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Research paper

Energy Efficiency of "Green Structures" in Cooling Period

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Abstract

The proposed methodology for estimating the reduction of CO_2 emissions by green constructions (green roof and facade greening) due to the "cooling effect" during the cooling period allows to calculate CO_2 savings in warm periods of the year. For Kyiv, in July, the reduction of CO_2 emissions per m^2 at coal using is 133 g / m^2, during the warm period of the year – 515 g / m^2; using gas – 78 g / m^2 and 303 g / m^2. It is established that the energy savings of a green roof depends on the thickness of the thermal insulation of buildings: the thicker insulation causes the less green roof contribution to energy savings. However, the significance of their effectiveness remains. Green roofs can be especially effective in switching from gas to local solid fuels: peat waste, pellets, etc. As a practical recommendation, it is proposed to coordinate the placement of greened and ungreen parts of the green roof with rooms under the roof, which allows to reduce the refrigeration load on air conditioning. In addition, recommendations on grass care on the green roof have been developed. To maximize the cooling effect, it is necessary to maintain grass height no more than 120 mm. Before the beginning of the transition period, it is necessary to stop mowing the grass, which reduces the cooling effect.

Keywords: *CO_2 emission; cooling effect; energy efficiency; greenstructures; green structure*.

1. Introduction

Today there is a global environmental problem in the world that is due to climate change, which is caused by greenhouse gas emissions. One of these gases is the main product of combustion of fuel – CO_2. Therefore, increasing energy efficiency of buildings can solve not only technical and economic, but also environmental problems. One of the biotechnical mechanisms for increasing the energy efficiency of buildings in green building is "green structures". One of their useful properties is the "cooling effect", which causes passive cooling of buildings. To date, there is neither precise definition of the concept of "cooling effect", nor the methods of its calculation in estimating the energy demand of buildings. Therefore, it is necessary to instruct a clear definition of this concept and develop methodologies for its correct definition.

2. Literature Analysis

Works [1-5] give very high values of the "cooling effect" of grass (up to 7 K). The cooling effect was determined as the temperature difference between green and non-greened surfaces. The temperature over the non-greened surface is determined in the sunny weather by its albedo, which varies widely. It depends on the color of the surface, the degree of its processing, the position of the sun, etc. Since the plants have a similar color, their albedo should change within narrower limits. Therefore, this definition of "cooling effect" takes into account, largely, the properties of an unheated surface that participates in a particular investigation. That is why different studies give significantly different rates. The correct definition of the "cooling effect" has to characterize the properties of the "green design" itself. There was no such definition in literary sources. There are also no methods for assessing the effect of the "cooling effect" on the energy efficiency of buildings.

An example of a dynamic mathematical simulation of the effect of green roofs on the energy efficiency of a building is the work of Tiana Rakotondramiarana with colleagues [6], which was performed in Madagascar in Antananarivo. Madagascar is located in the tropical zone where the climate is warm and humid. In Antananarivo, there is a period of rains (from October 15 to April 15); therefore, the weather is cooler and more rainy. As a result, energy consumption for heating the building is much more than cooling. The authors first showed the relationship between the green roof and the building and analyzed the efficiency of the green roof using the weather conditions of the city of Antananarivo. In order to determine the most influential parameters for energy requirements in premises under a green roof, the general sensitivity analysis is proposed for the mathematical model without taking into account specific weather data. The model considers the green roof as a system consisting of four elements: green layer, soil, drainage layer and supporting structure. It is compared to the usual roof of the bearing structures. The basis of the thermal balance of the walls is the Fourier-Kirchhoff equation. The mathematical model is formed using the following assumptions:

1. Layers are in good contact. Therefore, contact resistance is not taken into account.
2. Thermal sources are absent.
3. The change in the thermophysical properties of structures is not taken into account.
4. The thickness of multilayer elements is small compared to other sizes. Therefore, one-dimensional distribution of the temperature in these designs is adopted.

In these assumptions, the model is reduced to a system of equations, which allows determining in time the changes in the temperature of indoor air inside the building. The system of equations includes the equation of the thermal balance of the air volume in the room, as well as the heat transfer of the internal and external surfaces of each wall.

To compare the thermal efficiency of green roofs, the months of June and March are chosen as typical for usual winter and summer climatic conditions, because only sensible heat (chaotic motion of molecules) was taken into account. The hidden heat of vaporization is neglected. In winter, the day with the minimum temperature (July 25th) and the day with maximum solar radiation (July 20th) were accepted for calculations. For summer period, the day with the maximum temperature (March 16) is accepted. The temperature (θ_{ext}) of the external air, relative humidity (φ_r), wind speed (v), direct and diffused solar radiation (R_{dirh}, R_{difh}), and the temperature of the slope (θ_{sky}) for the city of Antananarivo are the source weather data for the model. The internal air temperature during heating is 19 °C for the cold period. For the warm period, two cases are presented for calculating the need for cold: without cooling and with cooling, in which the temperature of the internal air is 28 °C. In both cases, the roofs are compared by the following parameters: the temperature of the upper surface of the bearing structure of the roof (θ_{st}), the temperature of the internal air (θ_{in}), the need for energy. Analyzing the results of the simulation, the authors show the temperature change on the upper surface of the bearing structure for unheated (θ_{st} *) and green (θ_{st}) roofs during the three typical days in Antananarivo (Fig. 1).

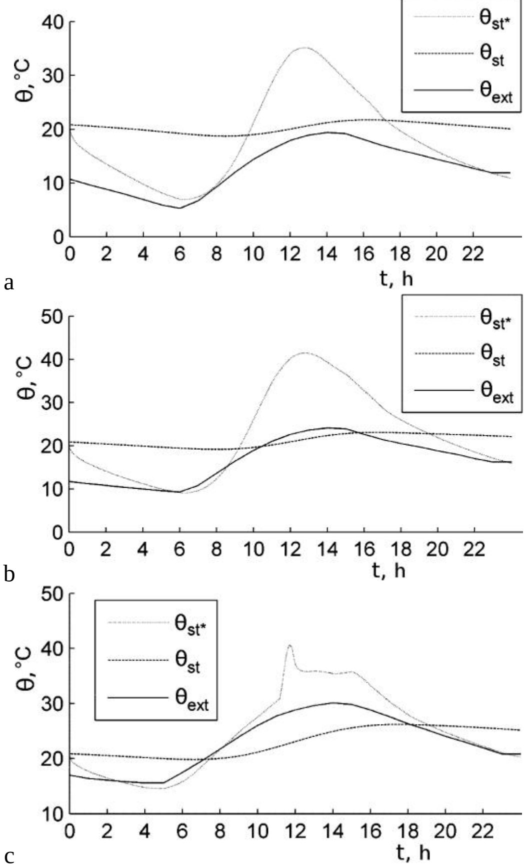


Fig. 1: Temperature changing on the upper surface of the bearing structure of unheated (θ_{st}*) and greened roofs (θ_{st}) during the three typical days in Antananarivo: a – cold winter; b – sunny winter; and c – hot summer.

The temperature range of the green roof (θ_{st}) is narrower. In fig. 1c (hot summer) for unknown reasons at 11.30 there is a burst of temperature up to 40 °C. Physical explanation for it is impossible to find, because it means the absence of thermal inertia: in 15 minutes, cooling is performed by 5 °C. Therefore, it is possible that there are errors in the program.

In the final conclusions, the authors point out that green roofs have a significant impact in buildings without thermal insulation. At the same time, they are best suited for energy saving and thermal comfort during the summer and winter days. The ranges of temperature of the upper surface of the supporting structure of the roof are reduced by 28 °C in the climatic conditions of Antananarivo using green roofs. The choice of plants with a high value of the planting index (LAI) and the percentage of landscaping (σ_f) greatly improves the thermal comfort and energy efficiency of the building during the summer. Adding a moderate amount of substrate thickness can help reduce energy demand. No specific weather data was taken into account during the analysis of the general sensitivity of the proposed model of buildings with a green roof. In insulated buildings, the green roof has a slight thermal effect.

Thus, the authors ranked the factors of influence as follows: σ_f - the percentage of landscaping, L_g - the thickness of the substrate, S_c - the coefficient of shading of translucent constructions, *LAI* - planting index, L_{can} - the thickness of the plant layer. These factors are more significant than weather conditions, such as diffused solar radiation (R_{difh}), outside air temperature (θ_{ext}) and wind speed (v).

We do not quite agree with the conclusions of the authors, because we believe that the influence of climatic factors is of great importance. For example, the wind speed affects the transpiration and "cooling effect", which is confirmed by our experiments. In addition, it is controversial to conclude insignificant influence of green roofs on insulated buildings. Most likely, this conclusion is associated with hot climatic conditions. As will be shown further in our experiments, we obtained a "cooling effect" at 1...3 °C. In our conditions, the proportion of the "cooling effect" in the temperature difference between the external and internal air θ_{ext} - θ_{in} is significant.

In previous works [7], the author proposed a new definition of the cooling effect of plants as the difference between the ambient air and the lower level of the vegetation layer (in the absence of heating or cooling from the soil or substrate) [°C]

$$\Delta\theta = \theta_{ext} - \theta_{veg}. \tag{1}$$

This definition characterizes only the properties of the plant layer, and it is recommended for general usage.

3. "Cooling effect" of Vegetation Layer

In the work [7], the author presented a technique for studying the "cooling effect" in laboratory conditions in a wind tunnel. According to the results of the research, a graph of the "cooling effect" dependence $\Delta\theta$ [°C], on the air velocity v [m/s] (Fig. 2) was constructed.

However, in order to calculate the energy loss from the "cooling effect", the results should be presented as a formula. The regression of the obtained results using the least squares method for grass height of 40 and 123 mm gives the following equation [°C]:

$$\Delta\theta = \left(0.508\,\mathrm{atan}\left(v\right) + 0.543\right)\mathrm{atan}^2\left(v\right) + 0.752. \tag{2}$$

Thus, to determine the "cooling effect" it is necessary to know the average wind speed around the structure. It depends on the height of the building and, for "green roofs", the design of the parapet. In this work, we will take the normative wind speed for the corresponding city for heat loss calculations of buildings.

In the presence of a deaf parapet, this speed will be smaller and should be determined by simulating the winding of the building [8]. By the Fig. 2 and equation (2) it is possible to suggest the following recommendations. For essential evaporative cooling in the warm period (cooling period), the effect of wind is required.

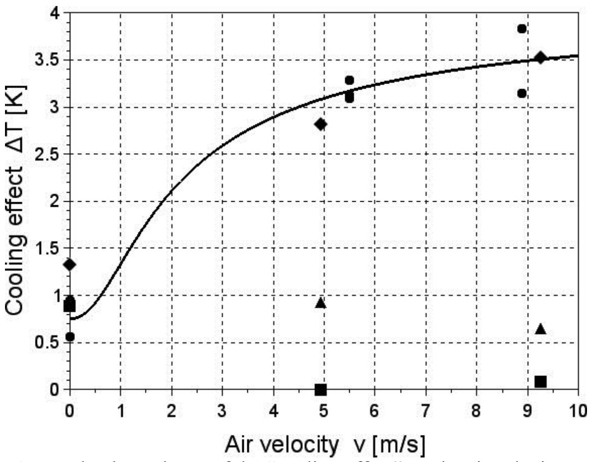


Fig. 2: The dependence of the "cooling effect" on the air velocity:
● - grass height 40 and 123 mm, different points;
▲ - grass height 399 mm, around the center of the model;
■ - the height of the grass is 399 mm, the angle with the windward side;
♦ - the height of the grass is 399 mm, the angle from the winding.

It is recommended to blow up the roof as much as possible for plants (to install perforated pallets). The simulation can be performed using simplified simulation of turbulent flows [9-11]. In the cold period, in order to reduce the transpiration and heat transfer coefficient, on the contrary, it is recommended to install a blind parapet. The most convenient way to achieve this is to use a regulated parapet (Fig. 3).

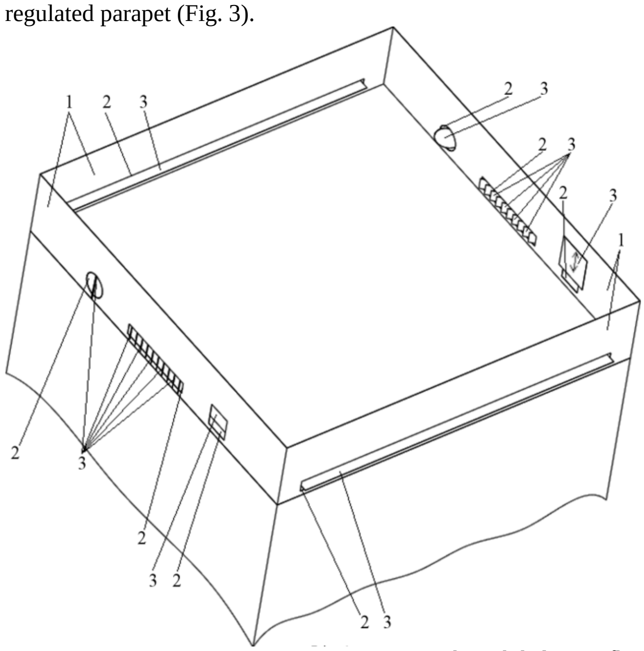


Fig. 3: Parapet of green roof. General view: 1 – wall, 2 – through-holes, 3 - flow rate and/or flow direction control.

The green roof parapet consists of a wall 1 with through-holes 2, at least some of which are equipped with flow rate and/or flow direction controls 3.
The placement of adjustable through-holes on the parapet of the green roof allows airflow control, which, in turn, makes possible the cooling effect and the air exchange control of the plants on the roof.
From Fig. 2 it is seen that the growth of grass up to 400 mm leads to a sharp decrease in the "cooling effect". This is a useful phenomenon for the transitional period when the building does not need cooling. In warm period of year, the grass should be mowed. Height of the grass should be no more than 120 ... 130 mm. Before the onset of the transition period, mowing should be stopped to let the grass growing up to the maximum possible size. This will worsen the venting conditions of the grass layer and minimize the "cooling effect". In future, we will assume that these recommendations are fulfilled in the warm period of the year and equation (2) is correct. Otherwise, the value of the "cooling effect" will be 0.7 ... 0.9 °C.

4. Methodology of Calculation the Reduction of CO_2 Emission on the Example of Kyiv

After that, we evaluated the reduction of CO_2 emissions by green roofs due to the "cooling effect" during the cooling period by the method of V. Bilousova [12].
Thermal resistance R [m^2 K/W] is taken from 0 to 10. The heat transfer coefficient is $U = 1/R$ (W/ (m^2□K)) [13, 14]. Air conditioners with an average refrigeration coefficient ε = 4 are considered. The average power output at combustion of fuel is taken η_{el} = 0,3. Two types of fuel are considered: coal and gas with heat of combustion Q_i^r = 17,62 MJ/kg and Q_i^r = 34,78 MJ/kg, respectively. The CO_2 emission factor k_C [kg C/GJ], is 25.58 and 15.04, respectively [12]. The degree of total oxidation of carbon to CO_2 k_{CO2} = 3.67 kg CO_2 / (kg C) [12]. The average length of the warm period of the year is N = 120 days. For each wind direction, the wind speed v [m/s] and its repeatability r_i [%] are taken by [15] without taking into account calm. Using the fair of the calm r_0 [%], the repeatability of each direction of the wind should be reduced [%]:

$$R_i = r_i\left(1 - 0.01 r_0\right) . \tag{3}$$

"Cooling effect" is determined by the formula (2). Saving [10] the cold [W/m^2] at each wind direction i [J/m^2]

$$\Delta\Phi_i = U\Delta\theta_i . \tag{4}$$

where $\Delta\theta_i$ – cooling effect [°C] by the equation (2) for the wind speed at i-th wind direction. Cold saving for July [J/m^2],

$$Q_i = 3600 \cdot 24 \cdot 31 \cdot \left(\frac{R_i}{100}\right) \cdot \Delta\Phi_i . \tag{5}$$

The values obtained for this formula are added for each direction of the wind. All further calculations are made on the received sum

$$Q = \Sigma Q_i . \tag{6}$$

Reduction of compressor work [16] in chiller per square meter of a green roof [J/m^2]

$$\Delta A = \Delta Q / \varepsilon . \tag{7}$$

Savings of thermal energy and fuel per square meter of a green roof

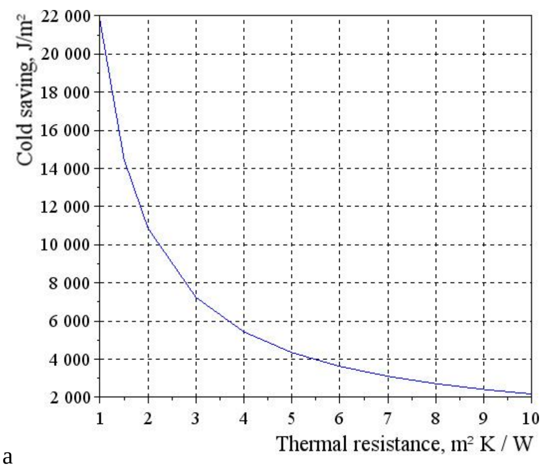
$$\Delta Q_f = \Delta A / \eta_{el} \text{ [J/m}^2\text{]}; \tag{8}$$

$$\Delta B = 10^{-6} \Delta Q_f / Q_i^r \text{ [kg/m}^2\text{]}. \tag{9}$$

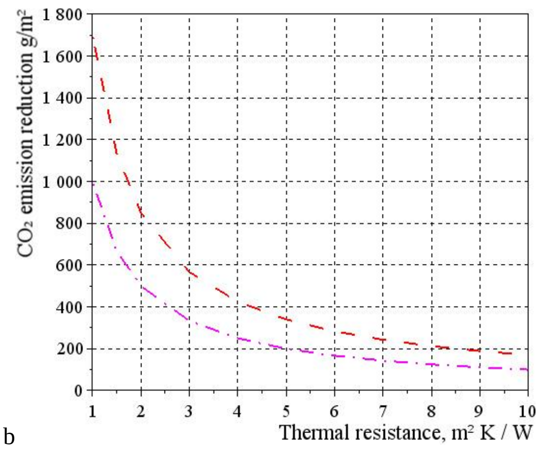
Reduction of CO_2 emissions [16] per square meter of a green roof [g CO_2/m^2]

$$\Delta M_{CO2} = \Delta B Q_i^r k_C k_{CO2} . \tag{10}$$

The savings of the cold and the work of the compressor are converted to the cooling period by multiplying by the number of days of the period and dividing by 31. The results of calculations by the equations (1-10) are shown in Fig. 4.



a



b

Fig. 4: The influence of "cooling effect" of plants of the green roof per its square meter: a – saving of cold; b – CO_2 emission reduction: red dashed curve – coal, purple dash-dotted curve – gas.

The results (Fig. 4) show the decrease of the passive cooling effect from green roofs with increasing of thermal insulation. However, this effect remains significant, unlike data [6]. According to DBN V.2.6-31: 2016 [14], the thermal resistance of a combined roof is 6 m^2·K/W. This reduces emissions (fig. 4) during the warm period of the year per 170 g/m^2 (for gas) or 240 g/m^2 (for coal). It should be taken into account that these values correspond to the reduction of CO_2 emissions only by the **"**cooling effect**"** due to the evapotranspiration. Comparing a building with a green roof and a building with a bituminous coating, which absorbs solar energy, gives orders of magnitude stronger effect. It should be calculated taking into account the heat from solar radiation through the roof using standard techniques. In addition, using this method, we can calculate the CO_2 savings for facade landscaping. According to DBN V.2.6-31:2016 [14] the thermal resistance of the walls is 3.3 m^2·K/W. This saves 130 g/m^2 (for gas) or 520 g/m^2 (for coal) CO_2 (fig. 4) per square meter of the wall during the warm period.

If a green roof covers the last floor with living or working rooms, maximum increasing of energy efficiency can be achieved by matching the placement of greened and ungreened parts with the rooms (fig. 5). In premises with increased needs in heat and cold, heat losses and heat transfer through a combined roof are reduced due to the thermal resistance of the grass layer.

In the warm period of year, there is passive cooling of the outer surface due to the evapotranspiration. In auxiliary rooms with less need for heat and cold, this effect is not present, but the total energy requirement will be less than in the uncoordinated arrangement of green areas.

By matching the placement of greened and ungreened parts with rooms under the roof, it is possible to reduce the heat load on the heating and cooling load of air conditioning.

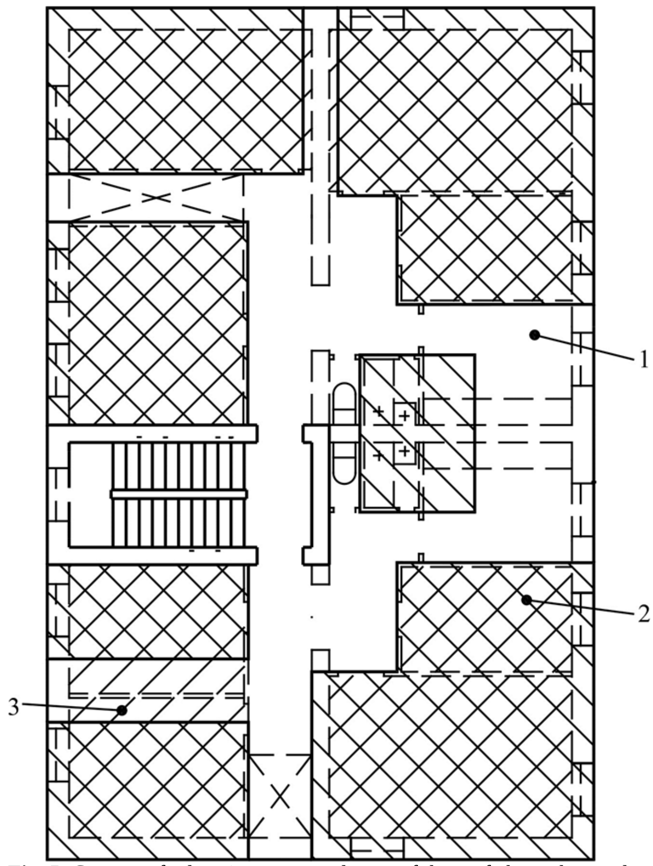


Fig. 5: Green roof, plan: 1 – ungreened parts of the roof above the auxiliary rooms; 2 – greened parts of the roof above the premises with higher microclimate requirements.

5. Conclusion

A new approach to the understanding and definition of "cooling effect" is proposed, which allows to ensure greater correctness of the obtained results. The existing definition involves comparing the temperature on the green and ungreened roof, which takes into account the light absorbing properties of the ungreened roof, that are variable and have no relation to green roofs. It is proposed to determine the "cooling effect" as the difference between the temperature between the environment and the bottom of the vegetation layer without heating and cooling from the bottom, which is the property of the green roof alone.

By approximation of the author's experimental data, the equation has been obtained for the cooling effect of the living grass layer of the green roof. The "cooling effect" of the green roof increases with increasing of wind speed, since it increases the evapotranspiration.

The proposed requirements for a parapet on green roofs allow maximizing energy efficiency. This demands maximum perforation of the parapet during the warm period and the maximum tightness of the parapet during the cold period.

It is proposed to coordinate the placement of greened and ungreened parts of the green roof with rooms under the roof, which allows reducing the heat load on the heating and refrigeration load on air conditioning.

The proposed methodology for estimating CO_2 emissions reduction by green structures (green roof and facade landscaping) due to the "cooling effect" during the cooling period allows calculation of the CO_2 savings in warm periods of the year. For Kyiv, the reduction of CO_2 emissions per square meter of a green roof during the warm period of the year is 170 g/m^2 (for gas) or 240 g/m^2 (for coal). The reduction of CO_2 emissions per square meter of a green wall during the warm period of the year is 130 g/m^2 (for gas) or 520 g/m^2 (for coal).

It is established that the energy savings of a green roof depends on the thickness of the insulation of buildings: the thicker insulation causes the less green roof contribution to energy savings. Green roofs can be especially effective when switching from gas to local solid fuels: peat waste, pellets, etc.
The practical recommendations for growing and care of the lawn on green roofs are obtained as a result of the research and allow us to make the most of the thermotechnical properties of the plant layer. In warm period of year, the grass should be mowed to increase the "cooling effect". Before the autumn period, which is characterized by significant winds, mowing of the grass is not recommended to reduce the "cooling effect" and enhance the thermal insulation properties. On the vertical greening, the assortment of plants should be selected to avoid a dense layer and to ensure its insufflation.

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