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EFFECTS OF VEGETATION SHADING ON THE ENERGY PERFORMANCE OF DETACHED PASSIVE SOLAR BUILDINGS WITH A SUNSPACE

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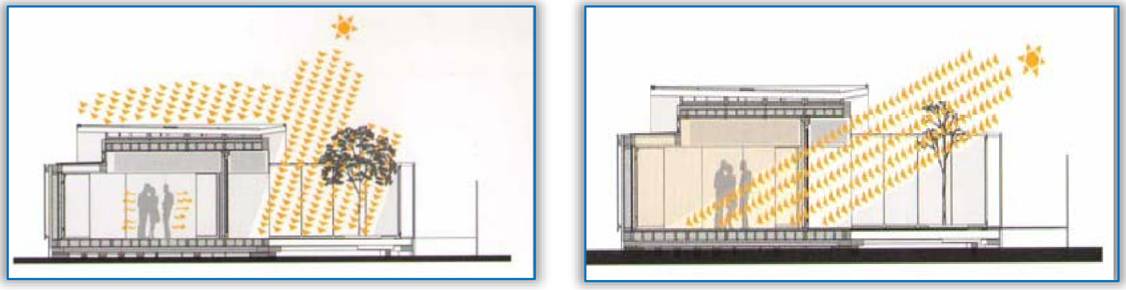
Abstract: This paper discusses the effects of vegetation shading on the energy consumption of a detached passive building with a sunspace in winter and summer conditions. The presented study was conducted by means of a dynamic simulation using EnergyPlus software for a created MODEL building with a sunspace. Nine different subvariants of vegetation planting adjacent to the building were established in order to determine the effects of vegetation shading on the energy required for heating and cooling. The subvariants comprise vegetation planted 5 m and 10 m away from the south-, east, and west-facing façades. The simulation results for different vegetation subvariants and for window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%, showed that tree placement does affect a buildings' energy performance. It was also determined that vegetation placement should be such as to make the south-facing façade shade-free while providing maximum shading of the east- and west-facing façades. The energy savings for cooling reached up to 15%, while the savings for total annual heating and cooling energy consumption reached up to 9.40%.
Keywords: passive solar buildings, sunspace, vegetation shading, energy performance

1. INTRODUCTION

Introduction of vegetation into urban spaces is one of the fundamental parameters of modern bioclimatic urban planning. Urban green spaces influence the formation of urban microclimates to a large extent. They also act as air purification filters, replace oxygen in the atmosphere, ensure a more favorable heat and radiation regime, increase air humidity, absorb dust and soot, decrease reflection, lessen the effects of environmental noise, and so forth. In urban design, tall tree clusters are used as protection against strong and cold winds. Planting vegetation around a building can decrease or increase air flow by steering light breezes toward the building during the summer or by blocking cold northern winds during the winter (Radosavljević, 2002).

Trees and other vegetation in the immediate vicinity of passive solar buildings (Figure 1) are considered a shading element (Littlefair et al. 2000), which is why it is important to position them properly and determine the size and type of vegetation depending on the intended level of shading (Bahgat, Reffat, and Elkady 2017).



(a) (b)

Figure 1. Effects of deciduous vegetation on sunlight availability during the summer (a) and winter (b) periods (Barbolini, 2014)

Deciduous trees and shrubbery exhibit seasonal variations in terms of their shading coefficient because they shed their foliage in the fall and winter (Hopper 2007). To a certain extent, evergreen trees may provide shading throughout the year. In case of passive solar buildings, deciduous trees are the better shading choice, as they provide free or only slightly reduced (up to 15%) reach of sunlight during the winter and achieve the best possible shading efficiency (approximately 90%) during the summer. The tree shade effect depends on the type of trees, the shape of foliage, the size and shape of the crown, height, position in relation to the building, and so on.

Hoi et al. investigated the effects of the position of deciduous and evergreen trees on the energy required for heating and cooling for the different climates of four U.S. cities (Hoi Hwang, Eric Wiseman, and Thomas

2016). Using EnergyPlus software, they sought the most favorable shading position of trees in relation to the building. Other authors also relied on EnergyPlus in their investigations of the effects of tree shading on the energy required for cooling (Hsieh et al. 2018).

Prior to the present study, the effects of vegetation shading on the energy performance of passive solar buildings with a sunspace have never been examined for the climatic conditions in Serbia.

2. METHODOLOGY

The analysis of the effects of vegetation on energy consumption in winter and summer conditions was performed by means of a dynamic simulation run through EnergyPlus software (US Department of Energy, 2019) for the MODEL building with a sunspace. The defined MODEL contains G+1 levels with the aspect ratio of 2.25:1 and a sunspace placed along the entire south-facing façade. The sunspace width is 1.2 m. The floor base has the length of 14.4 m and the width of 6.4 m. The floor base surface area is P_o=184.32 m^2, while the sunspace area is P_s=34.56 m^2 (Vukadinović, Radosavljević, and Đorđević 2020; Vukadinović et al. 2019).

Table 1 shows the characteristics of the thermal envelope of the model detached residential building with a sunspace.

Table 1. Values of U coefficient for the designated elements of a building's thermal envelope (Vukadinović, Radosavljević, and Đorđević 2020)

Type of structure	U [W/m^{2}K]
Façade wall	0.29
Ground floor base	0.28
Windows	1.50
Sunspace	1.50
Flat roof	0.15

To determine the effects of vegetation on the energy required for heating and cooling of the detached residential building with a sunspace, nine different subvariants of vegetation configuration adjacent to the building were established.

In the defined vegetation subvariants, the medium tree size was used, with the trunk height of 2 m, total height of 8 m, and the crown diameter of 6 m. The trees have variable shading coefficients depending on the season (Ko, 2018). The range of solar transmittance for various species of deciduous trees is 5-30% in the summer and 60-85% in the winter (Hopper, 2007). The crown was modeled with a solar transmittance of 15% for the summer and 80% for the winter. Winter and summer periods were considered separately in terms of required energy.

Table 2 shows the different vegetation subvariants with descriptions of the different configurations used in this study.

Table 2. Vegetation subvariants with the description of vegetation configurations used in the study

Vegetation subvariant	Vegetation configuration and distance from the building
Z1	No trees, reference MODEL
Z2	1 tree, 10m distance from the south-facing façade
Z3	5 trees in a row, 10m distance from the south-facing façade
Z4	1 tree, 5m distance from the south-facing façade
Z5	5 trees in a row, 5m distance from the south-facing façade
Z6	1 tree, 10m distance from the east-facing façade 1 tree, 10m distance from the west-facing façade
Z7	3 trees in a row, 10m distance from the east-facing façade 3 trees in a row, 10m distance from the west-facing façade
Z8	1 tree, 5m distance from the east-facing façade 1 tree, 5m distance from the west-facing façade
Z9	3 trees in a row, 5m distance from the east-facing façade 3 trees in a row, 5m distance from the west-facing façade

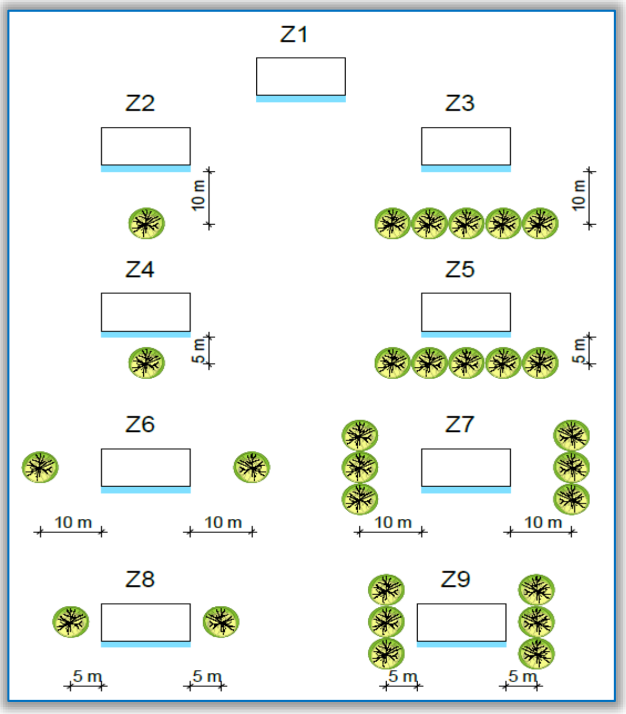


Figure 2. Vegetation subvariants (Z1-Z9) for which simulations were conducted

Subvariant Z1, which contains no vegetation, is the reference MODEL. Subvariants Z2-Z5 refer to vegetation planting adjacent to the south-facing façade at 5- and 10-meter distances, whereas subvariants Z6-Z9 refer to vegetation adjacent to the east- and west-facing façades at 5- and 10-meter distances. The simulations were run separately for the winter and the summer in order to analyze the different crown shading coefficients.

Figure 2 shows the model subvariants Z1-Z9, each of which refers to a different vegetation configuration adjacent to the building with a sunspace.

3. ANALYSIS OF ENERGY REQUIRED FOR HEATING AND COOLING OF THE BUILDING MODEL III S1 WITH DIFFERENT VEGETATION SUBVARIANTS

Table 3 shows the results of EnergyPlus (US Department of Energy, 2019) simulations for the created MODEL subvariants representing different vegetation configurations (Z1-Z9) and for WWR=20%. The simulations were run with the *Full Interior and Exterior* setting, which considers outdoor and indoor reflections and shading.

Table 3. Simulation results for the MODEL building with different vegetation types (subvariants Z1-Z9) and WWR=20%

Vegetation configuration	MODEL III S1 WWR=20%					
	Total energy required for heating [kWh]	Total energy required for cooling [kWh]	Total energy required for heating and cooling [kWh]	Percentage increase (+) or decrease (–) of the total energy required for heating	Percentage increase (+) or decrease (–) of the total energy required for cooling	Percentage increase (+) or decrease (–) of the total energy required for heating and cooling
Z1	8237.04	4763.70	13000.74	ref. MODEL	ref. MODEL	ref. MODEL
Z2	8284.62	4753.18	13037.80	+0.58%	– 0.22%	+0.29%
Z3	8171.64	4649.04	12820.68	– 0.79%	– 2.41%	– 1.38%
Z4	8235.85	4669.53	12905.38	– 0.01%	– 1.98%	– 0.73%
Z5	7992.24	4467.36	12459.60	– 2.97%	– 6.22%	– 4.16%
Z6	8237.22	4622.18	12859.40	+0.00%	– 2.97%	– 1.09%
Z7	8233.81	4455.63	12689.44	– 0.04%	– 6.47%	– 2.39%
Z8	8239.32	4353.80	12593.12	+0.03%	– 8.60%	– 3.14%
Z9	8213.73	4136.27	12350.00	– 0.28%	– 13.17%	– 5.01%

Figure 3 shows the total annual energy required for heating, the total annual energy required for cooling, and the total annual energy required for both, for different MODEL subvariants of vegetation (Z1-Z9) and for WWR=20%.

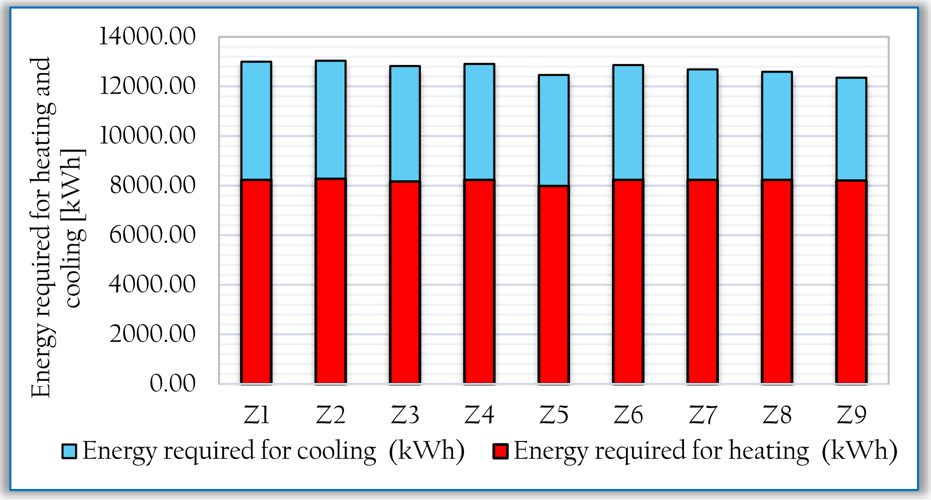


Figure 3. Total annual energy required for heating and cooling for MODEL III S1 for different vegetation subvariants (Z1-Z9) and for WWR=20%

Simulation results for the different vegetation subvariants and WWR=20% show that less cooling energy is required for all subvariants compared to the reference model without any vegetation. Subvariant Z3 (five trees in a row 10 m away from the south-facing façade) requires 2.41% less cooling energy than the reference model, while subvariant Z5 (five trees in a row 5 m away from the south-facing façade) require 6.22% less energy than the reference model. For subvariants Z2 and Z4 (one tree 10 and 5 m away from the south-facing façade, respectively), the cooling energy requirements are lower by 0.22% and 1.98%, respectively. In terms of cooling energy consumption and the total energy required for heating and cooling, it is much more beneficial to plant the trees in front of the east- and west-facing façades than in front of the south-facing one. Subvariant Z7 (three trees in a row 10 m away from the east- and west-facing façades) requires 6.47% less cooling energy than the reference model, whereas subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades) requires 13.17% less cooling energy than the reference model.

The heating energy requirements for all subvariants are either slightly higher or slightly lower than the reference model.

The total energy requirements for heating and cooling are lower than the reference model for each subvariant, the lowest being for subvariant Z5 (five trees in a row 5 m away from the south-facing façade), which requires 4.16% less heating and cooling energy than the reference model, and for subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades), which requires 5.01% less energy than the reference model.
Table 4 shows the results of EnergyPlus simulations for the created MODEL subvariants representing different vegetation configurations (Z1-Z9) and for WWR=40%.

Table 4. Simulation results for the MODEL building with different vegetation types (subvariants Z1-Z9) and WWR=40%

Vegetation configuration	MODEL III S1 WWR=40%					
	Total energy required for heating [kWh]	Total energy required for cooling [kWh]	Total energy required for heating and cooling [kWh]	Percentage increase (+) or decrease (−) of the total energy required for heating	Percentage increase (+) or decrease (−) of the total energy required for cooling	Percentage increase (+) or decrease (−) of the total energy required for heating and cooling
Z1	8346.75	9592.83	17939.58	ref. MODEL	ref. MODEL	ref. MODEL
Z2	8323.38	9528.11	17851.49	− 0.28%	− 0.67%	− 0.49%
Z3	8184.62	9357.24	17541.86	− 1.94%	− 2.46%	− 2.22%
Z4	8269.64	9368.83	17638.47	− 0.92%	− 2.34%	− 1.68%
Z5	7991.44	8986.25	16977.69	− 4.26%	− 6.32%	− 5.36%
Z6	8347.19	9215.48	17562.67	+0.01%	− 3.93%	− 2.10%
Z7	8345.24	8856.57	17201.81	− 0.02%	− 7.68%	− 4.11%
Z8	8354.65	8631.17	16985.82	+0.09%	− 10.02%	− 5.32%
Z9	8314.01	8154.29	16468.30	− 0.39%	− 15.00%	− 8.20%

Figure 4 shows the total annual energy required for heating, the total annual energy required for cooling, and the total annual energy required for both, for different MODEL subvariants of vegetation (Z1-Z9) and for WWR=40%.

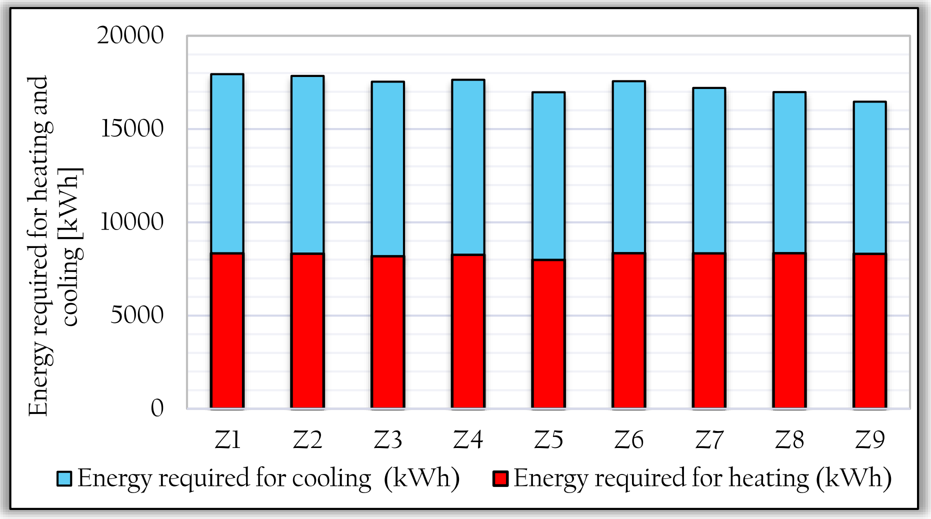


Figure 4. Total annual energy required for heating and cooling for MODEL III S1 for different vegetation subvariants (Z1-Z9) and for WWR=40%

Simulation results for the different vegetation subvariants and WWR=40% also show that less cooling energy is required for all subvariants compared to the reference model without any vegetation. Subvariant Z3 (five trees in a row 10 m away from the south-facing façade) requires 2.46% less cooling energy than the reference model, while subvariant Z5 (five trees in a row 5 m away from the south-facing façade) require 6.32% less energy than the reference model. For subvariants Z2 and Z4 (one tree 10 and 5 m away from the south-facing façade, respectively), the cooling energy requirements are lower by 0.67% and 2.34%, respectively. In terms of cooling energy consumption and the total energy required for heating and cooling, it is again much more beneficial to plant the trees in front of the east- and west-facing façades than in front of the south-facing one. Subvariant Z7 (three trees in a row 10 m away from the east- and west-facing façades) requires 7.68% less cooling energy than the reference model, whereas subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades) requires 15.00% less cooling energy than the reference model.
The heating energy requirements for all subvariants are either slightly higher or slightly lower than the reference model.

The total energy requirements for heating and cooling are lower than the reference model for each subvariant, the lowest once more being for subvariant Z5 (five trees in a row 5 m away from the south-facing façade), which requires 5.36% less heating and cooling energy than the reference model, and for subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades), which requires 8.20% less energy than the reference model.

Table 5 shows the results of EnergyPlus simulations for the created MODEL subvariants denoting different vegetation configurations (Z1-Z9) and for WWR=60%.

Table 5. Simulation results for the MODEL building with different vegetation types (subvariants Z1-Z9) and WWR=60%

Vegetation configuration	MODEL III S1 WWR=60%					
	Total energy required for heating [kWh]	Total energy required for cooling [kWh]	Total energy required for heating and cooling [kWh]	Percentage increase (+) or decrease (−) of the total energy required for heating	Percentage increase (+) or decrease (−) of the total energy required for cooling	Percentage increase (+) or decrease (−) of the total energy required for heating and cooling
Z1	8720.27	14189.40	22909.67	ref. MODEL	ref. MODEL	ref. MODEL
Z2	8699.19	14106.57	22805.76	− 0.24%	− 0.58%	− 0.45%
Z3	8558.78	13886.42	22445.20	− 1.85%	− 2.14%	− 2.03%
Z4	8652.91	13892.87	22545.78	− 0.77%	− 2.09%	− 1.59%
Z5	8378.63	13373.56	21752.19	− 3.92%	− 5.75%	− 5.05%
Z6	8721.58	13646.50	22368.08	+0.02%	− 3.83%	− 2.36%
Z7	8723.22	13121.11	21844.33	+0.03%	− 7.53%	− 4.65%
Z8	8734.47	12771.74	21506.21	+0.16%	− 9.99%	− 6.13%
Z9	8688.93	12066.71	20755.64	− 0.36%	− 14.96%	− 9.40%

Figure 5 shows the total annual energy required for heating, the total annual energy required for cooling, and the total annual energy required for both, for different MODEL subvariants of vegetation (Z1-Z9) and for WWR=60%.

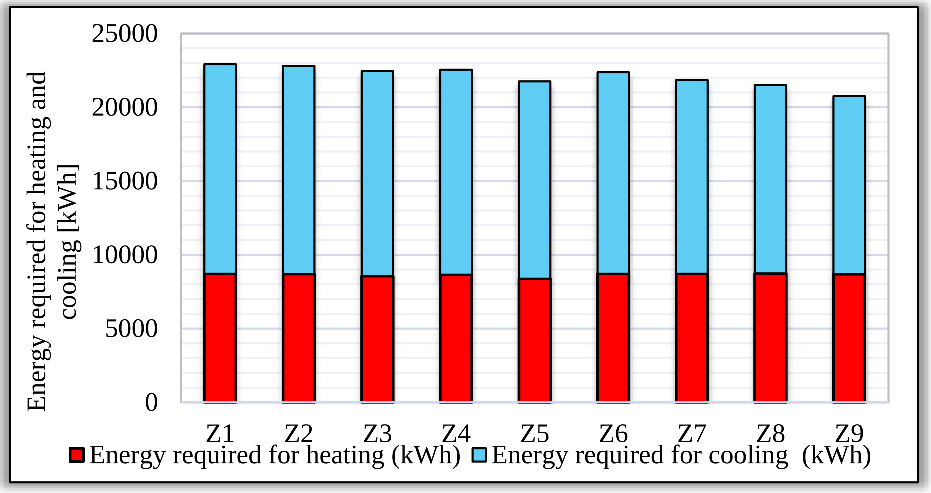


Figure 5. Total annual energy required for heating and cooling for MODEL III S1 for different vegetation subvariants (Z1-Z9) and for WWR=60%

Yet again, simulation results for the different vegetation subvariants and WWR=60% show that less cooling energy is required for all subvariants compared to the reference model without any vegetation. Subvariant Z3 (five trees in a row 10 m away from the south-facing façade) requires 2.14% less cooling energy than the reference model, while subvariant Z5 (five trees in a row 5 m away from the south-facing façade) require 5.75% less energy than the reference model. For subvariants Z2 and Z4 (one tree 10 and 5 m away from the south-facing façade, respectively), the cooling energy requirements are lower by 0.58% and 2.09%, respectively. In terms of cooling energy consumption and the total energy required for heating and cooling, it is once again much more beneficial to plant the trees in front of the east- and west-facing façades than in front of the south-facing one. Subvariant Z7 (three trees in a row 10 m away from the east- and west-facing façades) requires 7.53% less cooling energy than the reference model, whereas subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades) requires 14.96% less cooling energy than the reference model.

The heating energy requirements for all subvariants are either slightly higher or slightly lower than the reference model.

As with previous WWRs, the total energy requirements for heating and cooling are lower than the reference model for each subvariant, the lowest being for subvariant Z5 (five trees in a row 5 m away from the south-facing façade), which requires 5.05% less heating and cooling energy than the reference model, and for subvariant Z9 (three trees in a row 5 m away from the east- and west-facing façades), which requires 9.40% less energy than the reference model.

4. CONCLUSION

Planting vegetation next to a building can help improve the energy properties of passive solar buildings with a sunspace. In order to determine the extent of this contribution, this study introduced nine subvariants in which vegetation is planted either 5 or 10 m away from the south-, east-, or west-facing façades. Specifically, the analysis considered the cases of deciduous trees with solar transmittance of 15% during the summer and 80% during the winter. Simulations for the MODEL building with a sunspace, run through EnergyPlus software, determined that planting a row of deciduous trees 5 m away from the east- and west-facing façades prevents overheating during the summer with a minimum increase in the energy required for heating during the winter. It is more beneficial to plant trees 5 m than 10 m away from the façade. Tree rows should be positioned in such a way as to make the south-facing façade shade-free while providing maximum shading of the east- and west-facing façades. Cooling energy savings were at a maximum of 15%, while the total annual savings in heating and cooling energy reached a maximum of 9.40%.

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