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Hydrological and thermal response of green roofs in different climatic conditions

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Abstract. The paper presents a study on the thermal and hydrological response of lightweight extensive green roofs with lightweight mineral wool growing media in different European climate conditions. The green roof heat and mass transfer model was developed and experimentally validated. It was then integrated into a developed software tool for the whole year analysis of the green roof thermal and hydrological performance. The results of performed numerical analysis showed that heat losses in heating season and heat gains in summer months of the green roof is smaller compared to the reference non-vegetated roof in all considered climate conditions and depends on thickness of lightweight mineral wool growing media and especially on the green roof's irrigation scenario. The results of numerical analyses also demonstrated that the water retention of green roofs can be considerably improved if irrigation scenario considers the weather forecast. The weather forecast based green roofs' irrigation also improves retention at stormwater events.

1. Introduction

Green roofs gain great attention of urban planners and architects recently because of advantages comparing to other build elements of the urban environment. Besides improving urban microclimate conditions, the improved building energy performance and water retention are among most important advantages [1–4]. Because of that green roofs are gaining a predominant role in building retrofitting especially in the form of extensive green roofs because of low additional structural load, low maintenance and low cost comparing to intensive solutions [3–5]. Most common the advantages of green roofs are studied during summer time conditions [4, 6]. Beside reduced building's heat gains due to increased roof thermal resistance and high percentage of dissipated solar radiation by the foliage layer, considerable decreasing in outer surface temperature compared to traditional roof are observed [2]. Green roofs have significant impact on the thermal response of the building's envelope in the winter time conditions as well. Water in growing media enhance green roof thermal capacity [7] and can effectively store heat from solar radiation which reduces roof heat losses [8]. At freezing ambient air conditions, the process of water freezing further improves the energy efficiency of green roofs [9].

Especially in urban environment water retention is one of the key advantages of green roofs as it improves stormwater management [1, 10–12]. Green roofs, if properly designed, can retain significant stormwater and help mitigate flooding events thus addressing serious environmental impacts of excessive and uncontrolled urban runoff [10]. Selection of the growing media and plants influence green roof's retention capacity as well as evapotranspiration and thus irrigation needs. Wong and Jim [11]



reported that in case when mineral wool is used as substrate considerable water retention and sufficient peak mitigation can be achieved even with a thin substrate layer. Zhang et al. [12] established that plant composition could have an influence on reduced substrate retention capacity due to created preferential flow pathways (due to plant roots) within the green roof growing media. As demonstrated in several studies appropriate irrigation water use strategy, based on weather prediction, can save considerably amount of drinking water [13–14] and it also increases retention capacity of green roofs at stormwater events [12].

As it could be concluded from the literature review thermal and hydrological response of the green roof largely depends on substrate (growing media) thickness and composition. The objective of this research is to evaluate the thermal and hydrological response of lightweight extensive green roofs with mineral wool growing media in different European climate conditions. Thermal and hydrological response of green roofs with different substrate thicknesses and irrigation scenarios is compared with reference lightweight roof to show multilateral benefits of the green roof. The potential of weather predicted irrigation on stormwater management and reduction of irrigation water use is also evaluated.

2. Green roof thermal and hydrological model

Green roofs are roof constructions that enable vegetation growth on top of a flat or low sloped load-bearing roofs. Green roofs consist of several layers such as (waterproof) root membrane, drainage layer with filter membrane, substrate (growing media) and vegetation (foliage) as it is shown in figure 1. In recent years lightweight extensive green roofs emerge in the market with some competitive advantages such as simple installation, low investment and maintenance cost as well as lower thickness and weight compared to extensive (and intensive) green roofs. The growing media thickness is between 2 cm and 10 cm and overall weight 17–40 kg/m² when dry and 42–75 kg/m² when completely saturated. Lightweight extensive green roof of system Urbanscape® with lightweight mineral wool growing media and Sedum-mix plants which thermal and hydrological performance is studied in this paper is also shown in figure 1.

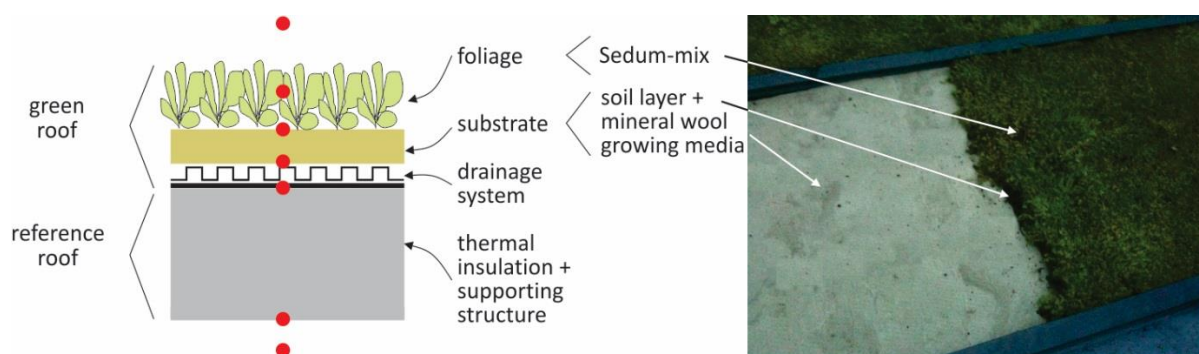


Figure 1. Schematics of reference and green roof composition (left), temperature nodes (red dots) and photo of green roof with Sedum-mix plants and lightweight mineral wool growing media (right).

To predict the green roof thermal response in summer and winter conditions and to study retention of the rainwater the quasi dynamic thermal and hydrological model of the green roof with a lightweight mineral wool growing media was developed. Because evapotranspiration process influences the heat and mass transfer, as well as green roof's growing media thermo-physical properties, the hydrological model was combined with the thermal response model of the green roof building construction. Heat transfer in the green roof is transient because of time dependent short- and long-wave radiation, outdoor and indoor temperatures and heat accumulation. Heat transfer can be determined considering one-dimensional transient heat transfer process between temperature nodes. At each temperature node energy balance equation is developed. For the greening layer (foliage and substrate) heat and mass transfer model is coupled considering two outdoor boundary planes – at the foliage temperature node

and at the substrate surface temperature node, and taking into account global solar radiation absorbed by the foliage $G_{glob,0,f}$ (W/m²) and the substrate $G_{glob,0,s}$, long-wave radiation exchange between the sky and the foliage $\dot{q}_{IR,f}$ (W/m²) or substrate $\dot{q}_{IR,s}$ as well as between the foliage and the substrate $\dot{q}_{IR,f,s}$, convective heat flux \dot{q}_{conv} and latent heat flux by evapotranspiration \dot{q}_l as it is presented in figure 2. Foliage convective heat flux \dot{q}_{conv} is determined according to Newton's cooling law where the convective heat transfer coefficient is calculated based on the leaf area index (LAI), aerodynamic resistance to heat transfer and leaf-air temperature difference [15, 16].

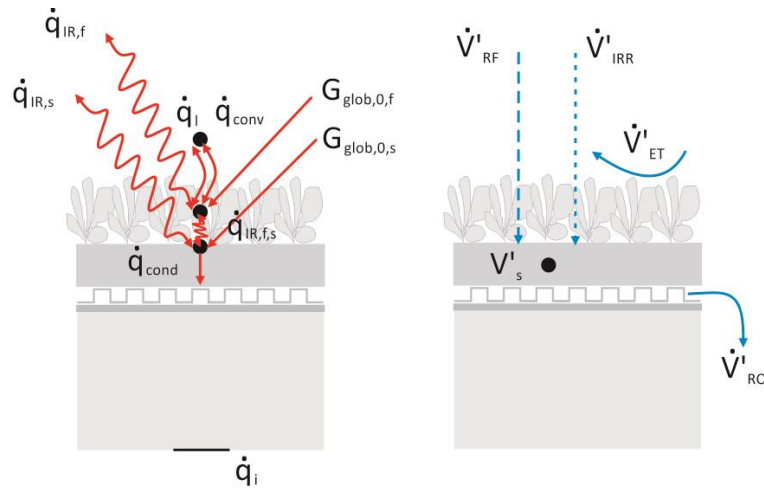


Figure 2. Heat fluxes considered in the energy balance at main temperature nodes (left) and mass fluxes considered in the water balance (right) of the green roof.

Latent heat flux \dot{q}_l is determined from the evapotranspiration \dot{V}'_{ET} , which is calculated using Penman-Monteth equation for hourly or shorter time steps [17]. The water content within green roof substrate, in our case lightweight mineral wool growing media, has a significant impact on heat conduction and heat accumulation in greening layers as it influences material properties such as thermal conductivity and specific heat capacity; therefore, water balance must be considered. Water content in greening layer also influence evapotranspiration. For this reason, Penman-Monteth equation was upgraded for water stress conditions using results from our laboratory experiments. The substrate water content for each time step τ is determined from the green roof water balance:

$$V'_s = V'^{i-1}_s + (\dot{V}'_{RF} + \dot{V}'_{IRR} - \dot{V}'_{ET} - \dot{V}'_{RO}) \cdot \tau \quad (1)$$

The substrate water content V'_s (mm/m²) is determined from the amount of rainfall \dot{V}'_{RF} (mm/h m²) and irrigation water \dot{V}'_{IRR} delivered to green roof in each time step (1 h) as well as amount of water lost due to the evapotranspiration \dot{V}'_{ET} and runoff \dot{V}'_{RO} of excess water in each time step. Runoff appears when calculated water content exceed the saturated water content $V'_{s,sat}$ of lightweight mineral wool growing media:

$$\dot{V}'_{RO} = (V'_s - V'_{s,sat})/\tau \quad (2)$$

Heat conduction and heat accumulation within the green roof growing media is calculated considering thermo-physical properties which varies with water content in the moistened substrate [18, 19]. Model also considers possible phase change (latent heat) at freezing temperature conditions [19]. Only for the loadbearing structure and thermal insulation layer (layers that are equal as for the reference non-vegetated roof) constant material properties are considered. Energy balance equations and thermo-physical properties calculation is presented in detail in [19].

For numerical model development the temperature in radiation flux equations and saturated water pressure terms are linearized. The implicit finite-difference equations are formed and they are solved using the matrix inversion method within MS Excel environment. Developed numerical model was validated with experiments as it is presented in chapter 3.

For year round thermal and hydrological response analysis, a software package “PET tool” was developed in the way that enables comparative all year thermal and hydrological performance analysis of the green roof and the reference (non-vegetated) roof. In the analysis, meteorological data from the Meteonorm 5 database are normally used. Thermal and hydrological response of the green and the reference roof is determined on the hourly time step interval whereby the indoor air temperature can be defined on monthly time scale.

3. Experimental validation

Thermal and hydrological response of green roofs have been extensively experimentally investigated since 2013 for three different compositions of lightweight extensive green roofs installed on the flat lightweight loadbearing thermally insulated ceiling of the laboratory test building [9] (Ljubljana, Continental climate). Green roofs consist of root membrane, drainage layer with filter membrane, lightweight mineral wool growing media and Sedum-mix blanket. Green roofs differ on thickness of lightweight mineral wool growing media (2, 4, 8 cm). Thermal and hydrological response of green roofs was simultaneously compared with reference roof (flat lightweight loadbearing thermally insulated construction without green roof layers). Each of the ceiling construction, called module, has dimensions of 1×3 m. The U-value of green roofs and reference roof is $0.157 \text{ W/m}^2\text{K}$. A weather station Vantage Pro 2 was installed to monitor meteorological parameters. Heat flux sensors were installed on the inner and outer surface of the thermal insulation layer. Temperatures inside lightweight mineral wool growing media, thermal insulation and loadbearing layers were measured using T-type thermocouples. Rainwater runoff from each module was measured using water tank with diameter of 250 mm with pressure sensor which monitors water column high. Developed green roof numerical model was validated with all year round experimental data for green roofs with different thickness of lightweight mineral wool growing media including also short dry periods with reduced evapotranspiration due to water stress conditions. Figure 3 shows measured and with numerical model determined inner surface heat fluxes \dot{q}_i for the green roof with a 2 cm thick lightweight mineral wool growing media for selected weeks during winter and summer weather conditions. Measured $\dot{q}_{i,exp}$ and modelled $\dot{q}_{i,num}$ inner surface heat fluxes differ in average less than 0.5 W/m^2 , slightly larger differences are noticed only for daily extreme values. Higher differences are observed for summer period because a constant inner surface heat transfer coefficient was assumed.

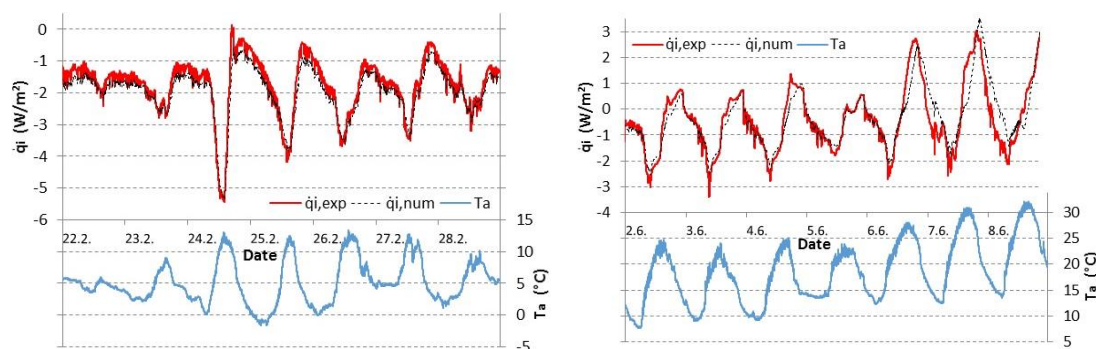


Figure 3. Measured $\dot{q}_{i,exp}$ and modelled $\dot{q}_{i,num}$ heat fluxes on the inner side of the green roof and ambient air temperatures T_a in winter and summer week.

Hydrological balance and modelling of the evapotranspiration \dot{V}'_{ET} was validated with comparison of measured and with numerical model determined water runoff from green roofs. Figure 4 shows

comparison of measured and with numerical model determined daily runoff water normalized on m^2 of the green roof area for the green roof with a 2 cm thick lightweight mineral wool growing media layer. Daily rainfall is shown as well. Figure 4 also shows with numerical model determined substrate water content $V'_{s,num}$ which indicate that water stress conditions occur (4.-5.8. and 10.-12.8.) and that developed model of evapotranspiration is adequate for such conditions as well. From the comparison of experimental and numerical results it can be concluded that developed green roof numerical model is adequate. Experimentally validated green roof numerical model was used to perform hour-by-hour whole year green roof thermal and hydrological response studies for different climate conditions.

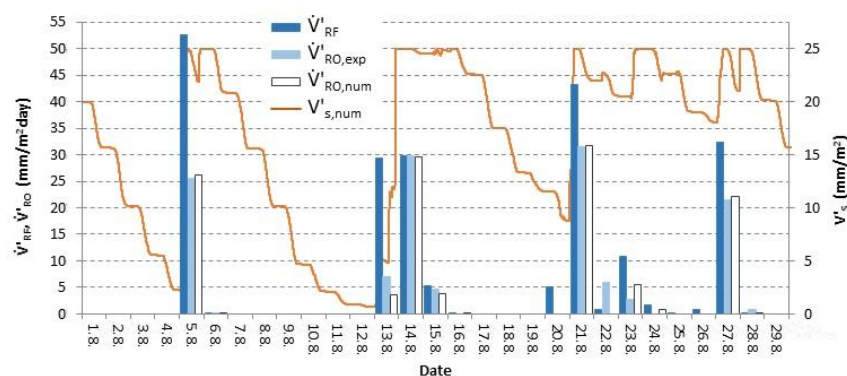


Figure 4. Measured daily rainfall \dot{V}'_{RF} and runoff $\dot{V}'_{RO,exp}$, modelled daily runoff $\dot{V}'_{RO,num}$ and hourly substrate water content $V'_{s,num}$ in the 2 cm thick green roof's lightweight substrate during selected summer time period.

4. Green roof performance analysis

Heat losses of lightweight extensive green roofs in heating season as well as heat gains in summer were compared to reference roof construction for selected European cities with different climate conditions. Analysis are performed for the case of lightweight reference roof construction with 10 cm of thermal insulation and U-value of $0.34 \text{ W/m}^2\text{K}$. Thermal response of reference roof is determined for the case of dark roof with solar absorptivity of 0.7. Green roofs with different thicknesses of lightweight mineral wool growing media (thickness of 2, 4, 6 and 8 cm) and different irrigation scenarios were considered in analysis and retention of rainwater as well as irrigation water needs are also evaluated. Maximum or saturated green roof water content depends on lightweight mineral wool growing media thickness. For the considered thicknesses (2, 4, 6 and 8 cm) the maximum water content $V'_{s,sat}$ is 25, 37, 54 and 66 l per m^2 of the green roof area are taken into account in the water balance (Eqs. 1 and 2). Three irrigation scenarios are considered in the analysis:

- no irrigation; maximum possible water retention, probably water stress conditions and risk of plant withering and reduced heat dissipation;
- irrigation; when substrate water content drops below 20 %; irrigation water amount corresponds to increase of the water content up to 50 % of saturated water content; in this way enabling good green roof performance and still some storage to handle stormwater events;
- irrigation considering 5 days weather forecast; no irrigation if precipitations are forecasted, otherwise regular irrigation (explained in previous paragraph).

Three cities – Ljubljana, Wien and Athens with different climate conditions (Continental high and medium rainfall and Mediterranean) were selected for analysis. Figure 5 shows average monthly ambient air temperature T_a , average daily solar irradiation on the horizontal plane $H_{glob,0}$ and monthly rainfall \dot{V}'_{RF} for selected cities. It can be seen that average yearly ambient air temperatures in Ljubljana and Wien are similar (approx. 10°C) while in Athens is over 18°C . Yearly solar irradiation in Athens

is 40% higher than in Ljubljana and Wien. The highest yearly rainfall is in Ljubljana – 1395 mm/m²a. Wien receives 44% and Athens 26% of that amount.

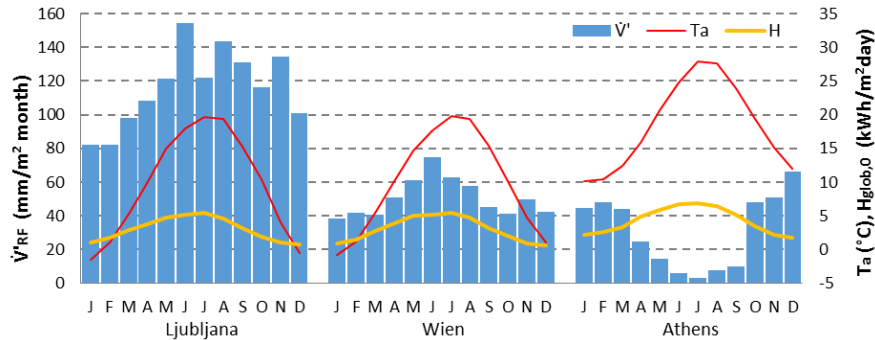


Figure 5. Average monthly ambient temperature T_a , monthly solar irradiation on horizontal surface $H_{glob,0}$ and monthly rainfall V'_{RF} for selected cities.

Indoor temperature and period of the heating and the cooling season were selected according to the city climate conditions: 20/24 °C and Nov.-Apr./June-Aug. for Ljubljana and Wien and 22/26 °C and Nov.-Mar./June-Sept. for Athens. For the reference non-vegetated roof heat losses and heat gains in defined heating and cooling period are shown in figure 6. For the green roofs reduction of heat losses Δq_h and heat gains Δq_c compared to the reference roof (absolute values) in kWh/m² in defined period are shown (figure 6) for different thicknesses of the lightweight mineral wool growing media and considering presented different irrigation scenarios: no irrigation (noIRR), regular irrigation (IRR) and irrigation considering weather forecast (IRR-wf).

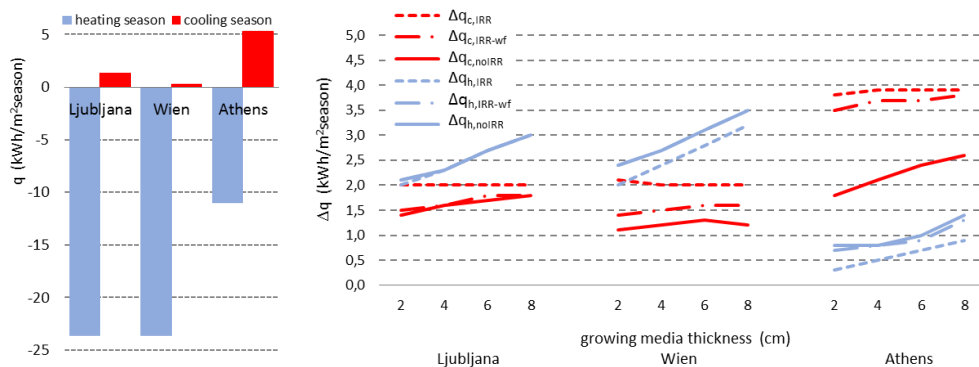


Figure 6. Heat losses and heat gains of reference roof in defined heating/cooling season (left) and reduction of heat losses and heat gains of green roofs compared to the reference roof at different green roof irrigation scenarios (right): no irrigation (noIRR), regular irrigation (IRR), irrigation considering weather forecast (IRR-wf).

It can be seen that heat losses in heating season in cities with Continental climate are almost the same, while in Athens they are more than 50% lower in spite of higher considered indoor air temperature. As expected the highest heat gains in the cooling season are observed in Athens with Mediterranean climate. Reduction of heat losses of green roof in comparison to reference non-vegetated roof is in case of no irrigation in the range from 7% to 15% for all three cities and is higher at higher thicknesses of lightweight mineral wool growing media. Green roof irrigation can influence the heat losses reduction for up to 5% in Athens and 2% in Wien, while it does have almost no influence in Ljubljana. Results indicate that although mineral wool growing media is moistened it provides some additional thermal insulation effect. In the cooling season the reduction of heat gains is the highest in case of regular irrigation thus avoiding reduced evapotranspiration due to water stress conditions. Results indicate that

in Ljubljana and Wien heat gains observed for reference roof turns into heat losses for all green roofs – also those without irrigation.

Lightweight mineral wool growing media thickness (2, 4, 6, or 8 cm in the study) and irrigation scenario can be selected regarding to energy savings or regarding to retained rainwater and water needs for green roof irrigation. As it can be seen from Figure 7 green roofs with 4 or 6 cm of growing media performs much better than one with 2 cm because retained water is higher and water need for irrigation is lower. Increasing thickness to 8 cm has an effect mostly only on reduced heat losses in heating season. Nevertheless, results clearly indicate that most favourable results are obtained if irrigation based on weather forecast is applied for green roofs: retained water is practically the same as in case of no irrigation but there is no risk of plants withering; use of irrigation water can be considerably reduced, especially in case of thin substrate; and it does not influence much the reduction of heat losses in winter season and reduction of heat gains in the cooling period – with only exception of Athens with very low rainfall amount in summer months. Analysis of outflow for Wien also showed that in case of weather forecast irrigation there is no outflow from green roof with at least 6 cm of growing media (only two events in case of 4 cm) in the most rainy months from April to September.

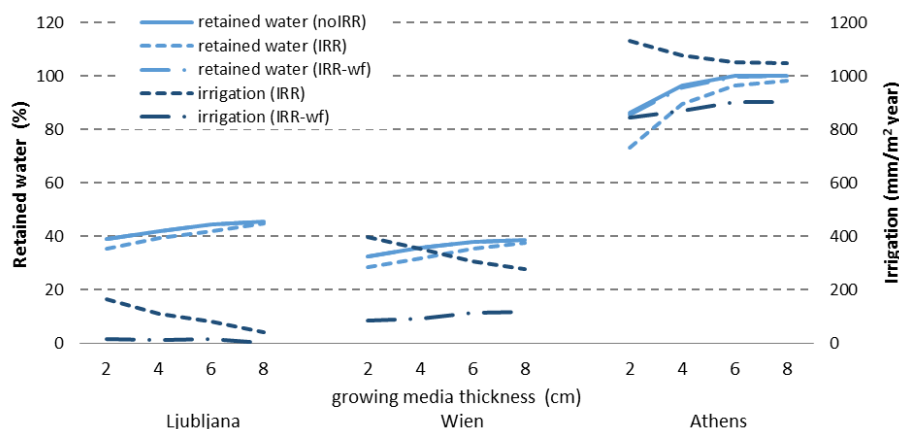


Figure 7. Retained water and water consumption for irrigation of lightweight extensive green roofs with different thicknesses of lightweight mineral wool growing media; irrigation scenarios: no irrigation (noIRR), regular irrigation (IRR), irrigation considering weather forecast (IRR-wf).

5. Conclusions

The thermal and hydrological response of lightweight extensive green roofs with lightweight mineral wool growing media was studied in different European climate conditions. In the analysis, the range of possible thicknesses of rock mineral wool substrate was considered, as well as three different anticipated irrigation scenarios. The thermal response was compared with the reference non-vegetated roof, which has, according to the calculation methodology, the same U-value of 0.34 W/m²K. The results showed an up to 15% reduction of heat losses in the heating season. The highest energy savings were observed for the thickest lightweight mineral wool growing media, which indicates on additional thermal resistance of moistened green roof substrate. The growing media thickness does not have an effect on the heat gain reduction in summer period, as most of the heat is dissipated through evapotranspiration. The weather predicted irrigation can reduce summertime cooling effect – on the other hand, it almost enables the theoretically highest water retention capacity – equal to that of no irrigated green roof. Analysis also showed that weather predicted irrigation can provide substantial savings of irrigation water, especially in case of lightweight mineral wool growing media thickness of up to 4 cm. The analysis also showed that the optimal green roof composition, i.e. the thickness of the substrate layer, can only be determined by taking local climate conditions into account.

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