IMPACT OF A BUILDING SHAPE FACTOR ON SPACE COOLING ENERGY PERFORMANCE IN THE GREEN ROOF CONCEPT IMPLEMENTATION

by

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The reduction of energy demand for space cooling requires adequate solutions at building and built environment scales in order to achieve sustainability goals. Since many existing buildings have inadequate envelopes for reducing heat gains in summer and heat losses in winter, environmentally friendly renovation techniques have to be considered. The roofs of existing buildings were identified as a field of intervention which could contribute to providing both energy savings and environmental benefits. The aim of the paper was to evaluate the contribution of green roofs to energy savings for space cooling depending on the building shape factor. Two groups of building models, with vertical and horizontal expansions, were analysed. The comparative analyses of the building models with conventional and green roofs showed small reduction of energy consumption – less than 1% in case of well-insulated roofs with the addition of the extensive green roof. The comparison of different building models with green roofs of the same volume, which is in this case the same cooling area, indicated a more effective solution for green roofs implementation with the aim to improve energy performances of existing buildings using this passive design technique.

Key words: *building shape, green roofs, sustainability, energy savings, comparative analysis, energy modelling*

Introduction

Bearing in mind that energy savings is a high priority in recent years, the energy efficient measures are being increasingly implemented in all sectors in developed countries. The building sector is a great energy consumer with approximately 40% of the total world energy consumption [1] where most of the energy is used for heating and cooling the buildings [2]. The design stage of a building is the best time to integrate sustainable strategies. In this stage, it is important to optimize design variables, which are directly related to heat transfer processes, and construction parameters in order to achieve an energy efficient building. According to Ekici and Aksoy [3], the design parameters which determine building energy requirements are: shape factor, transparent surface, orientation, thermophysical properties of building materials and building placement regarding its environment. The optimization of these parameters

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in the early stage of the building design reduces implementation costs, as compared to their application in the use phase. Considering already densely built urban areas and the characteristics of existing buildings, particularly the materials used for their envelope, it is necessary to conduct the renovation process to fulfil the requirements for efficient energy consumption. Inadequate building envelopes are responsible for increased energy consumption for space cooling in summer and extra heating in winter periods. In this paper, the renovation of the roof structure was discussed. The green roof concept has been identified as an energy efficient improvement method by numerous studies and publications. This approach has also been justified from the environmental aspect since greening the building envelope is the only way to increase green spaces in urban areas, which is important for obtaining ecosystem services for sustainable development [4].

As building shape is one of the factors which influence efficient energy consumption, it is considered in the design of new buildings. However, it could also be applied to the existing ones to evaluate the potential energy savings by the green roof concept implementation. The effects of architectural volumetric and building plan on energy performance of a building, in terms of space cooling, were investigated in the paper. The more effective size and/or proportions of buildings were determined through energy modelling of two groups of building models with conventional roofs and with the addition of green roofs, focusing on various vertical and horizontal expansions. The simulations of different building models of the same volumes with green roofs indicated a more suitable building model solution for their implementation, when considering energy savings as a primary benefit of green roofs.

Energy saving potential of green roofs

Green roofs could be seen as a design technique which contributes to achieving sustainable development postulates in urban areas. Diverse benefits of green roofs, from environmental, economic, and social aspects, have been confirmed by numerous studies worldwide. A green roof, as a protective and insulation layer in the roof structure, is a successful tool to gain economic and environmental benefits. Reduced energy consumption reduces the costs for end users, and also minimizes the environmental impact due to low emissions.

The green roof structure generally consists of the following layers: vegetation, substrate, filter, drainage, and a root barrier over the waterproofing layer [5]. The typology of green roofs is based on the complexity of their structure and function, and there are two main green roof types – extensive and intensive green roof systems. The essential difference is related to the thickness of the substrate layer which allows the development of different vegetation types. Extensive green roofs support the development of grasses and short-sedum species and have smaller substrate thickness. Intensive green roofs support the development of shrubs and trees, so higher substrate thickness is needed for their root system. The selection of the appropriate green roof type depends on performances desired.

The improvement of building thermal performances is the result of the increment of shading, better insulation and higher thermal mass of the roof system [6]. The extent to which the energy consumption for space heating in winter and space cooling in summer could be reduced depends on climatic conditions, building characteristics and applied green roof system. In terms of climate, the results of various researches indicate that energy savings by the implementation of green roofs are possible in all climatic zones [7]. Green roofs reduce energy consumption in areas with warm climates to a greater extent, *i. e.* their function in creating the cooling effect is more significant. The presence of vegetation limits the thermal loads due to solar radiation and air temperature, and the substrate layer presents an additional insulation of building envelope. This is confirmed by the studies which showed temperature decrease of the roof membrane underneath the green roof by up to 20 °C in comparison to the conventional roof [8, 9]. The research on the ability of a green roof to reflect and absorb solar radiation indicated the improvement of the roof structure thermal performances [5]. According to the findings, 27% of the total solar radiation was reflected, 60% was absorbed and only 13% was transmitted into the substrate layer. The moisture content in the substrate layer significantly affects thermal performances of a green roof. Certain studies indicated dependence between the increment of the substrate thermal conductivity and water content [10-12]. Ouldboukhitine *et al.* [11] found that values of substrate thermal conductivity, *c*, in relation to the percentage of the saturation ranged from 0.05 to 0.7 W/mK. Green roofs contribute insignificantly to energy savings in cold climates. This is confirmed by the research in the area characterized by warm summers and cold winters [8]. The findings showed the reduction of heat flux through the building envelope by an average of 13% in winter and 167% in summer. Beside the positive effects [5, 7, 13], some of the studies have shown that green roofs have no impact on reducing energy consumption for space heating [14] or increased consumption [15, 16]. These differences in the results lead to the conclusion that it is necessary to conduct the research study of local climatic conditions in order to evaluate the thermal performances of a green roof.

Energy savings achieved by the green roof implementation significantly depend on the characteristics of the existing buildings. Green roofs have a greater potential for uninsulated buildings [10]. The research conducted in the Mediterranean climate showed that energy consumption was reduced by up to 2% in case of insulated buildings, whereas these reductions ranged from 37% to 48% in case of uninsulated buildings. Moreover, an indoor temperature was reduced by 4 °C [17]. The number of storeys directly affects the thermal performances of a building with a green roof. Taking into consideration that green roofs mostly influence energy savings on the top storey, it can be concluded that buildings with fewer storeys achieve greater energy savings of the whole building system. The result of the study on the one-storey building with an extensive green roof showed the reduction of energy used for space cooling by 25% [18]. The study of a four-storey building in Genoa, Italy, focused on the estimation of the annual energy consumption for space cooling [10]. The result has revealed that energy consumed on the top storey is about 50% energy used in the whole building. This fact indicates the relevance of the top storey to energy savings in case of space cooling.

Regarding the green roofs typology, greater energy savings are achieved by the implementation of intensive green roofs due to higher thickness of the substrate layer and higher thermal mass, in comparison to extensive green roofs. Numerous studies have revealed that energy savings for space cooling range from 5% to 10% for extensive green roofs, and from 10% to 15% for the intensive ones [10]. The influence of plant species on thermal performances of a green roof was examined on extensive green roof vegetation in different climatic zones [19]. The results showed greater energy savings for space cooling through the implementation of tall gramineous vegetation in comparison to short-sedum vegetation, in both regions. Green roofs with tall gramineous vegetation reduced energy consumption by 8.2% to 8.5% more than green roofs with sedum vegetation. The usage of taller plants with greater leaf area index lead to the increment of energy savings for space cooling [8]. Therefore, buildings with green roofs, in comparison to the buildings with conventional ones, made energy savings by up to 60% [20].

The green roofs function as additional insulation directly affects the improvement of the building thermal performance, *i. e.* it affects the energy savings, and thus indirectly improves the microclimate in urban areas. This confirms the significance of their usage not only for an individual building but also at an urban scale.

Green roofs as a passive design technique for achieving energy efficiency

Sustainable building practice requires both efficient energy use and environmentally friendly design. In already densely built urban areas, the renovation of the energy inefficient buildings is necessary. Energy efficiency of a building can be improved by the implementation of either active or passive energy efficient strategies. The improvement of heating, ventilation and air conditioning (HVAC) systems, electrical lighting, *etc.* can be considered as active strategies, whereas improvement of building envelope elements might be seen as passive strategies [21]. The building envelope is a key factor which determines the quality and controls the indoor conditions irrespective of transient outdoor conditions. The roof as a component of a building envelope is highly susceptible to solar radiation and other environmental changes which affect the indoor comfort conditions. Buildings with large roof areas account for large amounts of heat gain/loss. One of the ways to achieve sustainability is to apply the green roof concept as an energy efficient and environmentally friendly design technique.

In order to achieve improved energy performances of a building with a green roof as a passive design technique, it is necessary to determine the parameters which indicate the suitability of a building for the green roof implementation. Considering the building location, these parameters are related to climatic conditions, building orientation and placement. Although the achievement of efficient energy use of buildings with integrated green roofs is confirmed in all climates, the greatest contribution of the green roof is achieved in hot and dry climates [21]. The wet environment of a green roof affects the reduction of its thermal properties, but the presence of moisture content in the substrate layer, on the other hand, is needed for the existence and development of vegetation. In hot and dry climates the level of evapotranspiration is high, so the wet green roofs have about double of the amount of evapotranspiration in comparison to dry green roofs, remove unnecessary heat from the building and act as a passive cooling system [22]. Regarding the building orientation, it is necessary to provide direct exposure to sunlight for a green roof. This is important when considering retrofitting sloped roofs. For flat roofs, which are commonly used for green roof implementation, it is more important to consider the building placement, *i. e.* the building position with regard to its environment, because of the potential of whole day shading. Getter *et al.* [23] based their research on different types of vegetation which could survive in conditions of unfavorable roofs orientation and shaded roofs by adjacent buildings. For the improvement of overall performances of green roofs, it is very significant to research vegetation species present in the local environment.

Methods for the building shape evaluation

Since the potential of green roofs for space cooling energy savings is confirmed, as well as the building external parameters which have impact on energy efficiency, it is necessary to determine more suitable building shape solutions for achieving improved energy performances. In order to establish the relation between energy consumption and building shape factor, the methods for evaluating building shape have to be analysed.

Energy performance of buildings depends on their volumetric and plan solutions which are primarily related to the building type and architectural and urbanistic requirements. Regarding energy demand, the main characteristic of a building is its compactness, *i. e.* the compactness of a certain useful (heating/cooling) area [24]. To reveal the effect of compactness, various evaluation criteria should be considered, thus allowing the comparison of the proposed building shape and the most compact solution which is the reference building model. The reference building model usually refers to a cube of the same volume as a proposed building [25]. Several methods have been used in available literature so far. Aksoy and Inalli [26] in their research on the impact of shape on heating demand expressed the compactness via shape factor, which corresponds to the ratio of the length to the depth of a typical building storey. In the research on the effect of shape on construction, energy and life-cycle costs, Bostancioglu [27] compared rectangular H-shaped building and star-shaped building of the same size through the ratio of the external wall area to the initial floor area EWA/FA. The most widely used relative value for compactness evaluation is the ratio of the external envelope area of a building to its useful inner volume A/V [28]. This value as the shape coefficient is described in the study based on determining the relation between energy consumption and the shape of a building [24]. In another study of an office building aimed to predict an impact of its shape on annual cooling and total energy use, the authors modified the shape coefficient to express relative compactness (RC) [29]. It stands for the relation between the designed shape factor of the building, $(A/V)_{\mathrm{building}}$, and the minimum shape factor of the reference building with the same volume, $(A/V)_{\mathrm{ref}}$. Simplified relative compactness expressed as the relation between the external envelope of reference and designed buildings is presented as a tool for optimizing a building shape and its envelope [30]. In both cases of eq. (1), relative compactness presents the deviation of the building shape from the reference one:

$$RC = \frac{\left(\dfrac{A}{V}\right)_{\mathrm{building}}}{\left(\dfrac{A}{V}\right)_{\mathrm{ref}}} = \frac{A_{\mathrm{ref}}}{A_{\mathrm{building}}} \tag{1}$$

Considering various building types and differences in storey heights, the shape factor A/V and the RC value may not be appropriate indicators of building compactness because identical architectural shapes and volumes of buildings could differ in the number of storeys, which means that their useful areas might not be the same. Thus, relative compactness does not indicate that a building with a larger area inside the same envelope will be more effective and more energy efficient. It is suggested that geometric efficiency (GE) should be used to express the compactness [24]. The GE stands for the A/S ratio, where A is the external envelope area of a building and S is its useful floor area, so it is defined as the area of a building envelope per unit of useful area. Considering that buildings with different compactness can have the same GE values, *i. e.* non-compact buildings with larger areas can have the GE values as the compact ones, it is suggested to use relative geometric efficiency (RGE) [24]. This value is expressed as the relation between the GE of a building and the optimal GE of a reference building (2). The RGE presents the deviation of the GE of a building from GE_{ref} or its potential to use energy and material resources effectively [24].

$$RGE = \frac{\left(\dfrac{A}{S}\right)_{\mathrm{building}}}{\left(\dfrac{A}{S}\right)_{\mathrm{ref}}} = \frac{GE_{\mathrm{building}}}{GE_{\mathrm{ref}}} \tag{2}$$

The selection of a more suitable method for the building shape evaluation depends on numerous physical characteristics of a building, as well as on its desired performances. On the other hand, the relation between any of the chosen methods and, for the purpose of this research, the efficiency of energy cooling could be established. The building shape factor is primarily significant for the optimization of the building shape in the early design stage, but it could also be successfully used to analyze the existing buildings' potential for the implementation of a new renovation design technique which is a subject of this paper – a green roof concept.

Methodology

In order to reduce energy consumption of existing buildings, the concept of green roofs is proposed as a viable solution. Extensive green roof type is more often applied than the intensive one, because of its characteristics such as: lightweight structure, lower capital cost, easier installation in a shorter period of time, and low level of maintenance [7, 31]. Although it could be applied on the sloped roofs with the optimal inclination up to 45° [32], the extensive green roof type is widely used on the flat roof surfaces. Their great potential for implementation is indicated by the fact that roofs occupy about 20-25% of urban areas, which are typically unused spaces [33]. Considering these facts, thermal performance of an extensive green roof type implemented on flat roofs has been examined in this study. Since greater contribution of green roofs to energy savings in poorly insulated buildings is expected, we investigated their effects on well-insulated roofs. The structures of the conventional flat roof and the commercial extensive green roof, Urbanscape type [34], materials and the thickness of layers, d [cm], used in this study are shown in fig. 1. This green roof system is available at relatively low price, does not require expertise for installation and specific maintenance, and it is lightweight, up to approximately 90 kg/m^2 saturated, which indicates no structural implication for the existing buildings.

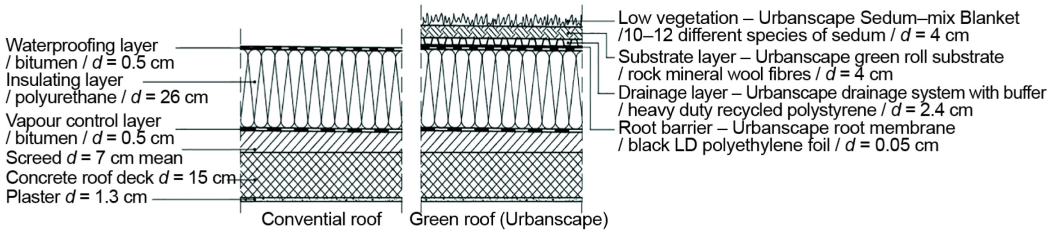


Figure 1. Conventional and green roof structures

The impact of building compactness on energy consumption was examined on rectangular-shaped building models. Two groups of building models were classified by vertical and horizontal expansions, fig. 2. Simplified models were presented as stand-alone buildings with fixed orientation, without any openings and with the same materials used for their envelopes with the exception of roof structures. The relative compactness was used as a building shape factor. The *GE* was not necessary to consider for the purpose of this study because the storey height was assumed to be fixed in all models. Since the research was focused on the improvement of roof structure for energy savings only, the building envelope area, A, in the *RC* formula was modified and it referred to the roof area of the proposed building model, A_{building}, and the roof area of the reference cubic building, A_{ref}. Investigating the improvement of the external walls, as a part of the building envelope, Ourghi *et al.* [29] used only the façades area for obtaining the *RC* values. The relations between the *RC* and the horizontal and vertical building expansions are shown in fig. 3. From the diagrams shown, it can be concluded that by increasing a building volume by vertical expansion (with the fixed roof area which corresponds to ground plan), *RC* values also increase, fig. 3(a). On the other hand, by increasing a building volume by horizontal expansion which increases a roof area, *RC* values decrease, fig. 3(b).

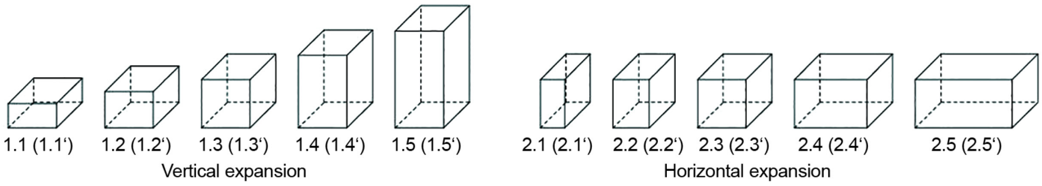


Figure 2. Groups of building models

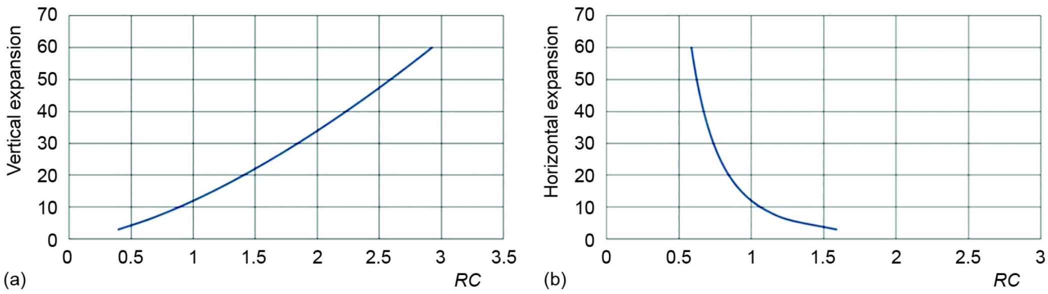


Figure 3. Relation between *RC* values and building expansion

This research was focused on the electricity consumption for cooling in summer period (*i. e.* June, July, and August), in a warm temperate climate of the city of Nis, Serbia. Since the City of Nis is located poleward of the Mediterranean climate region and has the highest average annual number of summer days recorded in Serbia (111 days), there is great potential for space cooling energy savings by the green roofs implementation. The models were presented as residential buildings with a permanent regime of cooling. The calculations were performed for the maximum inner temperature of 26 °C allowed for this building type in summer months, as required by national regulation [35]. To reveal electricity consumption for space cooling of proposed building models, according to their properties and environmental conditions, the engineering analysis package IES VE (Integrated Environmental Solutions), VistaPro module, was used as the support tool. This program package is intended for academic use. It is user-friendly, widely available at relatively low price, and it is recommended by the Serbian Chamber of Engineers as one of the most comprehensive program for energy modelling [36].

Building models for energy simulations

Both groups of buildings, with vertical and horizontal expansions, were modelled with conventional roofs (CR) and green roofs (GR). For comparative analysis of energy consumption, it was necessary to determine physical properties of each building model. The dimensions and orientations of the building models are shown in tab. 1. Vertical expansion within the first group of models was performed by the multiplication of a typical storey unit of 3 m in height. Regarding the second group of four-storey models, the horizontal expansion was performed by single axis, increasing only the length but not the width of the models. For stand-alone buildings with determined orientation, no shadings from surrounding buildings were assumed. Based on the roof system properties (materials used and the thickness elements applied) U-values [$\mathrm{Wm^{2-1}K^{-1}}$] for the roofs of the proposed simplified building models were calculated by the IES VE program package. The values were 0.09 for the conventional roof and 0.08 for the green roof, and they fall in the allowed range for both new ($U_{\max}$ = 0.20) and existing buildings ($U_{\max}$ = 0.15) according to current national regulations [35], which indicated good roof insulation. To reveal how much the building shape factor affects the energy consumption for space cooling, different building models with the same envelope properties, volumes and useful areas have been compared, tab. 2.

Table 1. Dimensions and orientation of building models

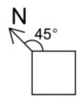
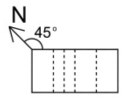
Vertical expansion	1.1	1.1’	1.2	1.2’	1.3	1.3’	1.4	1.4’	1,5	1,5’	Building orientation
Roof type	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	
Width [m]	12		12		12		12		12		
Lenght [m]	12		12		12		12		12		
Height [m]	6		9		12		18		24		
Horizontal expansion	2.1	2.1’	2.2	2.2’	2.3	2.3’	2.4	2.4’	2.5	2.5’	Building Orientation
Roof type	CR	GR	CR	GR	CR	GR	CR	GR	CR	GR	
Width [m]	12		12		12		12		12		
Lenght [m]	6		9		12		18		24		
Height [m]	12		12		12		12		12		

Table 2. Properties of comparative building models with green roofs

Number of comparison	I		II		III		IV	
Model pairs for comparison	1.1’	2.1’	1.2’	2.2’	1.4’	2.4’	1.5’	2.5’
Roof area [m^2]	144	72	144	108	144	216	144	288
Volume [m^3]	864		1296		2592		3456	
Useful area [m^2]	288		432		864		1152	
Relative compactness [–]	0.63	1.26	0.83	1.10	1.31	0.87	1.59	0.79

Results and discussion

According to the results of electricity consumption for all of the proposed building models, tab. 3, obtained by the IES VE software tool, it can be concluded that energy savings for buildings with well-insulated roofs with the addition of green roofs are negligible. Slight reduction of energy consumption of less than 1% could be expected. It is in the range of the results obtained by the study on well-insulated building in more suitable climatic conditions for green roofs thermal performance, which was calculated to be up to 2% in hot and dry climate [17]. It has to be noted that obtained values of energy consumption for space cooling in this research were derived from simplified models, but their comparison indicates the differences in energy consumption in systems with different roof structures.

Table 3. Electricity consumption for space cooling

Vertical expansion		1.1	1.1’	1.2	1.2’	1.3	1.3’	1.4	1.4’	1,5	1.5’
Roof type		CR	GR	CR	GR	CR	GR	CR	GR	CR	GR
Electricity consumption [kWh]	June	86.8	86.2	138.6	137.9	190.6	189.9	294.6	293.9	398.6	397.9
	July	365.9	364.9	548.7	547.8	731.5	730.6	1096.9	1096.0	1462.3	1.461.3
	August	411.2	410.6	612.7	612.1	814.1	813.5	1216.9	1216.3	1619.7	1.619.1
	Total	863.9	861.7	1300.0	1297.8	1736.3	1734.0	2608.4	2606.1	3480.5	3478.3
Horizontal expansion		2.1	2.1’	2.2	2.2’	2.3	2.3’	2.4	2.4’	2.5	2.5’
Roof type		CR	GR	CR	GR	CR	GR	CR	GR	CR	GR
Electricity consumption [kWh]	June	163.9	163.6	177.4	176.9	190.6	189.9	216.7	215.8	242.8	241.4
	July	544.3	543.9	638.6	637.9	731.5	730.6	915.5	914.1	1098.6	1096.6
	August	599.5	599.2	707.6	707.1	814.1	813.5	1025.2	1024.2	1235.2	1233.9
	Total	1307.7	1306.6	1523.6	1521.9	1736.3	1734.0	2157.4	2154.0	2576.5	2572.0

The relations between the electricity consumption and relative compactness of building models with different roof structures are shown in fig. 4. Regarding the building models based on vertical expansion, it can be seen that increase in electricity consumption caused by the increase in volume, corresponds to increase in *RC* values, fig. 4(a). For the group of horizontally expanded building models, the increase in electricity consumption, affected by horizontal expansion, corresponds to a decrease in *RC* values, fig. 4(b). Taking into consideration the values obtained for electricity consumption, it can be concluded that greater horizontal expansion affects greater energy savings for buildings with implemented green roofs.

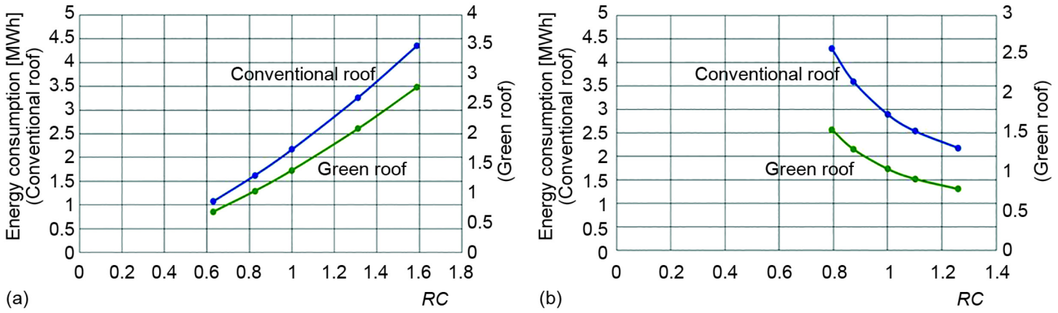


Figure 4. Relation between electricity consumption and relative compactness; (a) vertical expansion, (b) horizontal expansion

The comparison of electricity consumption in different building models with green roofs, which have different building compactness, the same volume and useful area, are presented in fig. 5. Energy consumption comparison for the first (1.1’ and 2.1’) and the second (1.2’ and 2.2’) pair revealed energy saving of 34.05% and 14.73% for the buildings 1.1’ and 1.2’, respectively. For the third (1.4’ and 2.4’) and the fourth (1.5’ and 2.5’) compared pair, the results showed energy savings of 17.35% and 26.06% for the buildings 2.4’ and 2.5’, respectively. The relation between the relative compactness values and electricity consumption indicates their dependence. Lower values of the relative compactness correspond to lower electricity consumption.

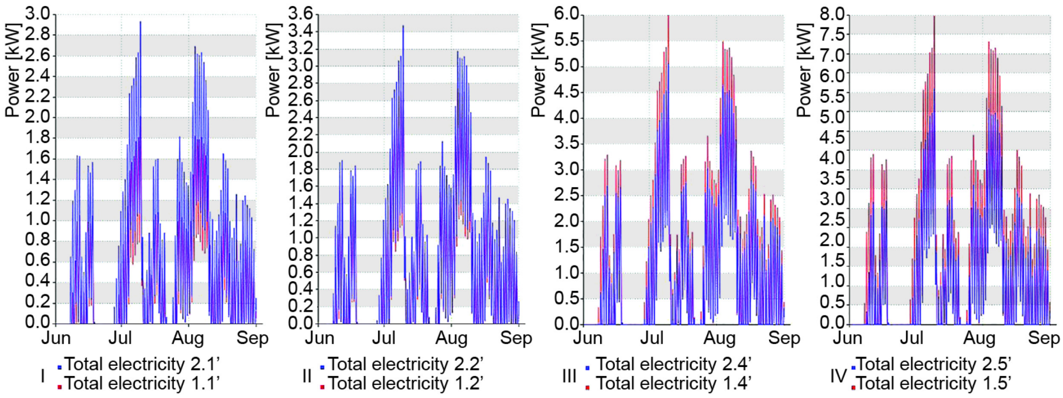


Figure 5. Electricity consumption of comparative building models

The physical properties of compared buildings justify the application of modified value of the building envelope area to the roof area in the *RC* formula. Considering relative compactness and relative geometry efficiency, the building envelope implies border elements of useful area, which are in this study external walls, roof and floor on the ground, as elements of the building thermal envelope. Thus, the values for the envelope area, A, of each pair of the compared building models would be the same. The same volume area indicates the same reference building models for the compared ones, which lead to the conclusion that the *RC* values would be equal. Applying the formula of relative geometry efficiency would also produce equal values because of the same useful areas, S, for both compared building models. This analysis confirms that the defined *RC* and relative *GE* values are not always suitable indicators for defining building compactness.

Conclusions

Green roofs obviously might be considered as an useful passive design technique for achieving efficient energy use in urban buildings. Their potential for energy savings was analysed due to great availability of the roof surfaces within urban areas, particularly flat roofs which are typically unused spaces. Since their cooling effect is more significant, the energy savings in the summer period were investigated by applying the extensive green roof type. Considering energy savings as the primary benefit of green roofs, this study has revealed the significance of building compactness. The proposed groups of models were obtained by vertical and horizontal expansions, and analysed with conventional and green roofs. The building relative compactness was used as the building shape factor, adjusted to the impact of a roof structure on energy consumption. The results obtained by the comparison of building models with different roof structures indicate the negligible energy savings for the buildings with green roofs which is a consequence of insulation properties of additional green roof layers placed over a well-insulated roof. Regarding the impact of relative compactness on energy savings, it can be concluded that lower values of the *RC* correspond to lower electricity consumption. It was confirmed by the comparative analyses of buildings with green roofs with different compactness and the same volumes.

This research indicates the significance of using the building shape factors not only in the design stage for optimizing the performances, but also in the use phase when considering the renovation with green roofs. Since the extensive green roofs provide somewhat improved cooling energy savings when applied on well-insulated buildings, it is expected that green roofs, and particularly systems with higher substrate thickness (*i. e.* greater thermal mass) would gain the popularity as a solution for retrofitting poorly insulated buildings.

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