Hygrothermal simulation of green roofs – new models and practical application

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SUMMARY:
Design and installation of green roofs on wooden constructions requires special care because of the low inward drying potential in the summer months. Within a research project new models to calculate green roofs reliably by the help of hygrothermal simulations were established. Based on experimental investigations of green roofs in Holzkirchen, Leipzig, Vienna, Kassel and Milan different models were developed which provide a reliable basis for moisture control design of extensive green roofs. After validation the model has been used to arrive at general practice recommendations for wooden light-weight green roofs. The critical condition in light-weight flat roofs is normally the water content in the exterior sheathing. For design purposes it shouldn't exceed a limit value of 18 % by mass – this is to prevent wood decay but includes a safety factor. To fulfil this requirement an additional insulation layer above the exterior sheathing is often necessary.

1. Introduction

Due to the fact that most city centres are soil sealed, green roofs become more and more popular as climatic compensation areas. The green roofs partly substitute the function of topsoil, because they can absorb and store rain water which subsequently can evaporate through growth medium and plants. The latent heat storage and the weight of the greening dampen diurnal and also seasonal temperature variation. The reduced temperature stress and strain increases the life expectancy of the roofing membrane and the substructure. Additionally undesirable heat gains in summer and heat losses in winter are generally lower than with other flat roof constructions. These benefits of green roofs are somewhat offset by potential moisture problems or construction damage. Such problems have been observed again and again in unventilated light-weight green roofs. One reason is the fact that flat roofs are vapour tight at the exterior surface and thus on the wrong side from the building-physics point of view. So drying is only possible towards the inside. In comparison to normal flat roofs, green roofs remain significantly cooler during summer time, which reduces the drying potential to the inside. The combination of greening and moisture sensitive wooden substructure may lead to a roof assembly, which is hardly fault-tolerant and requires special care for design and workmanship.

Until recently our knowledge about the hygrothermal conditions in the growth medium have been insufficient to accurately assess the moisture performance. This is the reason, why also advanced planners arrive at their limits and often recommend another roof assembly or require expensive preventive safety measures, for example a ventilated air layer, which can be unfavourable concerning energy performance. The missing basics for planning are opposed to the increased use of green roofs, which are ecologically worthwhile and energetically advantageous.

Within the research project (Zirkelbach & Schafaczek 2013) new models were developed in order to allow a green roof design by the help of hygrothermal simulations. The aim was to provide a reliable basis for safe moisture control design of extensive green roofs to designers and manufacturers of building materials and constructions.

2. Green roof models

2.1 Generic simulation model

The generic green roof model shall serve as a common approach, which can be used without additional information of the type of the specific growth medium and with climate files which don't contain information about the atmospheric counter radiation. It was developed on the basis of field studies in Holzkirchen, Leipzig (Winter, Fülle & Werther 2007-2010), Vienna (Teibinger & Nusser 2010) and Kassel (Minke, Otto & Gross 2009). Based on the measurements of Holzkirchen for inverted green roofs in the period from 1985 to 2004 the material data, surface transfer conditions and rain water absorption behaviour were adapted by the help of hygrothermal simulations to achieve good agreement between simulation results and measured data. Therefore a growth medium layer is simulated together with the roof assembly considering its moisture balance during the year. The plant cover influence is represented by adapted values for surface heat transfer and radiation exchange, and an additional moisture source inserts a part of the rain water directly into the substrate, to accelerate the rain water uptake in comparison to only capillary transport. Details about the iterative adaption extend the scope of this paper but can be found in the detailed report (Zirkelbach D. & Schafaczek B. 2013) as well as on IBP homepage. The simulations are performed with WUFI® (Künzel 1994), a model to calculate the simultaneous heat and moisture transport in building components under real climate conditions, developed by the Fraunhofer IBP and validated by numerous field. It fulfils amongst others the requirements of (EN 15026) and (ASHRAE Standard 160).

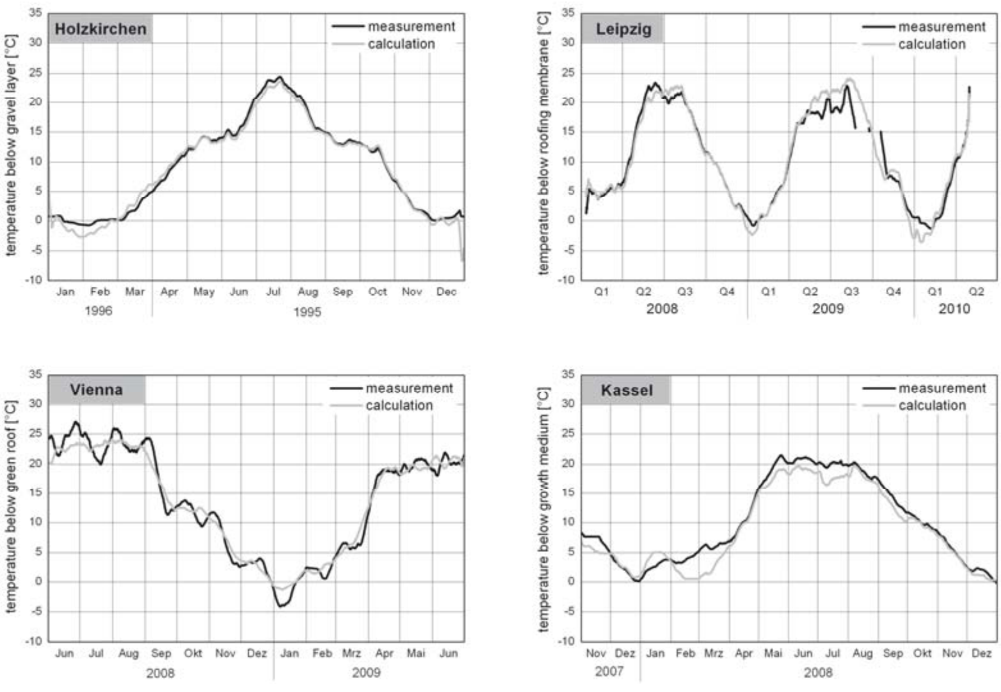

FIG 1. Calculated temperature (monthly average) below the green roof layers in Holzkirchen, Leipzig, Vienna and Kassel in comparison to the measured values.

The generic model for the simulation of green roofs generally shows a good agreement with the measured data at different locations and below different types of greening. Figure 1 shows the comparison between measurement and calculation of the temperatures below the green roof layers – i.e. on top of the insulated structure – as a monthly average for the investigated locations. In Leipzig additionally also the water content in the OSB-sheathing was measured. A comparison with the calculated water content (Figure 2) shows also a very good agreement. In the winter months there are remaining differences between simulation and measurements because of the intermittent snow cover which is not considered in the calculation. It has been attempted to adjust the generic green roof model in such a way that generally the simulation leads to more unfavourable results than the measurement. This is necessary to allow the evaluation of a green roof assembly on the safe side.

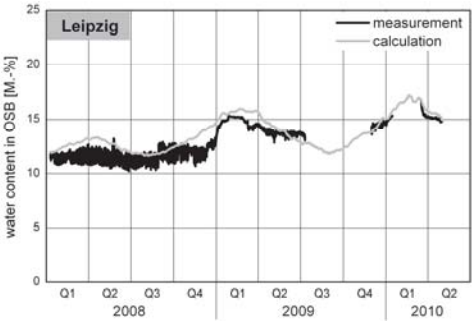

FIG 2. Calculated water content in the sheathing of a green roof in Leipzig in comparison to the measured data for the period January 2008 to April 2010.

The climate data available for the development of the generic model didn't contain any data for the atmospheric counter radiation, so it was necessary to consider this influence in a simplified way by the other climate data and appropriate surface transfer coefficients. This green roof model can be used if the radiation conditions are comparable to the ones at the examined Central-European locations. Other radiation conditions, especially those with clearly different cloud cover, should be considered by a detailed calculation of the long-wave radiation losses with one of the specific models.

2.2 Specific simulation models

To consider the long-wave radiation explicitly, new test roof sections with different growth media and thicknesses were established at the field test site in Holzkirchen (Figure 3). To provide product specific models different types of growth media were investigated:

- Single layer assembly with 8 cm growth medium
- Double layer assembly with 3 cm growth medium
- Multi-layer assembly with 10 cm new growth medium
- Multi-layer assembly with 10 cm ingrown growth medium

In each assembly the temperatures were recorded at two positions and in two resp. three levels. Additionally, in all test sections the moisture on the roofing membrane was determined indirectly by resistance measurements in thin wood specimens, because a measurement of the relative humidity in the mostly water saturated growth medium is not always accurate and the sensors often fail. On the other hand, even if the resistance measurement can only provide qualitative information it can show, if the growth medium dries out in summer time or if it remains humid all year round. Almost during the whole year the relative humidity in the growth medium layer didn't fall below 99 % - which is also the requirement for plant growth. An accurate measurement of the moisture in the growth medium layer is only possible by weighing. Therefore small baskets for manual weighing were installed in each test section.

The weather station on the field test side in Holzkirchen records all climate data required for a simulation. Additionally the interior surface temperature of the test roof was measured. To calculate the conditions in the different test sections detailed material data are required. Therefore, in addition to the manufacturer specifications, the following data were determined in the laboratory: density, diffusion resistance, water absorption factor, sorption moisture at different relative humidity levels and free water saturation. Based on these field and laboratory tests the generic simulation model was extended to specific models, which consider the specific material properties and the detailed radiation exchange at the surface.

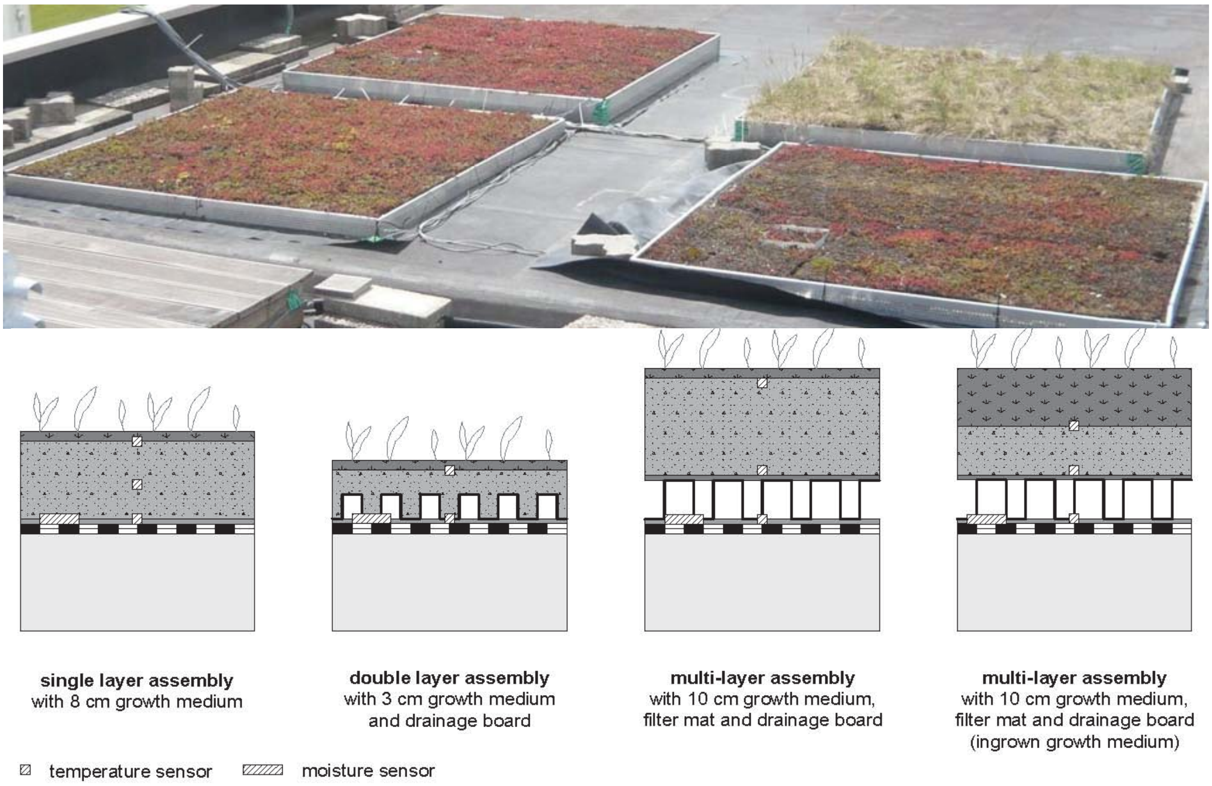

FIG 3. New field tests in Holzkirchen with different growth media and thicknesses. The drawing also shows the position of the temperature and moisture sensors.

During the iterative simulation of the hygrothermal behaviour of the different green roof assemblies the parameters which are unknown or difficult to determine experimentally due to their complexity are adapted to reach a good agreement with the measured values. The adaption was performed iteratively for each test section and each parameter to get an appropriate correlation between the variation of the input parameters and their influence on the results.

The following parameters had to be adjusted by this parametric study:

- the radiation exchange of the roof surface with the sky which is influenced by shading, changing colours and variability of the plant cover
- the moisture depending thermal conductivity of the substrate and the reduction of the effective heat transfer coefficient by the plant cover (the plants reduce the convective heat exchange and may even have an additional insulating effect)
- the influence of the drainage layers on moisture retention

The iteration steps and the results of the recalculation of the test fields are described in detail in the research report (Zirkelbach & Schafaczek 2013). Within this paper only the important results and the differences to the generic model will be explained.

On the exterior surface the detailed radiation exchange was considered by both the short-wave radiation absorption and the long-wave radiation emission. By introducing an additional plant cover layer at the surface also the insulation effect of the plants can be considered in the simulation. Furthermore the two dimensional and temporally variable properties of the drainage elements were represented with average material data. The results have shown that there is a need to differentiate between a drainage element filled with substrate and an unfilled element.

The aim of the adaption has been to reach a good agreement between calculation and measurement. In Figure 4 (top) the comparison between the measured (solid lines) and the calculated (dotted line) temperatures on the roofing membrane of the single layer assembly are displayed. In average the agreement is quite good – but looking at the hourly values (Figure 4, middle) there are still short term peak differences of up to 8 K. But also the difference curve between the two measurement positions (Figure 4, bottom) shows, that the measured temperatures in the same roof and on the same level also differs up to 6 K. This is the result of the inhomogeneity of the substrate and plant layer as well as local differences in moisture contents. These uncertainties cause the described discrepancy between calculation and experiment and show that no "correct" solution but only a good approach to the measurements is possible. Compared to the measurements, the simulation results should show lower temperatures on average in order to remain on the safe side.

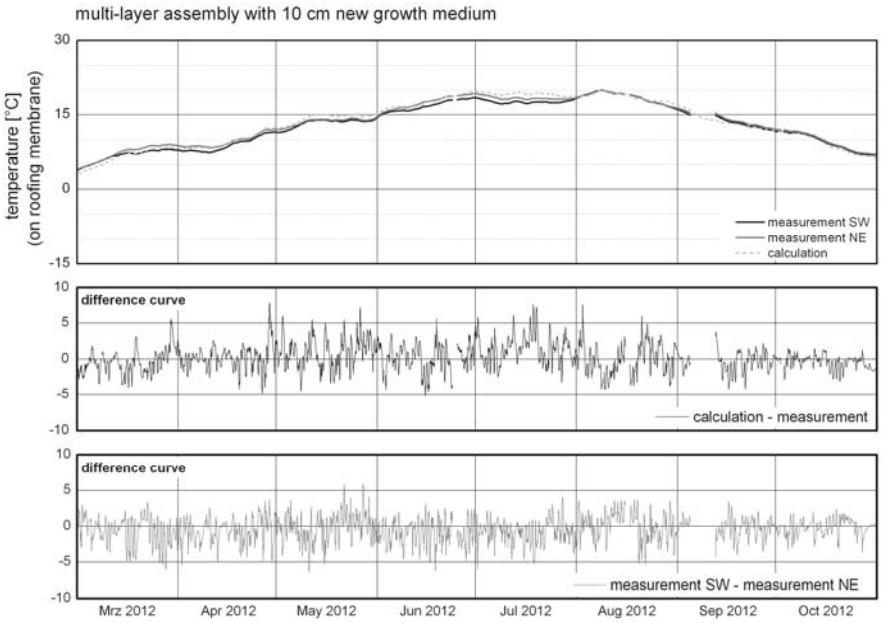

FIG 4. Monthly average of the calculated temperatures at the roofing membrane in comparison to the two measurement positions (top). In the middle and bottom diagram the difference curves are displayed.

Due to the fact that the specific models also consider the atmospheric counter radiation, there is the possibility to evaluate green roofs also in other climate regions with different radiation conditions. For additional validation some experimental data of a green roof research project in Milan were provided by Fiori & Paolini (2013). The first comparision over a short period have shown that the conditions below the green roof can be reproduced very well with the specific model. However, more validations are desirable and will be performed in future.

2.3 Verification of the green roof models by means of the impacts on a light-weight construction

Focus of the research project was a reliable design and evaluation of light-weight constructions. Therefore it is most important that the temperatures below the green roof on the roofing membrane can be well calculated. However, the simulations show temperature discrepancies up to 8 K to the measurement. Therefore, in the following it will be evaluated, if these short-time temperature differences have a significant influence on the hygrothermal evaluation of a roof.

Thus a light-weight construction with a very sensitive behaviour concerning the outdoor climate is analysed. To evaluate the remaining differences between measurement and calculation, as boundary conditions both, the directly measured values and the modelled conditions according to the new approach are used and compared.

The conditions below the green roof are considered as follows:

- measured temperatures on the roofing membrane in combination with a relative humidity of constant 100 %
- calculation of the green roof with the specific model using the measured outdoor climate data of Holzkirchen

For the evaluation, the water content in the OSB-sheathing of the two alternatives is compared. Experience shows that the OSB-sheathing presents the most likely location in the construction where damage due to high humidity conditions occurs. In Figure 5 the simulated water contents in the OSB-sheathing are displayed for two different boundary condition cases: For the first case the temperature of the roofing membrane is determined by the green roof model and in the second case the measured membrane temperatures from the green roof experiment are employed. For all considered assemblies the two curves run more or less parallel, whereby the water content of the approach with the green roof model is in case of difference maximum 1 M.-% higher than the one of the simulation with the measured values. That means that the hygrothermal results obtained by the new models are almost identical to those obtained by using real measured data as boundary conditions.

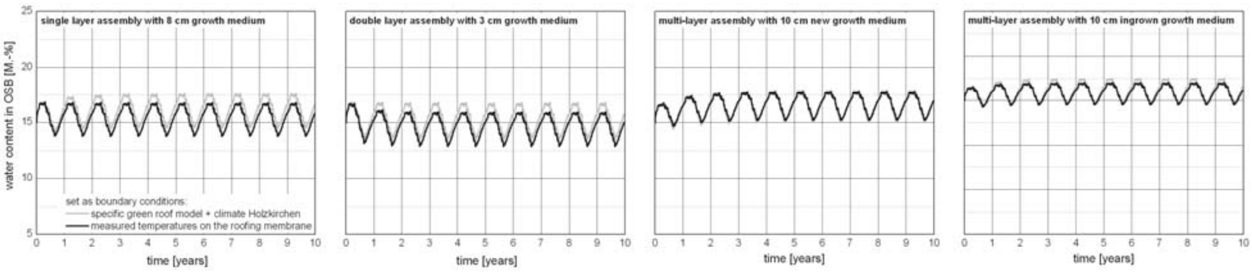

FIG 5. Calculated water content in the OSB-sheathing of a light-weight construction for the four roof assemblies using both the measured (black) and modelled green roof conditions (grey curve).

Altogether, it can be stated that the new green roof models can reproduce the conditions below the green roof very well. Thereby the temperatures of the simulation are slightly lower and consequently the calculated moisture conditions of the construction are on the safe side.

3. Application and practice recommendations

In wooden green roofs with vapour retarder only small moisture fluxes occur during the year. Therefore dynamic equilibrium is reached slowly – often only after a period of many years. Due to this fact the results of „short time“ field tests (less than five years) often provide only partially meaningful results to evaluate such constructions. The new green roof models allow a reliable simulation of the moisture conditions in light-weight assemblies as well as an evaluation of their long term behaviour.

Within the research project the hygrothermal behaviour of a typical light-weight roof was analysed depending on the green roof assembly, the insulation material, the thickness of the insulation layer and the vapor diffusion resistance of the interior surface materials. In this paper only one of these variation can be shown. In Figure 6 the calculated water content in the exterior OSB-sheathing in a roof with 20 cm insulation layer as function of the type of the vapor retarder is plotted: the left diagram shows the results for a membrane with a constant s_d-value of 2 m and the rigth one those with a variable vapour retarder (s_d-value < 0.5 m for humid and > 25 m for dry conditions). With previous design (without additional insulation) and a s_d-value of 2 m for the vapor retarder the water content in the OSB-sheathing shows a strong increase both with the thin light-weight growth medium layer (grey solid line) and with normal growth medium thickness (black solid line) and reaches values of 25 to 45 M.-% after 15 years. Also with an additional insulation layer of 5 cm above the exterior sheathing both alternatives (grey / black dotted line) slightly exceed the value of 18 % by mass (a well-accepted limit to prevent wood decay that includes a certain safety factor). In comparison to these results the construction with a variable vapour retarder (diagram on the right) shows more favourable conditions. With the light-weight growth medium the water content remains below the limit value even without an additional insulation layer. But with the normal growth medium thickness and previous design the limit value is also exceeded and can only be kept with an additional insulation.

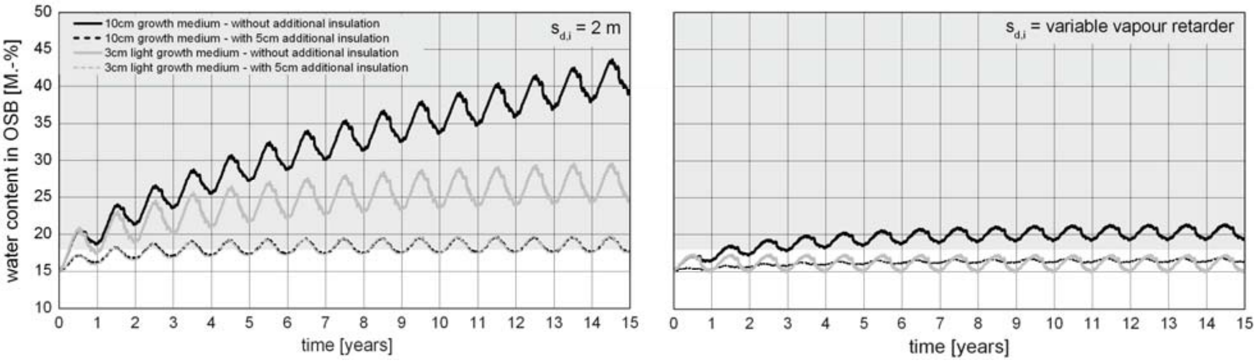

FIG 6. Calculated water content in the OSB-sheathing of a light-weight roof with 20 cm insulation depending on the thickness of the growth medium and the presence of an additional insulation layer. Vapour retarder with constant s_d-value of 2 m (left) and variable vapour retarder (right)

Due to the fact that the temperature on the roofing membrane rarely exceeds the outdoor air temperature and if so, only for a few degrees, drying towards the interior is only possible during a few weeks in summer time. A variable vapour retarder significantly improves the moisture balance and reduces the water content in the sheathing compared to a retarder with a constant s_d-value. Furthermore in almost all constructions an additional insulation of the exterior sheathing is necessary to keep the limit value. However, in practice wood decay can only occur if fibre saturation is reached at water contents above approximately 27 - 30 % by mass. Without the additional insulation the moisture level exceeds the safety limits within a couple of years in most cases, but usually remains within the range between 18 % and the beginning of fibre saturation.

As a result of all evaluated variations, the following practice recommendations can be given:

- variable vapour retarders provide a more favourable performance than retarders with constant sd-values
- for insulation layers thicker than 20 cm an additional insulation of the exterior sheathing is necessary to keep the limit values (for Central European climate conditions)
- the roofing membrane should be rather vapour tight, because drying to the outside doesn’t occur
- additional shading should be avoided
- high air-tightness level of the roof assemblies is recommended

4. Summary

The new green roof simulation models allow for a reliable calculation and design of green roofs by the help of hygrothermal simulations. This is of special importance for moisture sensitive wooden flat roofs.

The generic green roof model considers the effect of the atmospheric counter radiation in a simplified way by reduced short wave absorptivity and is suitable for locations in Central Europe or locations with similar climate conditions, especially concerning the radiation loads. It can be used if no measured data for the atmospheric counter radiation or no detailed information about the applied growth medium are available. The specific green roof models include the atmospheric counter radiation and thus all relevant climate elements in detail and should be also suitable for other climate regions. Prerequisite is the availability of data for the atmospheric counter radiation. The validations showed good results for green roofs in Holzkirchen and Milan.

Based on the evaluation results general practice recommendations for unventilated light-weight green roofs were worked out. Especially two points are of importance: 1.Variable vapours retarder should be preferred to a retarder with a constant s_d-value to improve moisture balance and drying to the interior. 2. Thicker insulations layers in-between the rafters require an additional insulation on the top of the wooden sheathing to limit the moisture increase during winter. Rather uncritical remain structures with whole insulation on top of the load bearing wooden structure as well as ventilated roofs as far as a sufficient ventilation rate can be ensured (Zirkelbach, D., Künzel, H.M. & Bludau, Ch. 2008).

For further information please refer to the detailed research report (Zirkelbach & Schafaczek, 2013) or the IBP homepage.

5. Acknowledgements

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