Tetiana TKACHENKO[1]✉ iD
Anna LIS[2] iD
Yurii TSIURIUPA[1] iD
Viktor MILEIKOVSKYI[1] iD
Adam UJMA[3] iD
Oleksii TKACHENKO[4] iD
Viktoriia SAKHNOVSKA[1] iD

[1] Kyiv National University of Construction and Architecture, Faculty of Engineering Systems
  and Ecology, Ukraine
[2] Czestochowa University of Technology, Building Faculty, Poland
[3] University of Applied Sciences in Nysa, Faculty of Technical Sciences, Poland
[4] Kyiv National University of Construction and Architecture, Faculty of Architecture, Ukraine

Planning of green roofs for the best thermotechnical effect

Introduction

The energy-efficient provision of indoor comfort for buildings is one of the most important requirements for modern construction. It can be achieved in two main ways: energy-efficient engineering systems and using natural measures such as the greening of buildings.

The last group of measures provides more opportunities. The experience in using these measures is significant, starting from sod roofs, invented in prehistory

✉tkachenkoknuba@gmail.com

(Berg, 1989). Despite this, the most limiting factor is the lack of systematic research on the positive effects.

Most of the energy-efficient engineering solutions consist of the optimally orientating buildings (Zhelykh et al., 2020), increasing the air-tightness (Corcoran & Duffy, 2019; Kuhnhenne et al., 2020) and the thermal resistance (Brunoro, 2024; Štastný et al., 2024) of the building envelopment; effective heating systems (Cholewa et al., 2018; Voznyak et al., 2021), etc.; optimizing ventilation strategies (Gładyszewska-Fiedoruk et al., 2019; Brunoro, 2024); effective inlet air treatment (Alsayah et al., 2024; Bari et al., 2024); optimizing air exchange organization (Voznyak et al., 2019; Voznyak et al., 2022); optimizing air volume control (Kim & Cho, 2022; Nassif, 2022); solar radiation protection (Muñoz-Viveros, 2022); and using renewable energy (Zhelykh et al., 2016; Shapoval et al., 2019a; Shapoval et al., 2019b; Shapoval et al., 2021; Venhryn et al., 2021; Voznyak et al., 2023). These measures are single-task solutions, which can only decrease the energy demands.

In contrast, increasing amounts of research is being devoted to all-in-one measures, such as green structures as a combination of living pants and building structures. They are solving different tasks simultaneously, including decreasing energy demands (Gioannini et al., 2018; Rey et al., 2020) and mitigating the urban heat island effect (Fallmann et al., 2014; Luthfiyyah & Widjajanti, 2019), heat insulation, and cooling effect through evaporative cooling caused by evapotranspiration; increasing the roof durability (Gioannini et al., 2018); cleaning pollution from the air (Chen et al., 2020); oxygenating the air by photosynthesis (Zhang et al., 2021); suppressing noise (Gioannini et al., 2018); effectively managing and treating rainwater (Chen et al., 2018; Zeng et al., 2019); supporting biodiversity, including pollinators (Gill et al., 2020); creating a close-to-natural aesthetic (Gioannini et al., 2018) environment, which provides mental health, calming (Nwankwo et al., 2022), eco-regulation and passive rehabilitation; inducing passive environmental education (Gioannini et al., 2018); and increasing the areas for recreation and business, including urban agriculture (Qiu et al., 2013).

Most of the works above are more qualitative than quantitative. Some of them are case studies, and the results cannot be applied broadly in most cases. Thus, optimizing such green structures is a problem requiring additional research.

In contrast to the above-mentioned works, there is a complex of multidisciplinary, quantitative and qualitative, laboratory and field research on the thermotechnical properties of grass layers revealing a significant cooling effect up

to 4 K (Tkachenko & Mileikovskyi, 2018a; Tkachenko & Mileikovskyi, 2020a); solar protection (Tkachenko & Mileikovskyi, 2018b; Tkachenko & Mileikovskyi, 2020b); rainwater management (Hlushchenko et al., 2022; Tkachenko et al., 2023b; Kravchenko et al., 2024; Tkachenko et al., 2024a); rainwater cleaning (Kravchenko et al., 2024); carbon dioxide sequestration (Tkachenko et al., 2019; Tkachenko & Mileikovskyi, 2022); air cleaning (Tkachenko et al., 2019); reparation of histor-ical places with out-of-context building (Tkachenko et al., 2024); and biodiversity (Tkachenko et al., 2023a).

Extensive green roofs that do not provide access for people usually cover the roof surface with grass and small shrubs, providing thermotechnical effects to the whole roof surface. Semi-intensive green roofs have paths for the people, which are usually covered by some pavement, which absorbs solar radiation and converts it to heat. If the roof is combined with the ceiling, the heat will pass to it and load the air-conditioning systems. The proposed solution for such roofs is to build these paths over the auxiliary premises, such as corridors, storage rooms, wardrobes, etc., which have low microclimate requirements.

This recommendation has been proposed without calculations based only on the presence of the effect. Thus, this should also be checked.

The work aims to estimate the heat distribution in green roofs with paths to ground the recommendations for planning green roofs for the maximum thermotechnical effect. The research object is green roofs combined with ceilings as the effective biotechnology of joining the building structures and living plants. The research subject is the heat transfer process inside green roofs combined with the ceiling.

Material and methods

To show the specifics of the heat transfer, we built a 3D model of a semi-intensive green roof fragment combined with a ceiling of a room, coated at the top by the ZinCo Perennial Garden system (ZinCo USA, Inc., n.d. a) and a ZinCo Hard Landscape system (ZinCo USA, Inc., n.d. b) path (Fig. 1, Table 1). We ignore very thin layers, such as the root barrier and the system filter, which cannot influence the heat transfer. The thermotechnical properties of most of the layers have not yet been researched. Thus, we will apply analogical materials according to Table 1.
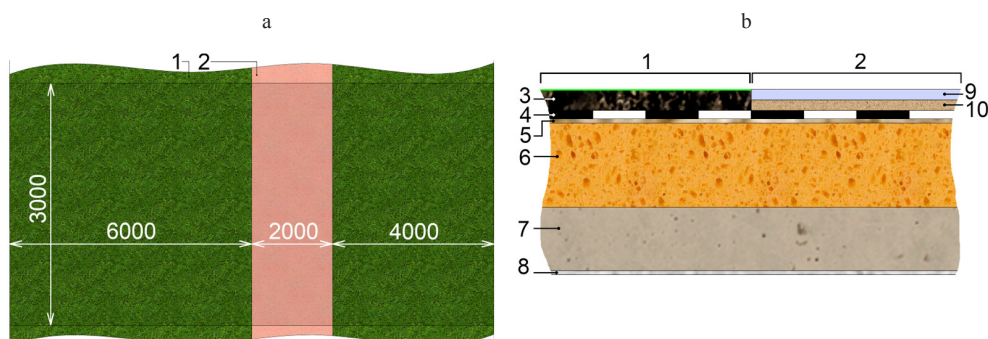
FIGURE 1. A semi-intensive green roof: a – top view, b – section; 1 – green part, 2 – path, 3 – substratum, 4 – drainage, 5 – protection layer, 6 – insulation, 7 – slab, 8 – plaster, 9 – pavement, 10 – bedding (see Table 1); the computational domain in Figure 1a is darkened

Source: own work.

Paths on green roofs are the heat-conductive inclusions. Such nodes cannot be analytically calculated. They should be simulated using the Fourier–Kirchhoff equation (Hojny et al., 2023). The simulation is performed using the finite element method:

$$\frac{c\rho\partial\theta}{\partial t} = \nabla^T\left(\lambda\nabla\theta\right)\Phi_V \text{ [W]},\tag{1}$$

where: c – specific heat [J·kg^{-1}·K^{-1}], ρ – density [kg·m^{-3}], θ – temperature [K], t – time [s], a – thermal diffusivity [m^2·s^{-1}], ∇^T – thermal gradient, Φ_V – power of internal heat sources per volume [W·m^{-3}].

TABLE 1. Layers

Position in Fig. 1	Layer	Material or analogue	Density (ρ) [kg·m^{-3}]	Specific heat (c) [J·kg^{-1}·K^{-1}]	Thermal conductance (λ) [W·m^{-1}·K^{-1}]	Thickness (δ) [mm]
3	substratum	claydite[a]	300	972	0.13	100
4	drainage	polycarbonate 40[a]	102.5	1 010	0.072	40
5	protection	synthetic carpet[a]	160	2 500	0.06	20
6	insulation	polystyrene	1 050	1 800	0.14	400
7	slab	cast concrete	2 000	1 000	1.13	300
8	plaster	lightweight plaster	600	1 000	0.16	20
9	pavement	cast concrete[a]	2 000	1 000	1.13	50
10	bedding	gravel[a]	1 840	840	0.36	50

[a]Analogue.

Source: own work based on Fareniuk et al. (2014); ZinCo USA, Inc. (n.d. a); ZinCo USA, Inc. (n.d. b).

The precision of Equation (1) corresponds to the precision of the thermophysical properties of the materials and boundary conditions. The main assumptions and boundary conditions are the following. There is no contact thermal resistance between materials. Air conditioning in the room below the roof maintains constant temperature θ_{IDA} equal to 298.15 K. The ceiling surface transfers heat with constant heat transfer coefficient α equal to 8.7 W·m^{-1}·K^{-1} (Hojny et al., 2023):

$$\Phi_A = \alpha(\theta_{ceil} - \theta_{IDA}) \ [\text{W·m}^{-2}], \qquad (2)$$

where: Φ_A – thermal flow density from the ceiling to the indoor air [W·m^{-2}], α – heat transfer coefficient [W·m^{-1}·K^{-1}], θ_{ceil} – ceiling surface temperature [K], and θ_{IDA} – ceiling surface temperature [K].

The path surface absorbs the convective heat (or transfers if negative) with constant heat transfer coefficient α equal to 23 W·m^{-1}·K^{-1} (Hojny et al., 2023):

$$\Phi_A = \alpha(\theta_{ODA} - \theta_{path}) \ [\text{W·m}^{-2}], \qquad (3)$$

where: θ_{ODA} – outdoor temperature [K], and θ_{path} – path surface temperature [K].

The path surface also absorbs solar radiation with a constant absorbance of 0.5. The solar radiation is calculated for the corresponding date and time moment. The surface under the grass has a temperature (Tkachenko & Mileikovskyi, 2020a):

$$\theta_{grass} = \theta_{ODA} - \Delta\theta \ [\text{K}], \qquad (4)$$

where: θ_{grass} – surface temperature under the grass [K], and $\Delta\theta$ – cooling effect of the grass;

$$\Delta\theta = (0.508 \ \text{atan}(v) + 0.543) \ \text{atan}^2(v) + 0.752 \ [\text{K}], \qquad (5)$$

where: v – wind speed [m·s^{-1}];

The regime of the heat conduction is quasi-periodical: the outdoor temperature change during each day is to be assumed as the same by repeating the weather data of a representative day until the temperature field change on the ceiling on the final day repeats the previous one with a maximum deviation less than 0.2 K.

The sun's movement will produce a temperature change on the outer surface of the paths, causing a thermal wave. It will attenuate in the structure's layers due to thermal inertia and cause some heat trace on the ceiling below.

Results and discussion

The simulation results were performed for two days: a warm day on July 11, 2024, and August 11, 2024, with moderate temperatures (Fig. 2). On both days, the path gives a trace of higher heat transfer on the ceiling (Fig. 3). Due to the thermal capacity of the concrete slab, the trace does not change from night to day.
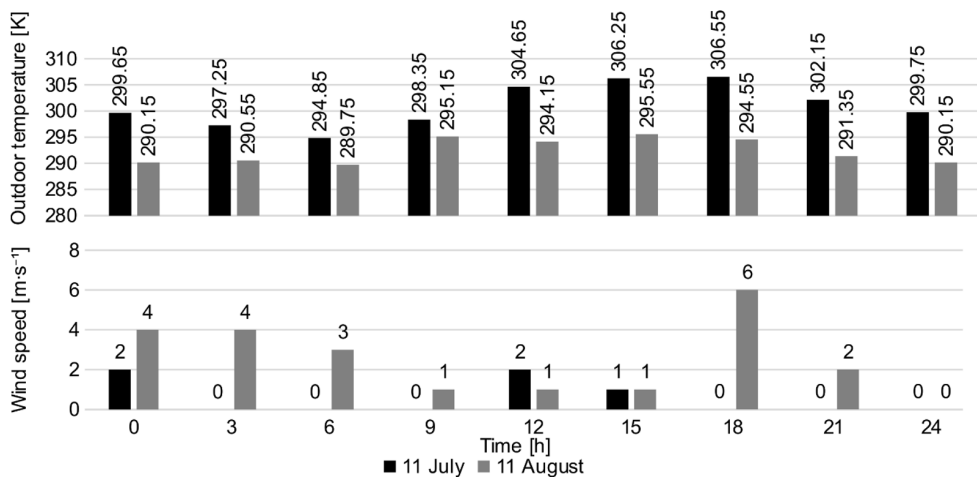

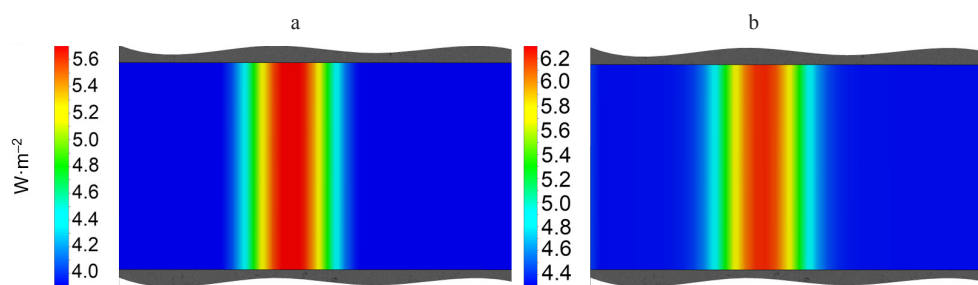FIGURE 2. Weather conditions

Source: own work.

FIGURE 3. Results of simulation of heat flow density across the whole day: a – with a moderate temperature (August 11, 2024); b – warm (July 11, 2024)

Source: own work.

The heat transfer difference is 2 W·m^{-2} for the warm day and 1.8 W·m^{-2} for the moderate temperatures. This value is not very big, but is significant. For a living room of 6 × 3 m, the heat gain is 32–36 W, which is comparable

to LED illumination (up to 32 W). Thus, avoiding these unnecessary heat gains should improve the energy efficiency of air-conditioning.

Let us consider the recommendation to align, if possible, the traditional paths with the auxiliary premises such as corridors or pantries. If these rooms have no external walls, the heat gained will be distributed to other air-conditioned rooms with some lag due to thermal inertia. If this lag continues after the end of the hot period, some energy demand decrease will appear. But in a steady state, it will be minimal.

For auxiliary rooms with external walls, some heat will be dissipated. If the additional heat gains $\Delta\Phi$ [W] appears, the temperature of the auxiliary room will slightly rise by $\Delta\theta$ [K]. If the hot period is long enough to achieve near-to-steady heat transfer, this heat will be distributed to other rooms and the environment through indoor and outdoor enclosures with a U-factor of U_i [W·m^{-1}·K^{-1}] and area A_i [m^2]. The portion and total will be, respectively:

$$\Delta\Phi_i = U_i A_i \Delta\theta \ [\text{W}]; \tag{6}$$

$$\Sigma\Delta\Phi_i = \Delta\Phi \ [\text{W}]. \tag{7}$$

From Equations (6) and (7):

$$\Delta\Phi_i = \frac{\Delta\Phi U_i A_i}{\sum\left(U_i A_i\right)} \ [\text{W}]. \tag{8}$$

Thus, in steady-state mode, the dissipated part of the heat gain through external wall number i equals 0:

$$\frac{\Delta\Phi_0}{\Delta\Phi} = \frac{U_0 A_0}{\sum\left(U_i A_i\right)} \ [\text{W}]. \tag{9}$$

In energy-efficient buildings, $U_0 \ll U_j, j \neq 0$, and in most buildings, $A_0 < \Sigma A_i$. Thus, most heat will be kept in the building and will load the air conditioning. For example, a corridor of size $1.2 \times 3 \times 3$ m with one external wall 1.2×3 m with a U-factor of 0.2 W·m^{-1}·K^{-1} and internal walls with a U-factor of 2.7 W·m^{-1}·K^{-1} in a steady state will dissipate to the environment only 0.92% of the additional gains.

It is possible to conclude that aligning the roof paths half-measure, which can mitigate the additional consumption by thermal inertia. We should therefore find stronger measures.

There are alternative options, which can produce the maximum effect based on planting the paths: using plant-permit pavement analogous to eco-parking, makes it possible to plant on pathways, or barefoot-in-dew systems such as ZinCo Soft Landscape with a denser substrate. Walking on lawns is a common European trend, which promotes more natural conditions close to the wild nature. In addition to the thermotechnical effect of covering all surfaces with cooling plants, it soothes and supports rest, and the rainwater drainage and retention abilities will increase through activation of the whole area. For green roofs with a lightweight substratum, the "virtual" paths with a denser substratum should be definitively highlighted by a noticeable difference in the appearance of the grass.

In both cases, a special grass should be planted for walking: perennial ryegrass (*Lolium perenne*), red fescue (*Festuca rubra*), meadow fescue (*Lolium pratense*), bluegrass (*Poa pratensis*), or clovers (*Trifolium* sp.). We did not see such innovative "green path" solutions on available green roofs.

Another possibility is using pavements with maximum reflectivity (cool roof). This solution has a disadvantage: it requires regular cleaning because dust and dirt, which are common on paths, absorb solar radiation.

Conclusions

The literature review shows that there is not enough research on the positive effects of green roofs to make recommendations for aligning green roof design and space-planning solutions. The simulation of a semi-intensive green roof with the ceiling of the room below combined with a roof path shows that the path induces a trace of higher heat transfer on the ceiling. The difference in the density of the heat flow below the path and the grass is not huge but is still significant, as it varies in the range of 1.8–2.0 $W \cdot m^{-2}$. Calculations show that such alignment of the paths above the auxiliary premises is a half-measure that operates almost due to inertia and lags in heat flows. Better solutions, which are innovative for green roofs, allow planting on the paths – from plant-permit pavement analogous to eco-parking and barefoot-in-dew systems such as ZinCo Soft Landscape with a denser substrate. It is necessary to use grass that can be walked on – perennial ryegrass (*Lolium perenne*), red fescue (*Festuca rubra*), meadow fescue

(*Festuca pratensis*, *Lolium pratense*), bluegrass (*Poa pratensis*), or clovers (*Trifolium* sp.). In the future, the authors plan to simulate the influence of joints and other linear and point inclusions on the thermal performance.

Acknowledgements

References

Alsayah, A. M., Faraj, J. J., & Eidan, A. A. (2024). A review of recent studies of both heat pipe and evaporative cooling in passive heat recovery. *Open Engineering*, *14*(1), 1–18. https://doi.org/10.1515/eng-2024-0012

Bari, M. A., Münsch, M., Schöneberger, B., Schlagbauer, B., Tiu, A. A., & Wierschem, A. (2024). Heat recovery optimization of a shell and tube bundle heat exchanger with continuous helical baffles for air ventilation systems. *International Journal of Air-Conditioning and Refrigeration*, *32*(2), 1–16. https://doi.org/10.1007/s44189-023-00046-4

Berg, A. (1989). *Norske tømmerhus frå mellomalderen.* Vol. 1. Landbruksforlaget.

Brunoro, S. (2024). Passive envelope measures for improving energy efficiency in the energy retrofit of buildings in Italy. *Buildings*, *14*(7), 2128. https://doi.org/10.3390/buildings1407212

Chen, H., Ma, J., Wang, X., Xu, P., Zheng, S., & Zhao, Y. (2018). Effects of biochar and sludge on carbon storage of urban green roofs. *Forests*, *9*(7), 413. https://doi.org/10.3390/f9070413

Chen, Y., Zheng, B., & Hu, Y. (2020). Numerical simulation of local climate zone cooling achieved through modification of trees, albedo and green roofs – a case study of Changsha, China. *Sustainability*, *12*(7), 2752. https://doi.org/10.3390/su12072752

Cholewa, T., Balen, I., & Siuta-Olcha, A. (2018). On the influence of local and zonal hydraulic balancing of heating system on energy savings in existing buildings – Long term experimental research. *Energy and Buildings*, *179*, 156–164. https://doi.org/10.1016/j.enbuild.2018.09.009

Corcoran, L., & Duffy, A. (2019). Experimental field-trial design to investigate the effects of a defective internal vapour layer on timber frame wall constructions including initial findings. *MATEC Web of Conferences*, *282*, 02047. https://doi.org/10.1051/matecconf/201928202047

Fallmann, J., Emeis, S., & Suppan, P. (2014). Mitigation of urban heat stress – a modelling case study for the area of Stuttgart. *Journal of the Geographical Society of Berlin*, *144*(3–4), 202–216. https://doi.org/10.12854/erde-144-15

Fareniuk, H., Kolesnyk, E., Fareniuk, Ye., Pavliuk, P., Bilous, O., Prishchenko, A., & Tymofeiev, M. (2014). *Methods for choosing of insulation material for insulation of buildings* (DSTUB V.2.6-189:2013). Minrehion Ukrainy. https://eurobud.ua/wp-content/uploads/2022/08/dstu-b-v.2.6-189-2013-metody-vyboru-teploizolyacijnogo-materialu-dlya-uteplennya-budivel.pdf

Gill, A. S., Purnell, K., Palmer, M. I., Stein, J., & McGuire, K. L. (2020). Microbial composition and functional diversity differ across urban green infrastructure types. *Frontiers in Microbiology*, *11*, 912. https://doi.org/10.3389/fmicb.2020.00912

Gioannini, R., Al-Ajlouni, M., Kile, R., VanLeeuwen, D., & St. Hilaire, R. (2018). Plant communities suitable for green roofs in arid regions. *Sustainability*, *10*(6), 1755. https://doi.org/10.3390/su10061755

Gładyszewska-Fiedoruk, K., Zhelykh, V., & Pushchinskyi, A. (2019). Simulation and analysis of various ventilation systems given in an example in the same school of indoor air quality. *Energies*, *12*(15), 2845. https://doi.org/10.3390/en12152845

Hlushchenko, R., Tkachenko, T., Mileikovskyi, V., Kravets, V., & Tkachenko, O. (2022). "Green structures" for effective rainwater management on roads. *Production Engineering Archives*, *28*(4), 295–299. https://doi.org/10.30657/pea.2022.28.37

Hojny, M., Głowacki, M., Bała, P., Bednarczyk, W., & Zalecki, W. (2023). Multiscale model of heating-remelting-cooling in the Gleeble 3800 thermo-mechanical simulator system. *Archives of Metallurgy and Materials*, *64*(1), 401–412. https://doi.org/10.24425/amm.2019.126266

Kim, H., & Cho, Y. (2022). Optimization of supply air flow and temperature for VAV terminal unit by artificial neural network. *Case Studies in Thermal Engineering*, *40*, 102511. https://doi.org/10.1016/j.csite.2022.102511

Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T., & Mileikovskyi, V. (2024). Improving the efficiency and environmental friendliness of urban stormwater management by enhancing the water filtration model in rain gardens. *Water*, *16*(10), 1316. https://doi.org/10.3390/w16101316

Kuhnhenne, M., Reger, V., Pyschny, D., & Döring, B. (2020). Influence of airtightness of steel sandwich panel joints on heat losses. *E3S Web of Conferences*, *172*, 05008. https://doi.org/10.1051/e3sconf/202017205008

Luthfiyyah, D. N., & Widjajanti, R. (2019). Green Roof to Overcome Urban Heat Island Effects in the Center of Semarang. *E3S Web of Conferences*, *125*, 07018. https://doi.org/10.1051/e3sconf/201912507018

Muñoz-Viveros, C., Pérez-Fargallo, A., & Rubio-Bellido, C. (2022). Influence of the type of solar protection on thermal and light performance in classrooms. *Energy Reports*, *8*, 5329–5340. https://doi.org/10.1016/j.egyr.2022.04.007

Nassif, N., Tahmasebi, M., Ridwana, I., & Ebrahimi, P. (2022). New optimal supply air temperature and minimum zone air flow resetting strategies for VAV systems. *Buildings*, *12*(3), 348. https://doi.org/10.3390/buildings12030348

Nwankwo, M., Meng, Q., Yang, D., & Liu, F. (2022). Effects of forest on birdsong and human acoustic perception in urban parks: a case study in Nigeria. *Forests*, *13*(7), 994. https://doi.org/10.3390/f13070994

Qiu, G., Li, H., Zhang, Q., Chen, W., Liang, X., & Li, X. (2013). Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. *Journal of Integrative Agriculture*, *12*(8), 1307–1315. https://doi.org/10.1016/s2095-3119(13)60543-2

Rey, C. V., Franco, N., Peyre, G., & Rodríguez, J. P. (2020). Green roof design with engineered extensive substrates and native species to evaluate stormwater runoff and plant establishment in a neotropical mountain climate. *Sustainability*, *12*(16), 6534. https://doi.org/10.3390/su12166534

Shapoval, S., Spodyniuk, N., Zhelykh, V., Shepitchak, V., & Shapoval, P. (2021). Application of rooftop solar panels with coolant natural circulation. *Pollack Periodica*, *16*(1), 132–137. https://doi.org/10.1556/606.2020.00218

Shapoval, S., Zhelykh, V., Venhryn, I., & Kozak, K. (2019a). Simulation of thermal processes in the solar collector which is combined with external fence of an energy efficient house. *Lecture Notes in Civil Engineering*, *47*, 510–517. https://doi.org/10.1007/978-3-030-27011-7_65

Shapoval, S., Zhelykh, V., Venhryn, I., Kozak, K., & Krygul, R. (2019b). Theoretical and experimental analysis of solar enclosure as part of energy-efficient house. *Eastern-European Journal of Enterprise Technologies*, *2*(8), 38–45. https://doi.org/10.15587/1729-4061.2019.160882

Štastný, P., Antošová, N., Kalús, D., & Mučková, V. (2024). The importance of using active thermal protection following restoration work on old buildings. *Acta Polytechnica*, *64*(2), 118–127. https://doi.org/10.14311/ap.2024.64.0118

Tkachenko, T., Kravchenko, M., Voloshkina, O., Mileikovskyi, V., Tkachenko, O., & Sipakov, R. (2024a). Evaluating rain-garden bands: filtration properties and implications for urban water management. *World Environmental and Water Resources Congress*, *2024*, 960–968. https://doi.org/10.1061/9780784485477.085

Tkachenko, T., & Mileikovskyi, V. (2018a). Energy efficiency of "Green structures" in cooling period. *International Journal of Engineering & Technology*, *7*(3.2), 453–457. https://doi.org/10.14419/ijet.v7i3.2.14570

Tkachenko, T., & Mileikovskyi, V. (2018b). Geometric basis of the use of "Green constructions" for sun protection of glazing. *Advances in Intelligent Systems and Computing*, *809*, 1096–1107. https://doi.org/10.1007/978-3-319-95588-9_94

Tkachenko, T., & Mileikovskyi, V. (2020a). Methodology of thermal resistance and cooling effect testing of green roofs. *Songklanakarin Journal of Science and Technology (SJST)*, *42*(1), 50–56. https://doi.org/10.14456/sjst-psu.2020.8

Tkachenko, T., & Mileikovskyi, V. (2020b). Assessment of light transmission for comfort and energy efficient insolation by "Green Structures." *Advances in Intelligent Systems and Computing*, *1296*, 139–151. https://doi.org/10.1007/978-3-030-63403-2_13

Tkachenko, T., & Mileikovskyi, V. (2022). Capturing carbon dioxide from human-driven vehicles by green structures for carbon neutrality. *IOP Conference Series Earth and Environmental Science*, *1111*(1), 012056. https://doi.org/10.1088/1755-1315/1111/1/012056

Tkachenko, T., Mileikovskyi, V., Kravchenko, M., & Konovaliuk, V. (2023a). Simulation of illumination and wind conditions for green and fed cities using CFD software. *IOP Conference Series Earth and Environmental Science*, *1275*(1), 012014. https://doi.org/10.1088/1755-1315/1275/1/012014

Tkachenko, T., Lis, A., Tsiuriupa, Y., Mileikovskyi, V., Ujma, A., Tkachenko, O., Sakhnovska,V. (2025). Planning of green roofs for the best thermotechnical effect. *Sci. Rev. Eng. Env. Sci.*, *34* (1), 42–54. DOI 10.22630/srees.9954

53

Tkachenko, T., Mileikovskyi, V., & Ujma, A. (2019). Field study of air quality improvement by a "Green Roof" in Kyiv. *System Safety Human – Technical Facility – Environment*, *1*(1), 419–424. https://doi.org/10.2478/czoto-2019-0054

Tkachenko, T., Mileikovskyi, V., Ujma, A., & Hajiyev, M. (2024b). Treatment of out-of-context buildings during the restoration of historical territories using green structures. *International Journal of Conservation Science*, *15*(SI), 129–140. https://doi.org/10.36868/ijcs.2024.si.11

Tkachenko, T., Voloshkina, O., Mileikovskyi, V., Sipakov, R., Hlushchenko, R., & Tkachenko, O. (2023b). Using rain-garden bands for rainwater drainage from roads. *IOP Conference Series: Earth and Environmental Science*, *1254*, 1207–1214. https://doi.org/10.1061/9780784484852.110

Venhryn, I., Shapoval, S., Voznyak, O., Datsko, O., & Gulai, B. (2021). *Modelling of optical characteristics of the Thermal Photovoltaic Hybrid Solar Collector. 2021 IEEE 16th International Conference on Computer Sciences and Information Technologies (CSIT),* Lviv, Ukraine. https://doi.org/10.1109/csit52700.2021.9648738

Voznyak, O., Savchenko, O., Spodyniuk, N., Sukholova, I., Kasynets, M., & Dovbush, O. (2022). Improving of ventilation efficiency at air distribution by the swirled air jets. *Pollack Periodica*, *17*(1), 123–127. https://doi.org/10.1556/606.2021.00419

Voznyak, O., Spodyniuk, N., Antypov, I., Dudkiewicz, E., Kasynets, M., Savchenko, O., & Tarasenko, S. (2023). Efficiency improvement of Eco-Friendly solar heat supply system as a building coating. *Sustainability*, *15*(3), 2831. https://doi.org/10.3390/su15032831

Voznyak, O., Spodyniuk, N., Savchenko, O., Sukholova, I., & Kasynets, M. (2021). Enhancing energetic and economic efficiency of heating coal mines by infrared heaters. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *2*, 104–109. https://doi.org/10.33271/nvngu/2021-2/104

Voznyak, O., Yurkevych, Y., Dovbush, O., & Serediuk, Y. (2019). The influence of chairs and passengers on air velocity in bus passenger compartment. *Lecture Notes in Civil Engineering*, *47*, 518–525. https://doi.org/10.1007/978-3-030-27011-7_66

Zeng, J., Huang, G., Luo, H., Mai, Y., & Wu, H. (2019). First flush of non-point source pollution and hydrological effects of LID in a Guangzhou community. *Scientific Reports*, *9*(1), 13865. https://doi.org/10.1038/s41598-019-50467-8

Zhang, J., Zhang, Q., Shuang, S., Cun, Z., Wu, H., & Chen, J. (2021). The Responses of Light Reaction of Photosynthesis to Dynamic Sunflecks in a Typically Shade-Tolerant Species *Panax notoginseng*. *Frontiers in Plant Science*, *12*, 718981. https://doi.org/10.3389/fpls.2021.718981

Zhelykh, V., Kozak, C., & Savchenko, O. (2016). Using of thermosiphon solar collector in an air heating system of passive house. *Pollack Periodica*, *11*(2), 125–133. https://doi.org/10.1556/606.2016.11.2.11

Zhelykh, V., Shapoval, P., Shapoval, S., & Kasynets, M. (2020). Influence of orientation of buildings facades on the level of solar energy supply to them. *Lecture Notes in Civil Engineering*, *100*, 499–504. https://doi.org/10.1007/978-3-030-57340-9_61

ZinCo USA, Inc. (n.d. a). *Perennial Garden | ZinCo Green Roof Systems USA*. https://zinco-usa.com/systems/perennial-garden

ZinCo USA, Inc. (n.d. b). *Walkways on roofs and plaza decks | ZinCo Green Roof Systems USA*. https://zinco-usa.com/systems/walkways

Summary

Planning of green roofs for the best thermotechnical effect. The energy-efficient provision of indoor comfort for buildings is one of the most important requirements for modern construction. The greening of buildings is a natural measure to achieve this, for which the most limiting factor is the lack of systematic research on its positive effects. At the Kyiv National University of Construction and Architecture, a series of research on thermotechnical benefits and gas exchange in plant layers has been performed. The cooling effect of plants is up to 4 K. Semi-intensive green roofs on rooms have paths, which absorb solar radiation and load the air-conditioning systems. The proposed solution is to build the paths on the auxiliary premises with low microclimate requirements. The work aims to estimate the heat distribution in green roofs with paths to test the recommendation. Simulation using the Fourier–Kirchhoff equation shows that the path has a trace of higher heat transfer on the ceiling up to an additional 1.8–2.0 W·m^{-2}. Thus, aligning the paths above the auxiliary premises is recommended, if possible. A better solution is to allow planting of the paths. Using plant-permit pavements and barefoot-in-dew systems such as ZinCo Soft Landscape are examples of such solutions. It is necessary to use grass that can be walked on.