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Green roof energy performance in different climate zones: a simulation study

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Green roof energy performance in different climate zones: a simulation study

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Abstract. Green roofs are widely used as a passive building design technique to decrease the cooling demand in buildings. The vegetation uses the energy of the surroundings during the evapotranspiration process, leading to a temperature decrease in air. This paper investigates the effectiveness of green roofs in 45 cities in different climate zones. The simulation of the energy performance of buildings is performed using DesignBuilder software, which integrates the EnergyPlus engine. The results show that green roofs effectively reduce the cooling load but increase heating energy consumption. The highest performance in total energy savings was in the arid zone with savings ranging from 3.2% to 9.1%, despite having a high heating demand. Tropic and temperate zones show relatively lower results, which vary from 1.4% to 4.1% and -0.2% to 4.2%. The cold zone shows the worst result, ranging by around 1%. Thus, green roofs show better performance in cities with high-temperature ranges, direct radiation, and humidity level.

1. Introduction

Climate change is a significant issue that causes a decrease in thermal comfort level, an increase in energy demand, and heat-related mortality [1, 2]. The Report of the Intergovernmental Panel on Global Climate Change claims that the temperature around the world increased by 0.74 ° C in the last century due to the greenhouse effect [3]. Moreover, the urban heat island effect (UHI) influences the urbanized zones, increasing the temperature inside cities [4]. Buildings consume around 37% of energy and contribute 40% of direct and indirect carbon dioxide emissions [5]. Additionally, cooling and heating loads range from 18% to 73% of total energy consumption in the building envelope [6]. In 2018, 55.3% of the world's population lived in cities, and it was estimated that the urban population would increase to about 7 billion people by 2050 [4, 7]. Thus, climate change is a concern for most of the population around the world.

A possible mitigation strategy is green roofs that are used as a passive building design measure to decrease the cooling load of the building envelope [8]. Green roofs are covered with different vegetation varying according to different needs. The vegetation on the roof uses the energy of the surrounding environment during the evapotranspiration process, reducing the level of air temperature and humidity. Different physical characteristics of vegetation can affect its performance which are height, width, density, specific heat, diffusivity, thermal conductivity, thermal absorptance, solar absorptance, leaf area index, reflectivity, emissivity, minimum stomatal resistance, and volumetric moisture content. For example, for the arid zone, the most effective plants were found to be Mentha virdis and Callistemon rigidus as they have a high tolerance to drought [9]. While vegetation with a height of 1.80 m shows a reduction of the temperature by 0.7-3 °C in warm cities [10]. It means that proper characteristics can be adjusted for different climates. Additionally, green roofs can be classified as extensive and intensive. The intensive has a deep soil substrate and may consist of trees and shrubs. While extensive has a soil substrate in the range of 6 to 20 cm, making it a lighter and cheaper solution. In addition, the characteristics can also affect the efficiency of green roofs in reducing energy consumption reduction. It was examined that green roofs show low impact when the building exceeds 60 m in height [11]. Thus, the effectiveness of green roofs may depend on the different factors and efficient results can be achieved by considering them correspondingly.

Several research papers investigated the effect of green roofs on decreasing the cooling load in cooling dominant zones, where there is negligible heating consumption. It was discovered that green roofs may reduce energy consumption by 48% and temperature by 4 °C [12]. Additionally, numerous studies use numerical simulation tools, such as EnergyPlus, to perform energy-saving and thermal comfort level analysis [12, 13]. EnergyPlus uses the Fast All-season Soil Strength (FASST) soil and vegetation model which allows inputting green roof parameters to simulate energy balance. In this research work, the effect of green roofs on heating and cooling in tropical, arid, temperate, and cold zones would be investigated. Moreover, it should be noted that many research works use air temperature as a measurement of thermal comfort. However, green roofs also may affect other environmental factors, such as humidity, velocity, and direct radiation ratio. Therefore, the Fanger model was used to assess the level of thermal comfort and as a set point for the Heating, Ventilation, & Air Conditioning (HVAC) system, as it considers several factors, including air temperature, humidity, mean radiant temperature, metabolism, air velocity, and clothing insulation. The model with an extensive green roof was simulated using DesignBuilder software which uses the EnergyPlus program to simulate in 45 cities with different climate conditions.

2. Methodology

2.1. Reference Building

The building model was made using DesignBuilder software, which can be seen in Figure 1. The effectiveness of green roofs may vary depending on the geometrical and thermal characteristics of the building. For this reason, it was decided to use ASHRAE and CIBSE suggested standards for the building envelope. The height of the building is 3 m with the width to length ratio of 1:1.5 and a window-to-wall ratio of 30%. The window consists of two glazing panes with thickness of 0.003 m and 0.0013 m air gap between them. The conductivity value of glazing is 1.978 W/m^2-K. The model orientation is the same as in the DesignBuilder recommendation example for the green roof analysis. It was used to simplify the simulation process. The occupancy of the building is adjusted according to ASHRAE standards for office buildings, which can be seen in Figure 2 [14]. The exterior wall and roof compositions were made according to the Chartered Institution of Building Services Engineers (CIBSE) standard [15]. The exterior wall consists of 105 mm brickwork outer, 50 mm expanded polystyrene (eps) insulation, 100 mm light concrete blockwork, and 13 mm lightweight plaster in the innermost layer. The roof consists of 70 mm outer gravel, 10 mm bitumen, 200 mm aerated concrete slab, 20 mm cement mortar, and 15 mm plasterboard in the innermost layer. Packaged terminal heat pumps (PTHP) were used as the HVAC system for the model. The physical characteristics of PTHP include the maximum air supply temperature of 35 ° C with an air humidity ratio of 0.0156, while the minimum air temperature was 12 ° C with an air humidity ratio of 0.077 [16]. The schedule of the HVAC system was adjusted according to the occupancy of the building. The Fanger model was used for set points, which is explained in Section 2.4.

2.2. Green roof characteristics

For this research project, an extensive green roof was selected as it has a lower cost of maintenance. The roof vegetation is mentha virdis because of the availability of characteristic data. The height of the plant is 0.6 m, the leaf area index (LAI) is 2.7, the leaf reflectivity (LR) is 0.22, and the leaf emissivity (LE) is 0.95. The green roof is placed above the gravel layer and consists of 40 mm of natural rubber, 100 mm of soil, and vegetation above. The thermal conductivity, density, and specific heat of natural rubber are 0.130 W/mK, 910 kg/m^3, and 1100 J/kgK, and for soil are 1.280 W/mK, 1460 kg/m^3, and 880 J/kgK. The thermal properties were derived from DesignBuilder library which are based on ISO 10456.

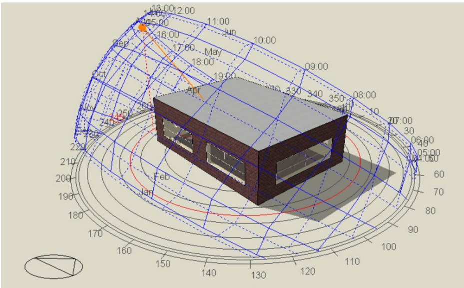

Figure 1. Building model

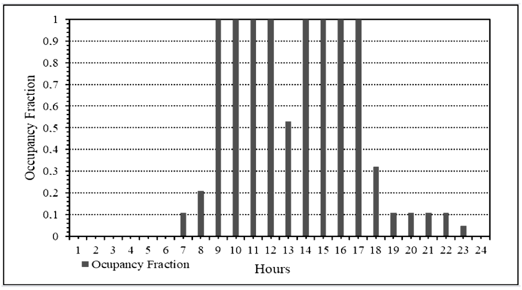

Figure 2. The occupancy schedule for the ASHRAE office building

2.3. *Simulation tool*
The simulation was performed by using EnergyPlus which is a console-based program that produces an output text file of data related to energy. It has an integrated and simultaneous solution, multiple time step approach, reporting mechanisms, modification of input value, and thermal, energy, & environmental data calculation. The model was created by DesignBuilder BIM software which uses EnergyPlus to perform simulation. It was selected because it has a user-friendly interface. The performance of EnergyPlus in the simulation of green roof buildings has been confirmed in several research works. For example, validation was performed using the temperature of the information on the roof of Building 2 at Portland State University, the Student Union Building at the University of Florida, and the Florida Solar Energy Center [17, 18].

2.4. *Thermal Comfort Model and Energy Saving Calculation*
The thermal comfort level was measured using the Fanger predicted mean vote (PMV) model. PMV considers several factors, which are air temperature, mean radiant temperature, air velocity, air humidity, clothing insulation, and metabolic rate, which make it more convenient in thermal comfort. Using these factors, the model shows the potential level of satisfaction of the person. The range of the PMV index is from -3 to +3. To perform energy analysis, the setpoints for the HVAC system were adjusted using the PMV range. In the model, HVAC starts to work when the PMV increases to more than 0.5 or drops to less than -0.5. It was used as the PMV range between -0.5 and +0.5 is considered a normal level of thermal comfort [19].

The difference between energy consumption with and without green roof of the same building presents energy saving. To compare the level of efficiency of green roof on energy saving for the specific country, the percentage of savings was used. It is defined as the ratio of the saving value to the energy consumption of a building without green roof and shows the magnitude of the savings in terms of the savings without green roof.

2.5. *Climate zones and cities*
For this research work, the Köppen Geiger map was used for climate classification purposes. It is a vegetation-based climate classification published in 1961, and it is considered one of the most widely used classification systems [20]. The map is constantly updated with improved resolution and current topographic information [20]. However, the fact that it is mainly based on vegetation growth means that it has no direct link between outdoor and indoor climate, and it does not present the influence of climate on the energy consumption of the building.

It consists of five main zones which are tropical (A), arid (b), temperate (C), continental (D), and polar (E), while every zone has several subtypes which consist of the level of precipitation (which are desert (W), steppe (S), fully humid (f), dry summer (s), dry winter (w), monsoonal (m)) and temperate (such as hot (h), cold (k), hot summer (a), warm summer (b), cool summer (c), cold (d), and polar (F)). Cities were selected from the most populated climate zones using the 1980-2016 Köppen-Geiger map with a resolution of 1 km [20]. 45 cities were selected from 15 zones, which are Am, Af, Aw, BWh, BSk, BSh, Cfa, Cwa, Csa, Cwb, Cfb, Csb, Dfa, Dfb, and Dfc, which can be seen in Table 1.

3. Results and Discussions

The final results of total, heating, and cooling saving are demonstrated in Table 1. It can be seen that total energy saving is not equal to the sum of heating and cooling savings. The main reason is that total energy includes other sources, such as interior light, electricity, and fans. Furthermore, the percentage of total savings can also be lower than the percentage of cooling or heating savings, as total consumption includes factors that are not affected by a green roof, such as lighting.

In the tropical zone (A), it can be seen that there is no heating consumption needed. It is because of the high temperature throughout the year in that zone, which is constantly higher than the comfortable range. While cooling energy savings show high results, which are between 173 kWh (Bangkok) and 52 kWh (Belo Horizonte). Total site energy saving varies from 1.4% (Belo Horizonte) to 4.1% (Douala) while cooling savings varies from 3.3% (Belo Horizonte) to 7.3% (Bangkok). The highest cooling-saving percentage was in Bangkok. It should be noted that Bangkok has the highest cooling saving percentage, but Douala has the highest total site energy saving percentage. This can be explained by the fact that in Douala the consumption of fans is drastically reduced.

In the arid zone (B), cities show different patterns, depending on the temperature range of the zone. BSk, which is the cold arid zone, has a heating energy consumption. The negative results are due to the cold zone of BSk. While other B zones did not need heating consumption, except Marrakech, which had negligible heating consumption. The percentage varied from 3.2% to 9.1%. Marrakech showed the lowest savings, with a total savings of 3.2% and a cooling savings of 7.7%. It had the highest elevation among the B zones. While Astana had the highest savings, which are 9.1% of total savings and 41.8% of cooling savings. However, it also shows significant drawbacks in heating, showing a net increase of 32.2% in heating consumption. For the total consumption saving values, the highest results of saving were in Abu Dhabi with 421 kWh for total site energy and 410 kWh for cooling energy. In general, the B zone had high results in saving cooling energy and negative savings in heating. The fact that the total percentage of energy savings at the site is significantly lower than the cooling means that the savings from the fan are low.

In the temperate (C) zone, it can be seen that Cfa, Cwa, and Csa show significantly better results than Cwb, Cfb, and Csb. It can be explained by the fact that Cfa, Cwa, and Csa zones have hot or warm summers, while Cwb, Cfb, and Csb zones' summer temperatures are cold. The highest total savings results are shown in Ha Noi, which is in the Cwa zone, with 209 kWh and 4.2% savings. However, it should be noted that other cities in that zone have significantly lower results, For example, Hong Kong and Kathmandu at 3.0% and 2.9% total savings respectively.

The continental zone (D) shows comparatively low energy savings. The temperature range and humidity of this zone are low. Thus, the percent saving is mostly lower than 2%. The Dfa is the highest savings, while Dfc is the lowest, which is negligible. The temperature range of the Dfa zone is higher than that of Dfc, which means that it needs more cooling load. It should be noted that Almaty shows the highest cooling saving with 218 kWh at 16.2%, which differs drastically from the other two cities in this zone. The potential reason is that the temperature increases drastically during the summer period with a high increase in solar radiation, which is not considered in the Köppen-Geiger climate classification.

Overall, it can be said that the results obtained are appropriate. Various studies have results ranging from a saving of virtually no impact [21] to 15% [22]. So, the results from the simulation studies performed in this paper are not unusual. Also, this paper covers a diverse range of cities. So, the energy savings are also diverse. Therefore, it is recommended that the results from this study should not be generalized to all climate zones.

Table 1. Energy saving data of cities with green roofs

		Total Energy consumption		Heating		Cooling	
Zones	Cities	Savings	Percentage of Saving	Savings	Percentage of Saving	Savings	Percentage of Saving
Am	Mumbai	153.2	3.3%	-	-	146.9	6.6%
	Phuket	124.5	2.8%	-	-	121.0	5.7%
	Douala	192.6	4.1%	-	-	133.0	6.2%
Af	Jakarta	104.3	2.1%	-	-	101.1	3.9%
	Kuala Lumpur	130.8	2.9%	-	-	127.1	6.0%
	Singapore	105.6	2.3%	-	-	102.6	4.7%
Aw	Belo Horizonte	53.8	1.4%	-	-	51.9	3.3%
	Brasilia	104.1	2.7%	-	-	100.5	6.8%
	Bangkok	177.4	3.7%	-	-	172.3	7.3%
BWh	Dubai	419.3	7.0%	-	-	407.9	11.3%
	Cairo	283.2	5.9%	-	-	274.9	11.5%
	Abu Dhabi	421.0	7%	-	-	409.6	11.3%
BSk	Astana	305.0	9.1%	-54.8	-32.2%	350.8	41.8%
	Pavlodar	139.0	3.6%	-22.3	-59.6%	156.8	10.5%
	Valencia	163.0	3.9%	-1.2	-70.7%	159.3	8.7%
BSh	Marrakech	126.4	3.2%	-0.4	-100%	122.9	7.7%
	Monterrey	271.5	5.3%	-	-	263.7	9.6%
	Ahmadabad	247.4	4.8%	-	-	240.5	8.8%
Cfa	Buenos Aires	116.7	3.4%	6.1	1%	-0.6	-0.1%
	Melbourne	133.8	3%	-	-	129.9	6.0%
	Milan	142.7	3.8%	-5.9	-118.4%	144.2	10.2%
Cwa	Hong Kong	133.8	3.0%	-	-	129.9	6.0%
	Kathmandu	132.7	2.9%	-	-	48.2	2.2%
	Ha Noi	208.8	4.2%	-	-	202.8	7.8%
Csa	Barcelona	129.9	3.3%	-0.5	-36.7%	126.4	8.1%
	Rome	121.5	3.2%	-3.0	-253%	120.8	8.2%
	Lisboa	127.1	3.2%	-2.9	-16.8%	126.0	8.1%
Cwb	Johannesburg	-6.8	-0.2%	-41.5	-18.1%	34.6	4.4%
	Mexico City	144.3	3.1%	-	-	140.2	6.0%
	Addis Ababa	100.3	2.4%	-	-	112.3	5.3%
Cfb	Paris	65.1	1.9%	-16.9	-34.7%	79.8	7.6%
	London	17.7	0.5%	-28.7	-19.8%	45.7	6.1%
	Amsterdam	15.2	0.5%	-22.6	-12.8%	37.2	4.8%
Csb	Cape Town	-5.6	-0.2%	-10.5	-4.2%	5.0	0.9%
	San Francisco	10.9	0.3%	-40.8	-54.1%	51.1	6.1%
	Vancouver	36.8	1.1%	-11.6	-22.1%	47.1	4.6%
Dfa	Toronto	69.1	1.9%	-15.4	-43.1%	82.2	6.6%
	Kansas City	146.9	3.4%	-1.5	-164.1%	157.6	8.2%
	Almaty	224.4	6.1%	-0.5	-100.0%	218.0	16.2%
Dfb	Stockholm	25.1	0.7%	-25.9	-15.2%	50.0	6.0%
	Montreal	72.0	2%	-7.9	-34.3%	77.6	6.2%
	Ottowa	70.2	2%	-12.1	-55.0%	80.0	6.8%
Dfc	Tromso	-13.5	-0.4%	-32.1	-5.2%	18.8	4.1%
	Umea	2.6	0.1%	-34.4	-9.5%	31.6	5.0%
	Helsinki	17.5	0.5%	-24.9	-15.6%	41.7	4.9%

4. Conclusions

In conclusion, green roofs do not effectively decrease the cooling load of cities in all zones. The heating load generally increases, leading to negative savings. Among all zones, the highest total savings result was shown in the BWh zone, ranging from 5.9% to 7.0%. The highest percentage saving though was in Astana in the BSk zone with a total saving of 305 kWh at 9.1%. Zone A showed comparatively poor results, which means that it is not efficient to use green roofs in that area. The D zone also had low energy savings results, as the temperature range is lower than a comfortable level. It should be noticed that sometimes high negative saving percentages can be seen. The heating consumption of those cities is low which means that small changes in consumption result in a high percentage decrease. The green roof effectively works in cities with high temperatures, direct radiation, humidity levels, and a wide range of sky cover. It means that cooling dominant cities still may have lower saving percentage results because of other factors, such as direct solar radiation.

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