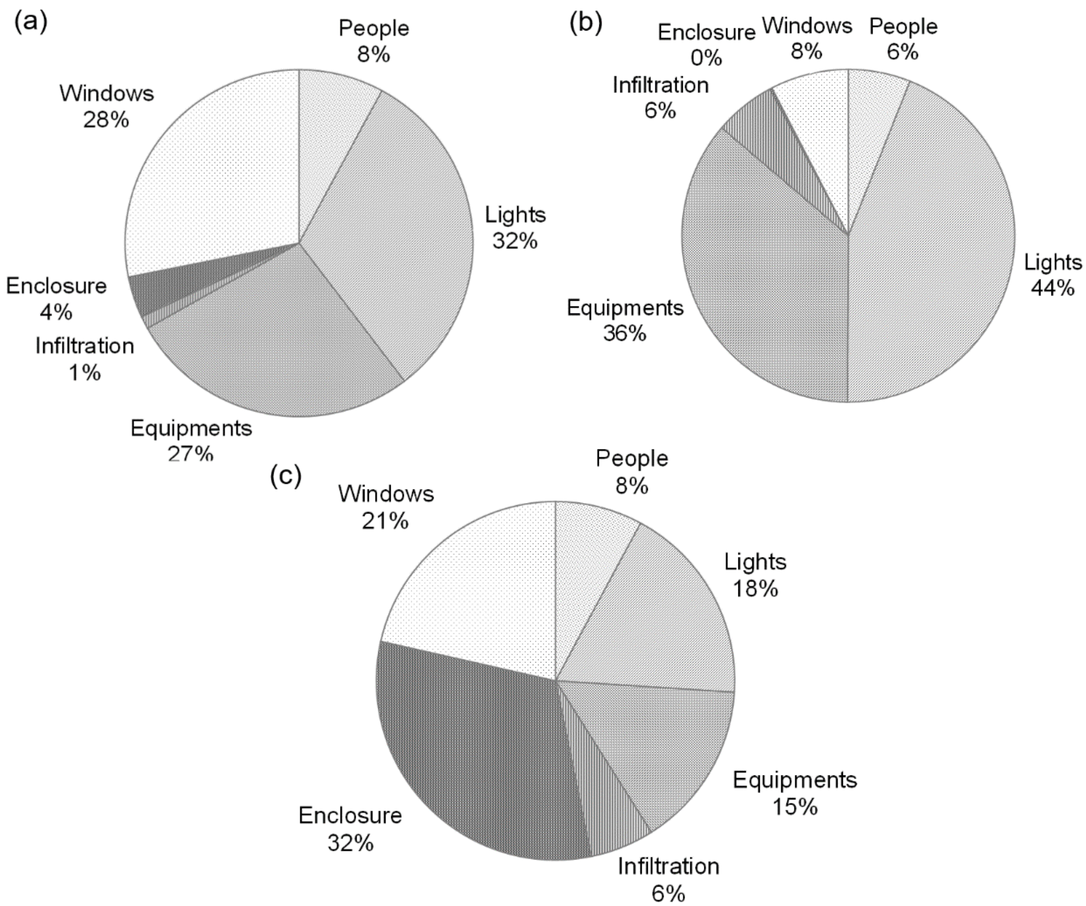


Figure 8. Heat gain distribution for pre-1980 baseline buildings in Los Angeles in peak cooling period, (a) medium office, (b) hospital, (c) primary school

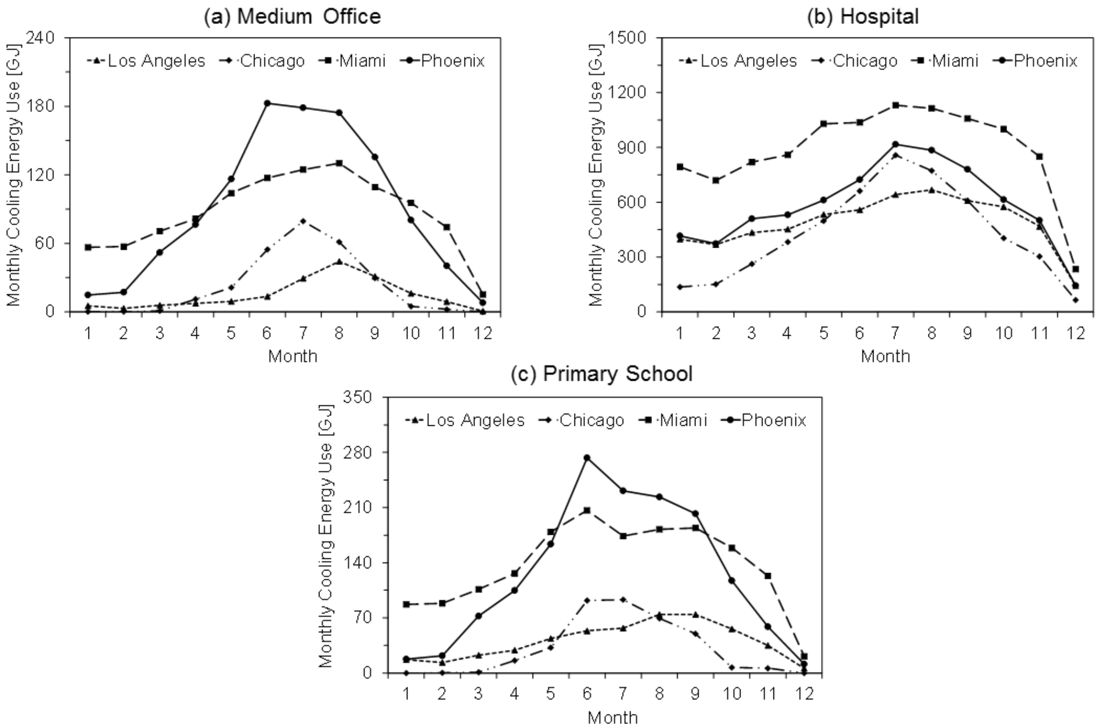


Figure 9. Monthly cooling energy use of three building types in four cities

Chapter 4

Conclusion

This study investigated the effect of exterior greenery system (green roof and living wall systems) on cooling energy consumption of the Department of Energy reference buildings. To examine the impacts of building type, climate, and built year, three types of DOE reference buildings (medium office, hospital, and primary school) were simulated with three construction years (pre-1980, post-1980, and new construction) in four climates, i.e., Los Angeles (warm and dry), Chicago (cool and humid), Miami (very hot and humid), Phoenix (hot and dry). The followings are the major findings of the present study.

(1) Buildings with poor insulation have a higher cooling energy saving potential when exterior greenery systems are installed. It's cost-effective to apply green roof or green wall to a building with high roof and wall U-values.

(2) With regard to green walls, south and west living walls have greater cooling effects than other orientations. In Los Angeles, south living wall can save cooling energy as twice as west living wall. In other three cities, south living wall has a similar saving potential compared to west living wall.

(3) Climate has a significant impact on vegetation cooling effect. In hot and dry climate, exterior greenery system can have a better cooling potential. For example, in Phoenix, annual cooling energy saving can be a up to 10% for the medium office building and 20% for the primary school when adding both green walls and green roof .

(4) Plants and soil evaporation has notable effects on lowering the temperature around the building surface and the heat removal rate at the building envelope is between 500 W/m^2 and 900 W/m^2 during the peak period depending on climate.

(5) Exterior greenery system can only reach a 1.5% annual cooling energy saving by adding green wall or green roof in hospital that has high internal load and 24-h operating schedule. However, the energy saving can reach up to 20% by the same approach in a single floor primary school.

Results reveal that exterior greenery system have a better cooling performance in building with low internal load, poor insulation, and located in climate like Phoenix. Further studies need to be conducted considering plants types in different climates. Evapotranspiration effect varies with different plants. For example, we might need to apply drought resistant plants in Phoenix whose evapotranspiration effect is limited. Furthermore, some factors like irrigation which also has a significant impact on evapotranspiration can be considered in future studies to reveal more insight.

Appendix

Green Plant and Soil Thermal Properties

Plants Properties

Height of Plants [m]	0.2
Leaf Area Index	2.5
Leaf Reflectively	0.22
Leaf Emissivity	0.95
Minimum Stomatal Resistance [s/m]	180

Soil Properties

Roughness	Medium Rough
Thickness [m]	0.1
Conductivity of Dry Soil [W/m·K]	0.35
Density of Dry Soil [kg/m³]	1100
Specific Heat of Dry Soil [J/kg·K]	1200
Thermal Absorptance	0.9
Solar Absorptance	0.7
Visible Absorptance	0.7
Saturation Volumetric Moisture Content of the Soil Layer	0.3
Residual Volumetric Moisture Content of the Soil Layer	0.01
Initial Volumetric Moisture Content of the Soil Layer	0.1
Moisture Diffusion Calculation Method	Advanced

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