Low Cost Green Roofs for Cooling:
Experimental series in a hot and dry climate

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ABSTRACT: Green roofs have many benefits over conventional roofs, they reduce storm water runoff, the heat island effect in cities, and energy requirements for cooling; all of this while sequestering some CO2 from the atmosphere. But because of their expense, the building industry has yet to fully embrace their large scale implementation. Over the course of three summers several test structures with green roofs have been built and tested at the Lyle Center for Regenerative Studies in Cal Poly Pomona University to determine their cooling potential combined with night ventilation. Results indicate that the test cell with the uninsulated green roof consistently performs better than the test cells with the insulated green roof and the conventional white insulated roof. This indicates that in mild climates with warm summers, green roofs can be thermally coupled with the interior of the space to improve the performance of night cooling systems, reducing energy consumption and greenhouse gas emissions.
Keywords: night ventilation, passive cooling, green roofs, experimental series, low cost sustainable housing

INTRODUCTION
A living or green roof is a roof that is substantially covered with vegetation. Such a strategy has been proven to have positive effects on buildings by reducing the stress on the roof surface, improving thermal comfort inside the building, reducing noise transmission into the building, reducing the urban heat island effect by reducing "hot" surfaces facing the sky, reducing storm water runoff, re-oxygenating the air and removing airborne toxins, recycling nutrients and providing habitat for living organisms, all of this while creating peaceful environments.

The positive thermal effects of green roofs are usually described by the reduction of the external surface temperature due to the effect of vegetation, and the reduction of the thermal transmittance of the assembly, mostly due to the effects of insulation, usually placed between the sustaining material and the interior space of the building. A green roof without this added insulation has a low thermal resistance, but does have thermal mass. Apart from providing protection against overheating, a green roof can also provide some cooling through the evaporative process in the plants [1]. Their vegetative matter absorbs solar radiation through the biological processes of photosynthesis, respiration, transpiration, and evaporation. However, the solar radiation that bypasses these processes can seep into the building envelope [2].

Studies have demonstrated that a well planned and managed green roof –with insulation- acts as a high quality insulation device in the summer [3]. But little has been done to take advantage of the mass of the green roof as a heat sink in temperate or hot climates. By reducing daily thermal fluctuations on the outer surface of the roof and increasing thermal capacity in contact with the indoors, green roofs can contribute to the cooling of spaces if the mass of the soil is cooled. There has been some research in this direction that indicates potential to reduce the cooling loads inside buildings [4] [5].

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. This ventilation system can be either fan forced or natural through windows that are opened and closed at appropriate times. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates [6]. The main parameters that determine the efficiency of night-ventilation can be classified in three broad groups: climatic parameters, building parameters and technical parameters of the technique [7]. This paper discusses changes in the performance due to changes in building parameters.

During the course of three summers several green roofs have been built and tested at the Lyle Center for Regenerative Studies in California State Polytechnic University Pomona. Cal Poly Pomona is located in a hot and dry climate with mild winters about 30 miles east of Los Angeles in southern California (Fig 1).

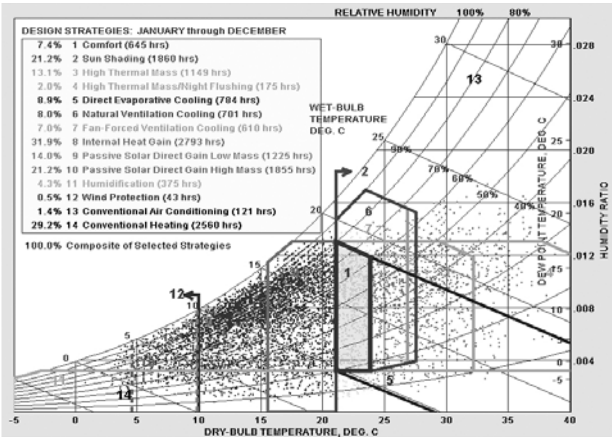

Figure 1: Climate Zone 9, location of the tests

This paper analyzes the cooling potential of green roofs combined with night ventilation by looking at the internal temperature of experimental test cells and in a full size residential building.

EXPERIMENTAL SYSTEM

Three test cells with a dimension of 1.2 x 1.2 x 1.2 meters were built using 2 by 4 inch stud wall construction with drywall on the inside, plywood on the outside and batt insulation in between for a U value of 0.12 W /m^2 K. Exterior is white and the three cells have 0.61 m by 0.61 m (2' x 2') single glazed windows facing south that were replaced by double glazed windows in 2007 the last series (Fig. 2). All of the cells have 3.8 cm thick concrete pavers as the slab.

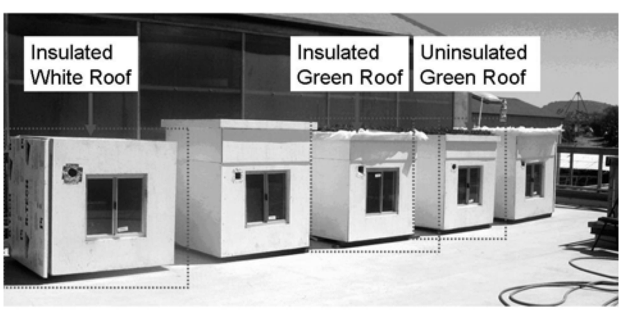

Figure 2: The Test Cells

The roof is the only difference between the cells. The first cell has a code compliant insulated roof, with a U value of 0.055 W /m^2 K, painted white, the second cell has an insulated green roof, and the third one an uninsulated green roof (Fig 3). The growth medium in the uninsulated green roof is thermally coupled with the interior via a metal plate, while in the the other green roof there are 10 cm of matt insulation between the space and the soil. Night ventilation is provided with a fan and all of the cells are equipped with dimmers and timers to adjust the ventilation rate and start/end times.

The green roofs were of the extensive type. Two types were built. The first one, in 2005, was covered with Saint Augustine grass above a layer of soil 7.5 cms thick with 2.5 cm of gravel and a plastic liner underneath. Drainage tubes were spread through the gravel with perforations that capture the excess water and drain it outside the building. The plastic liner is spread above a metal plate, supported by wooden joists. The metal plate assures thermal coupling between the mass and the space underneath (Fig 3). The green roof in the cells was substituted by another one in 2007, designed so that it could be built at a large scale with minimal technology, low cost materials, and little maintenance [8]. "Rice sack" tubular bags developed by the Cal Earth Institute, were cut and filled with a growth medium containing 50% native soil and 50% perlite. These bags were placed above an impermeable layer of plastic, which was placed on top of the roof decking as a moisture barrier. Slits were cut into the topside of the bag where sedums and succulents were planted, which have little need for water, maintenance, or soil depth. The bags were photodegradable to sunlight, thus over time the surface of the bags disappeared creating a soil strata evenly distributed over the roof. This same system was also used in an affordable low cost house prototype for Tijuana, Mexico, that was tested in the Fall of 2008.

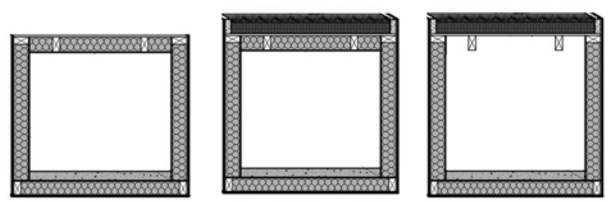

Figure 3: Cells with insulated white roof and green roof and uninsulated green roof

EXPERIMENTAL RESULTS

Series were performed over the course of several years and some of them are presented in this section.

Surface Temperature Surface temperatures in all cells were higher than the ambient temperature and the surface temperature of the white roof was significantly higher than the surface temperature of the green roof. In a series recorded in 2008 with succulent plants, the surface temperature under the plants averaged 11.2 C less than the surface temperature in the white painted roof (Fig. 4). If the roof was painted a darker cooler the temperature difference would be even more significant. Surface and ground temperatures in these cells are studied in more detail in another paper in this conference titled “Green Roofs: Beneficial in a Semi-Arid Climate” by M Figueroa.

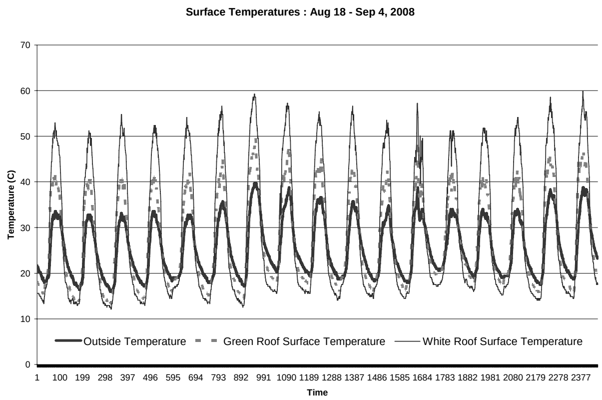

Figure 4: Comparison of Surface Temperatures Fall 2008.

Control and Validation Series Several series were performed in 2005 and 2008 to ensure that had similar thermal performance. Figure 5 shows results of a series in 2008 comparing both green roof cells with the same level of insulation. Both curves are very close together and there is no need for a correction factor. The insulation was then taken off again in one of the cells to continue comparing the performance of insulated and uninsulated green roofs.

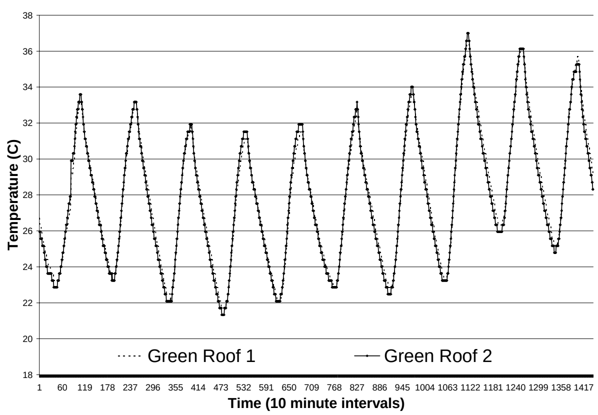

Figure 5: Comparison of Insulated Green Roof Cells.

Indoor Temperature with Different Window Dimensions The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable inside the building; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level, which determines the upper temperature limit of indoor comfort with still air or with air movement [9]. During the measurement period, night temperatures and relative humidity were sufficiently low for nocturnal ventilative cooling and all three cells have a timer that sets the fan set to operate from 9 PM to 5 AM at 25 air changes per hour.

The main building parameters that affect the effectiveness of nocturnal ventilative cooling are the insulation level, the amount of thermal mass and the amount of glazing. Three series were performed in 2005 with the same amount of thermal mass and insulation. The window dimension was “modified” by covering with insulation, affecting direct solar radiation and conduction. Three series were performed with different window dimensions: 0.37 m^2 window, 0.165 m^2 window, and no window.

Series 1: 100% window In this series initiated September 7, 2005, the window area is 0.37 m^2, or 25% of the floor area. Temperatures in all three cells are always higher than outdoor, especially during the daytime, due to the solar gain through the windows (Fig. 6). The values of the maximum temperature in the control cell are an average of 10.4 °C above the outdoor temperatures in the insulated green roof they are 7.6 °C above the outdoor temperatures, and in the uninsulated green roof they are 4.5 °C above the outdoor temperature.

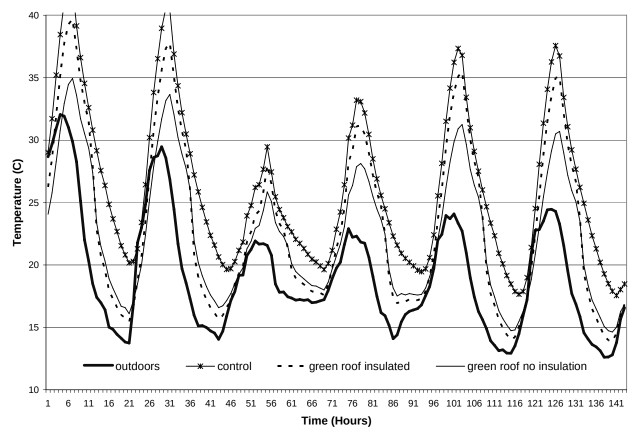

Figure 6: Series 1: 100% window, glazing to floor ratio 25%

Series 2: 50% Window In this series initiated September 7, 2005, the window is 0.185 m^2, or 12.5% of the floor area. During the day, the values of the maximum temperatures in the control cell are an average of 4.8 °C above the outdoor temperature, in the insulated green roof they are 3.2°C above the outdoor temperatures, and in the uninsulated green roof they are 1.2 °C above the outdoor temperature. Because the glazing to floor ratio is smaller, the difference between the maximum temperatures inside all cells and the outdoor maximum temperature is less than in the previous series (Fig. 7).

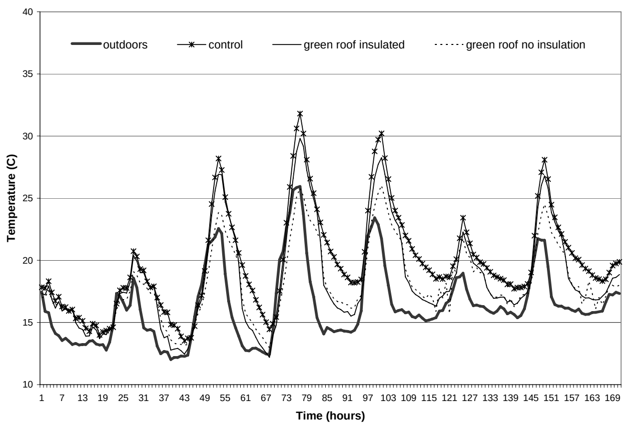

Figure 7: Series 2: 50% window, glazing to floor ratio 12.5%

Series 3: No window In this series initiated September 7, 2005, there is no window. During the day, the values of the maximum temperatures in the insulated control cell are an average of 0.7 °C below the outdoor temperature, in the insulated green roof they are 2.6 °C below the outdoor temperature, and in the uninsulated green roof they are 3.6 °C below the outdoor maximum temperature.

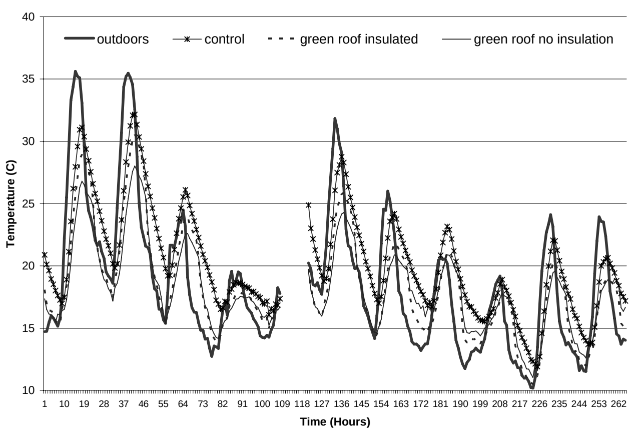

Figure 8: Series 3, No window.

Tests with different plants, shading and windows. In 2008 the single glazed window was substituted by a double glazed window, shaded with a 60 cm overhang that provided complete shading during the summer noon hours and partial shading during the morning and afternoon hours. The Saint Augustine grass was substituted in 2007 by succulent species that needed little water. Results of tests in 2008 are consistent with previous series and also indicate that the green roof with no insulation performs better than the insulated green roof and the insulated white roof (Fig 9).

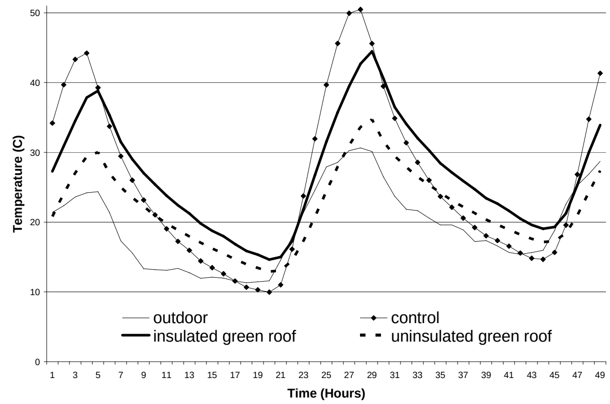

Figure 9: Two days in the 2008 series.

Temperature Difference Ratio The three series performed in 2005 are compared with each other using the Temperature Difference Ratio, TDR. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations [11] TDR is calculated using:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \qquad (1)$$

Where:
TDR: Temperature Difference Ratio
T_{maxout}: Maximum temperature outside
T_{maxin}: Maximum temperature inside
T_{minout}: Minimum temperature inside

The TDR concept normalises the capacity to reduce the indoor maximum temperature, as a function of the outdoor swing, permitting comparison of the different series. In a well ventilated building the TDR can't be higher than 1.0 and the resulting fraction can be expressed as a percentage. A higher value (closer to one), indicates a better performance and a larger temperature difference between outdoors (hot) and indoors (cool) and more cooling. A negative value indicates that the average maximum temperature inside is higher than outdoors. TDR is calculated for the three series and averaged for each one. The best TDR is in the uninsulated green roof, which performs much better than the other cells (Fig 10). The equations that predict TDR as a function of the floor to window ratio (FWR) are:

For the control cell:
$TDR = -4.352*FWR +0.0361$ (2)
In equation (2) $R^2 = 0.99$

For the green roof with insulation:
$TDR = -3.9325*FWR + 0.194$ (3)
In equation (3) $R^2 = 0.98$

For the green roof without insulation:
$TDR = 3.0588*FWR+0.2955$ (4)
In equation (4) $R^2 = 0.98$

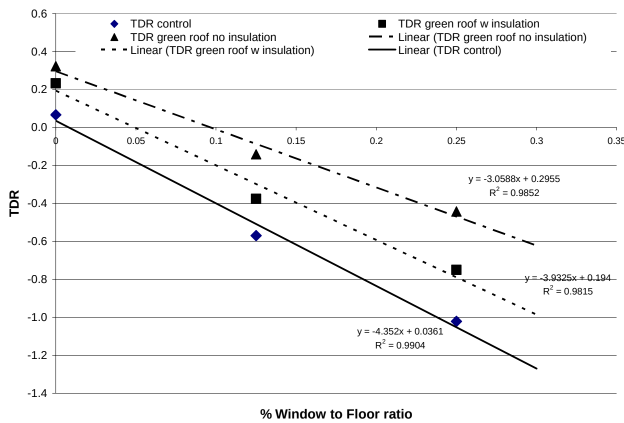

Figure 10: TDR as a function of the window to floor ratio

After TDR is calculated for a building using equations (2), (3), and (4) it is possible to predict the indoor maximum temperature using equation (1) and solving for T_{maxin}

$$T_{maxin} = T_{maxout} – [TDR * (T_{maxout} - T_{minout})]$$

Where outdoor maximum and minimum temperatures, or daily temperature swing, must be known. These equations would be valid in buildings with slab on grade concrete floors with a thickness of 4 cm.

Tests in a real building The green roof was tested in a real size building: the low cost housing prototype built at the Lyle Center for Regenerative Studies in Cal Poly Pomona for Tijuana, Mexico [11]. The walls are made of papercrete a mixture of cement and paper, the floor slab is concrete and the windows are single pane glass [12].

Figure 11: Green Roof of the Tijuana House (north view)

A low cost green roof similar to the one in the test cells has been built on the larger west-facing roof. The green roof was built with an impermeable layer directly on top of the roof deck with the perimeter of the roof boxed in to contain the growth medium. The roof is supported by a series of trusses built from reclaimed pallet wood. The same “Cal Earth” bag system that is used in the test cells is used here, with the growth medium, made of a mixture of native soil and vermiculite to reduce weight. The bags are cut in two foot sections that are easy to transport onto the roof, and placed on the roof in rows perpendicular with the downward edge of the roof. They also provide structure around the soil while the roots establish themselves.

Three series were performed in this building, in the late summer of 2008: continuous ventilation, night ventilation and minimal ventilation with all the windows closed. Results for the series with night ventilation, the same strategy used in the test cells are presented (Fig. 12). The maximum temperature inside the house is an average of 6.1 C below the maximum average temperature outdoors. The daily temperature swing averages about 21.3 C and the reduction in maximum temperature is about 29% of the average swing.

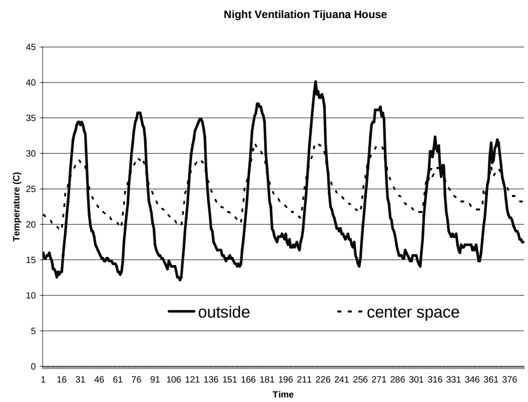

Figure 12: Green Roof of the Tijuana House

Equation (4) for night ventilated spaces with uninsulated green roofs and concrete slabs was tested. Maximum and minimum outdoor values were used. The south window to floor glazing ratio of the main living space where the main data logger sensor that is placed is 5% and TDR is 0.14256 applying equation (4). Predicted values using equations (1) and (4) are compared with measured values and a good correlation is observed between the predicted values and measured values on cloudy days (Table 1 & Fig 13). Because the house was not built to test these equations there are several variables that could account for the difference in performance between cloudy and sunny days: a) In the building there are additional windows that did not exist in the test cells, including east facing clerestory windows, b) the volume to envelope ratio of the space is much larger, and c) the U value and thermal lag of the walls is much different.

Table 1: Indoor Predicted and Measured Temperatures

	SUNNY	CLOUDY	CLOUDY	CLOUDY	SUNNY	SUNNY
Predicted Tmaxin=	**34.8**	**28.5**	**25.7**	**25.1**	**30.7**	**35.9**
Measured Tmaxin=	**28.3**	**27.9**	**26.3**	**25.2**	**27.1**	**28.1**
numerical difference	6.5	0.6	-0.6	-0.1	3.6	7.8
difference ratio	22.9%	2.2%	-2.2%	-0.2%	13.4%	27.9%

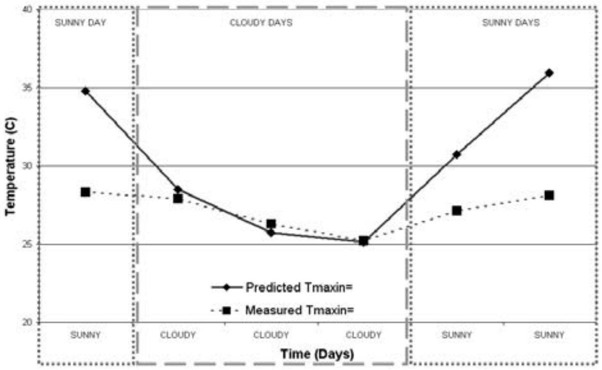

Figure 13: Calculated and Predicted Indoor Temperatures in the Green Roof of the Tijuana House

CONCLUSION

An uninsulated green roof combined with night ventilation can help cool a space in two ways: the canopy layer reduces the effect of solar gains by reducing the sol-air temperature, and the growth medium acts as a heat sink.

Results of tests over several years with different types of plants, windows, and shading systems, consistently indicate that in this climate, the uninsulated green roof performs better than the insulated green roof and the insulated white roof. This indicates that in a warm or mild climate with cool nights it is possible to combine a green roof with night ventilation, coupling the soil layer with the interior of the building. The vegetation in the canopy layer improves the performance of the system by blocking solar gains.

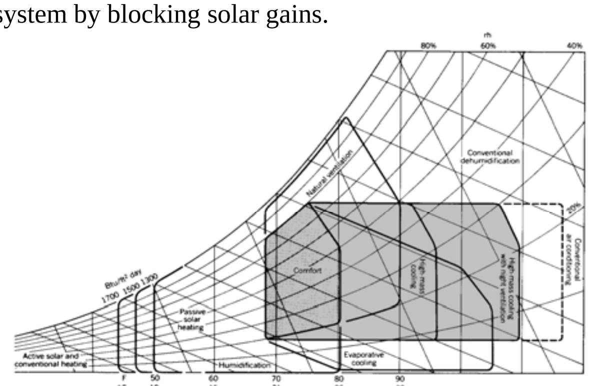

Figure 14: Applicability of uninsulated green roofs with night ventilation.

Simple equations are derived from the experimental work that permit to calculate internal maximum temperatures as a function of outdoor maximum temperature, daily swing, and glazing to floor ratio. One of these equations is tested in a real size building with acceptable results on cloudy days. More series should be performed under different climates and with different types of buildings to determine the effect of volume, thermal lag, thermal capacity and other building variables. Until these series are performed an applicability range similar to that indicated for thermal mass and night ventilation in Givoni and Milne's chart is proposed (Fig 14). In climates with moderate heating needs, where heat loss by conduction is not a critical issue, the uninsulated green roof could probably also be combined with a passive solar heating system (direct or indirect). This will be the subject of future research.

Green roofs, when combined with night ventilation can lead to more comfortable conditions inside buildings, with increased energy efficiency. This should give them added value increasing their applicability.

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