"PET tool” – a software tool for lightweight extensive green roofs performance analyses

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Abstract. Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems and are becoming a predominant solution in connection with urban planning and building envelope retrofitting. To support design and marketing of Urbanscape® lightweight extensive green roofs a special software tool was developed, which is presented in the paper. Performance evaluation tool (PET tool) is validated based on extensive and continuous 5-years in-situ monitoring of thermal and hydrological response of different Urbanscape green roofs. The key performance indicators of Urbanscape green roofs are evaluated based on calculated thermal and hydrological response. To emphasize the advantages of green roofs thermal response and performance indicators are determined also for non-vegetated roof for the same boundary conditions. PET tool enables i) evaluation of Urbanscape green roofs’ whole year thermal and hydrological response, ii) to search for the optimal design of the Urbanscape green roof system in terms of energy and water performance, iii) evaluation of comparative advantages compared to non-vegetated roof, iv) energy savings and CO₂ emission reduction analyses for heating and cooling season. Analyses can be made for arbitrary worldwide climate conditions since meteorological parameters are gathered from Meteonorm database.

1. Introduction

In the past, the primary role of greenery on the building envelopes – green roofs and green facades – was its aesthetics, while their impact on the building and the external environment has become the subject of research in the last decade [1]. Nowadays, green building envelopes are recognized as having a high positive influence on urban microclimate and living comfort in cities, since they address many environmental issues, such as urban heat island mitigation, water retention and detention, sink of CO₂ and other pollutants [2-3], all resulting from the impact of global climate change and urbanization [4]. The survey of research activities and state of the market reveals that among green building envelope technologies green roofs (both extensive and intensive) are the most developed and established technology. Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems [2, 5] and are becoming a predominant solution in urban planning and an increasingly used alternative at building envelope retrofitting especially in the form of extensive green roofs because of low additional structural load, low maintenance and low cost in comparison to intensive solutions [2, 6]. Green building envelopes are part of the green infrastructure, which is quoted in numerous strategic documents, initiatives and directives of the European institutions [7-10] and city administrations, where they are recognized as technology
that contributes: to improving the energy performance of buildings, to stormwater and water resource management, to achieving greater biodiversity and to the transition to a climate change neutral Europe.

Green roofs are adaptive (and even multifunctional) building envelope constructions, so their characterization, selection and evaluation of thermal performance can not be based on standard/basic building construction thermal performance metrics e.g. steady-state thermal transmittance (U-value), which is easily recognized by building designers, stakeholders and experts [11]. Due to lack of suitable performance metrics for static and adaptive building constructions the advantages of green roofs, in comparison to non-vegetated roofs are most commonly studied experimentally or numerically using developed numerical models [12] and considering equal boundary conditions. Green roof models were also developed for building energy simulation tools EnergyPlus and TRNSYS [12] however they firstly do not consider latent heat of water at water freezing ambient conditions, which considerably influence green roof thermal response and secondly they are not adapted to lightweight mineral wool growing media, which has a very high water retention capacity and low thermal conductivity and density (equal to mineral wool thermal insulation) in a dry state.

Due to limitations of existing green roof models in building energy simulation (BES) tools a software tool named ‘PET tool’ was developed to enable yearly thermal and hydrological response analysis for arbitrary climate boundary conditions. Software tool was made based on the developed and thoroughly validated green roof and non-vegetated roof numerical models. PET tool is designed in a way to support design and marketing of Urbanscape® lightweight extensive green roofs. It’s functionality and performance metrics are presented in this paper.

2. Green roof performance evaluation tool
PET tool is a user-friendly software tool, developed within MS Excel, intended for comprehensive analyses of Urbanscape green roofs’ thermal and hydrological performance and presentation of their advantages compared to existing non-vegetated flat roofs. PET tool, its features, functionalities, performance and analyses are the result of collaboration between Knauf Insulation, Urbanscape Green Solution Team experts and stuff of Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana. PET tool is one of the results of a five-year industrial research project [13-14] financed by Knauf Insulation, Škofja Loka, Slovenia.

Instructions for proper use of PET tool and correct interpretation of presented results can be accessed from the PET tool welcome screen (figure 1a). Instructions (figure 1b) provide also further calculation examples and interpretations of results according to frequently asked questions of customers.

![Figure 1. ‘PET tool’ welcome screen (a) and screenshot of PET tool instructions for use and results interpretation (b).](image)

2.1. Numerical model and model validation
Green roof energy and hydrological performance is determined with developed one-dimensional transient heat and mass transfer numerical model, which considers main heat fluxes that influence green roof thermal response as well as green roof’s water balance. The green roof model is presented in detail
in [12]. Compared to existing green roof models it also takes into account heat transfer phenomena at freezing temperature conditions – a latent heat accumulation in green roof’s lightweight mineral wool growing media. As demonstrated in [12], latent heat accumulation considerably alters the green roof’s thermal response; peak heat flux as well as heat losses are also reduced. Green roof’s numerical model equations are solved within MS Excel environment using the matrix inversion method. Number of temperature nodes is fixed to 32, where 6 of them are being used for the green roof growing media. Specially developed algorithm determines optimal number of nodes for each roof layer, according to the layer thermal resistance, in order to achieve optimal accuracy of numerical calculations. Thermal and hydrological response of the green roof is determined using a time step of one hour, which equals the time step of meteorological data, which are obtained from Meteonorm 7 software [15]. Alongside with the green roof numerical model also a numerical model of reference (non-vegetated) roof was developed in order to enable comparative green and reference roof performance analysis.

PET tool was validated based on extensive and continuous 5-years in-situ monitoring of thermal and hydrological responses of different compositions of Urbanscape Green Roof Systems performed on Faculty of Mechanical Engineering, University of Ljubljana. Experimental green roofs were installed on a flat roof of a laboratory test building presented in figure 2. There are four modules, each with dimensions of 1 × 3 m, one of them representing the reference non-vegetated roof. Until now 8 different Urbanscape green roof compositions were tested, each with in-situ monitoring period of at least 1 year. One green roof composition remains unchanged since 2013 for evaluation of long-term effects on thermal and hydrological response. Results of PET tool numerical model validation are presented in yearly reports [13-14] and published research papers [12].

![Figure 2. Lightweight extensive green roof modules on a roof of the laboratory test building after installation in 2013 (top left), some used measurement equipment (weather station Vantage Pro 2, pyrgeometer Kipp&Zonnen CG1, heat flux meters, developed outflow volume-flow meters) (top right) and green roof vegetation (Sedum-mix) appearance in different periods of the year (bottom).](image)

### 2.2. Definition of roof compositions and boundary conditions

PET tool is a MS Excel .xlsm file with separate .xlsx file with Meteonorm meteorological data for several worldwide locations. The screen that appears after the welcome screen is shown in figure 3a. At
first, the composition of a loadbearing construction (i.e. the ‘Reference roof’), on which Urbanscape Green Roof System is placed, is defined. Up to 6 layers can be defined, from drop-down boxes where materials are organized in groups. For each layer thickness needs to be specified and U-value is displayed at the top of the screen. For the reference roof the absorptivity of solar radiation also need to be selected. Follows the selection of Urbanscape lightweight extensive green roof system composition. As a vegetation layer a Sedum-mix blanket with 2 cm soil layer is added automatically. For the green roof the overall thickness and maximum water content are displayed on screen. Irrigation scenario – N/Y and at which water content green roof is irrigated – needs to be also specified. In the numerical model it is set that at each irrigation event 30% of maximum water content is added. At the end the climate conditions are specified by firstly selecting the country and then the city. Data that are imported in PET tool and are needed in numerical model are hourly values of ambient air temperature and relative humidity, wind speed, rainfall and solar and incoming longwave radiation on horizontal plane.

The second PET tool screen presents graphically and numerically meteorological parameters (figure 3b) what helps the green roof expert to define indoor temperature in heating (winter) and cooling (summer) season and to select months that are going to be included into seasonal energy savings analysis. Months that are not selected are not considered in seasonal energy performance analysis. Displayed meteorological data are valuable also for optimization of green roof composition and irrigation scenario.

Figure 3. Screenshots of ‘PET tool’; definition of reference roof composition and lightweight extensive green roof composition and irrigation and selection of site meteorological parameters (a) and indoor boundary conditions definition and selection of months for seasonal analysis and graphs presenting meteorological parameters (b).

2.3. Presentation of performance indicators
When boundary conditions as well as heating and cooling season are defined thermal and hydrological response is calculated with validated numerical models of lightweight extensive green roof and reference roof. In the PET tool calculation progress is shown by displaying calculated monthly values. Thermal and hydrological response calculations do not end at the end of the year. Calculations are repeated in order to balance initial conditions. Calculations stop when calculated values does not differ from those obtained in the first run. Figure 4 presents screen with displayed results where hourly, monthly, seasonal and yearly values are presented for the green and the reference roof. The first graph (top-right) presents hourly values of specific heat flux q̇ i in (W/m²) on inner surface of reference roof (red line) and green roof (green line). It enables comparison of peak heat fluxes which directly influences required heating and cooling power. Graph also visualizes green roof heat flux attenuation due to increased roof heat capacity, shading and evapotranspiration as well as due to latent heat accumulation in green roof substrate caused by water freezing and melting at freezing ambient conditions. On the left hand side of the screen monthly average specific heat values are presented as an indicator of monthly heat losses and gains. The difference between reference and green roof value indicates the potential monthly energy
savings. The same graph presents also monthly peak heat fluxes what indicates the expected peak heat losses and gains in each month. Numeric values are listed in the report (section 2.4).

For the months that were selected for heating and cooling season the seasonal specific heat gains or heat losses \( q_i \) (kWh/m\(^2\)) are presented for the reference roof (red bar) and for the green roof (green bar). These values can be used to evaluate Urbanscape lightweight extensive green roof energy savings as well as for green roof composition optimization.

One of the recognized advantages of green roofs is also urban heat island mitigation. This benefit of green roof in comparison to the reference roof can be evaluated from the graph in the middle of the screen (figure 4), which presents hourly values of calculated outdoor surface temperatures of both roofs. Lower outer surface temperatures indicate other environmental and social benefits of green roofs. This graph also enables evaluation of water stress conditions on temperatures and heat transfer.

Green roof water balance is presented at the bottom of the screen with presented results (figure 4). Right graph shows hourly values of green roof substrate water content (orange line), outflow from green roof (green line) and green roof irrigation (blue line). From this graph green roof expert can analyse influence of different irrigation scenarios and different drainage systems (with/without water storage) on retained water and water for irrigation. One can evaluate green roof also regarding to the stormwater management.

Yearly hydrological performance of Urbanscape green roof system (on the bottom left graph in figure 4) presents dark blue bar showing yearly rainfall from meteorological data what in analysis equals the outflow from the reference roof. Next to outflow from Urbanscape green roof is presented with green bar and above both bars the share of retained water in case of green roof installation. Estimated amount of water for irrigation of each m\(^2\) of green roof is shown in light blue bar.

![Figure 4](image)

Figure 4. Screen with results of numerical calculations in the form of graphs presenting hourly, monthly, seasonal and yearly values of calculated parameters.

2.4. Report

PET tool report enables further analysis and presentation of additional results like numerical average monthly heat flux values and monthly water balance results. The report can be saved as a separate pdf file. As one of the purposes of PET tool is to support marketing, the results in the report can be presented in imperial units. There are also two tailored versions of PET tool in French and German language.
Report contains the information on reference and green roof composition and their U-value. In case when expanded polystyrene (EPS) drainage layer with water storage is used in green roof, also informative U-value of green roof, determined considering the calculation methodology for inverted roofs, is displayed as shown in figure 5. In case when green roof area is specified all graphs and numerical values are presented for specified roof area and not as specific values for each m² of green and/or reference roof.

![Image](image.png)

**Figure 5.** Part of the report presenting reference and Urbanscape green roof composition and basic characteristics; in case of used EPS drainage layer U-value of green roof differ from U-value of reference roof.

![Image](image.png)

**Figure 6.** Part of the report where energy savings and CO₂ emission reduction (environmental indicator) due to green roof installation can be determined.
In the energy section of the report the building heating and cooling system, their seasonal efficiency and energy carrier can be specified. Based on selected or entered values the reduced final energy use for heating and cooling is presented as well as energy savings per energy carrier for each season. Additional yearly reduction of CO$_2$ emissions due to installed green roof is presented.

3. Upgrades and additional functionalities

With constant development of Urbanscape green roof solutions also the PET tool is being constantly upgraded. New drainage systems and new lightweight growing media solutions are added to the drop down list, while their thermo-physical properties are determined with laboratory experiments and validated with green roof in-situ thermal and hydrological response measurement results. New materials for loadbearing (reference) roof construction and meteorological data can also be added to enable analysis for specified reference roof design and location.

Further more advanced analyses are also possible with an open version of PET tool. As an example of such analysis the influence of historical weather data (observed climate changes) on green roof hydrological response is presented below. Namely, often raised question is how representative are the weather data, which are typical years for selected location. Results obtained using historical data for the period from 1985 to 2016 was statistically analysed and compared with results obtained with Meteonorm typical year for case study green roof in Mexico City. Figure 7 presents some of the obtained results. From the hydrological response graphs for selected years (typical year, 2016 extremely high and 1990 low precipitation amount) it can be concluded that typical year suitable covers the rainy periods in Mexico City.

![Figure 7. Results of green roof hydrological response analysis considering weather data from 1985 to 2016; water balance graph in case of typical year (top), 2010 and 1990 (bottom); yearly balance in case of typical year and box plot considering all 33 sets of meteorological data.](image)

Box plot in figure 7, which covers all weather data sets further reveal wide range of yearly rainfall where more than ¾ of the years had a rainfall below that of a typical year. Historical data show that the amount of precipitation is increasing. Two outliers indicate two years with extreme rainfall, both appearing in last decade. One additional outlier in green roof outflow indicates that there was also one another year with high rainfall in a short period (month with extremely high rainfall). Low outflow for other years indicate high water retention capacity of case study green roof. Obtained results for required irrigation water gives indication on range that is expected regarding to the variations of meteorological conditions in the Mexico City.
4. Conclusions

Due to the lack of suitable thermal performance metrics for green roofs and limitations of BES tools that do not enable thermal response analysis of lightweight extensive green roofs with lightweight mineral wool growing media a ‘PET tool’ was developed and presented in this paper. In comparison to existing models the PET tool green roof model additionally considers different heat and mass transfer at water stress conditions and at freezing temperature conditions. As it was shown the PET tool enables: a) evaluation of Urbanscape green roofs’ thermal and hydrological response, b) to find the optimal green roof composition in terms of energy and water management performance, c) evaluation of the comparative advantages of green roof compared to existing reference flat roof and d) energy savings and CO$_2$ emission reduction analysis for heating and cooling season. Analyses can be made for: i) arbitrary composition of lightweight or massive reference flat roof – on which Urbanscape system is installed, ii) different composition of Urbanscape green roof system and irrigation scenarios and iii) different worldwide climate conditions.

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