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IMPACT OF GREEN ROOF IN BUILDING ENERGY PERFORMANCE: EXPERIMENTAL AND NUMERICAL STUDY

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Abstract

Green roofs are considered an effective solution in contributing to the resolution of several environmental problems at building and urban levels. The present paper provides a numerical and experimental study of the impact of a green roof on energy performance of a building. A model of green roof thermal behavior was coupled with a building thermal code which permitted the evaluation of green roof foliage and soil surface temperatures. The model was experimentally validated according to green roof platform which was elaborated. It consists of 5 buildings, than 4 street canyons where 2 buildings were covered with various vegetated elements. Roof support surface temperature was evaluated, a reduction of the maximum temperature by 30 °C was found in the summer due to the green roof. The impact of the green roof on thermal comfort, cooling and heating demand was evaluated. With a green roof, summer indoor air temperature was decreased by 2 °C and annual energy demand was reduced by 6 %. Finally, the results found in this study lead us to better understand the influence of green roofs on the building thermal behavior.

Keywords: Green roofs, heat and mass transfer, experimental validation, thermal building code, albedo, water balance.

1 INTRODUCTION

Green roofs are considered an effective solution in contributing to the resolution of several environmental problems at building and urban levels. One of the most reasons often cited for green roofs is the buildings thermal insulation, this thermal point constitute an important part of the studies performed in this subject [1-3]. Green roofs play an insulating role introducing a reduction in the consumption of heating and cooling. However, the insulation characteristics of this type of roof depends on a number of parameters such as substrate thickness, building insulation thickness, climate zone, the moisture in the substrate, the cooling caused by the evaporation of the substrate and the transpiration of the vegetation and the shadows on the roof due to the foliage layer LAI (Leaf Area Index). The variation of all these factors can have very different effects on the roof insulation behavior [1-11].

Modeling green roof component and including it in a dynamic code to predict the thermal behavior of buildings is essential to build a useful tools for prediction of energy savings intended for engineering construction. In addition the integration of green roof model in a simulation tool of urban climate will also assess the impact of green roof on climate phenomena encountered in urban areas. The integration of a green roof in a building is more successful during the initial stages of the building design process, but it is, nevertheless, feasible on existing buildings [12].

In this study, an experimental platform was elaborated to validate a proposed green roof coupled model of heat and mass transfer. This developed model is coupled to a building model in a way that limits the estimation to the green roof system only and allows an objective comparison with conventional roofs. The performed experimental platform provides the experimental data of the hydrothermal behavior of green roofs and their interactions with building energy performance.

2 METHODOLOGY

2.1 Mathematical model

Modeling the thermal behavior of green roofs implies combining several phenomena, as heat and mass transfer and plants physiology. Many green roof models are available in the literature [5, 6, 8-11, 15, 16], ranging from simple to detailed. The simplest decreases the roof U-value [6, 9, 10]. Many other studies presented a green roof heat balance considering the important effect of foliage solar shading and cooling by evapotranspiration [5, 8, 11, 15]. Frankenstein and Koenig [8] developed a model with two heat balances at the roof soil ground and foliage surface. Main influencing parameters that affect the heat transfer in green roof were considered: foliage height, leaf area index (LAI), fractional vegetation coverage, albedo and stomatal resistance. The heat and mass transfer in the canopy was studied by considering the leaf as a solid body in which air circulates.

Based on Frankenstein and Koenig's works [8], Sailor [5] developed an energy balance model for green roofs. This model seems to be well adapted to evaluate the performance of the green roof system, because it considers several heat transfer phenomena in a relatively simple way and its well adapted to being coupled to thermal software.

The experimental validation in this study is performed for a coupled heat and mass green roof model [19] where the thermal modeling part was based on the work of Sailor [6] and Frankenstein and Koenig [13]. In addition, a water balance model was developed and coupled to the previous thermal balance model integrating the evapotranspiration process [16]. Indeed, the moisture transfer process accompanies energy transfer through the building envelopes and has a significant influence on indoor air humidity and air-conditioning loads, especially latent cooling load [17-19]. The present study is more interested in what happens at the soil level including and taking into account several proprieties of this medium. The green roof substrate is a medium with high porosity so that the proprieties changes with the presence of water which can affect the heat transfer through the roof.

2.2 Integration to building thermal modeling

Besides green roof modeling, coupling the green roof models with the building energy software (TRNSYS, EnergyPlus…) is an important issue. Models should limit estimation to the green roof system; and thus prevent it from making simplifications concerning heat transfer in the roof structure mainly about thermal mass and heat exchange between the roof and inside. This is important not only for an accurate evaluation of the thermal impact green roofs but also for the comparison with conventional roofs.

A schematic presentation of the coupling of the green roof model with the building is illustrated in Fig. 1. This approach allows us to limit the estimation to the green roof system (soil and canopy). In fact, a detailed calculation of the building thermal behavior is done in the building block (Fig. 1) using a building thermal software like TRNSYS and EnergyPlus. This detailed calculation includes the heat transfer through the roof support (that considers the thermal mass) and the heat transfer between the inside surface of the roof and the inside of the building. Tr present the temperature in the top of the roof support. Us is the U-value of the soil (W/m2 K).

In this work, the proposed model is coupled with TRNSYS software by creating a new component. Once the new component is included in TRNSYS, it can be used, in the same way as any other TRNSYS standard component, to evaluate the impact of green roofs on the building energy performances.

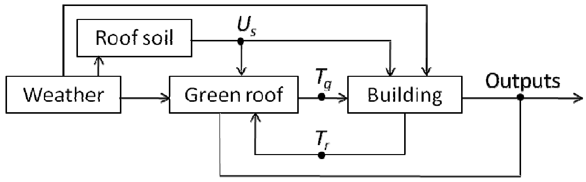

Fig. 1: Coupling the green roof model to building thermal model

3 EXPERIMENTAL VALIDATIONS

An experimental platform with green roofs (scale 1: 10) was constructed on the site of the University of La Rochelle. The objective of this installation is to obtain an experimental data about the hydrothermal behavior of green roofs and their interactions with building energy performance. It is also used to undertake comparisons with the numerical results and thus validate the developed mathematical models. This work is part of the AGROBAT project funded by the Poitou-Charentes region (France), which is the study of the impact of green roofs on building energy performance with multidisciplinary approach.

To reflect a real urban setting, the conception of the reduced models requires both physical and geometrical similarities with reality. Reaching a geometric similarity is not fundamentally complicated. For our case of study, we focused on a simple repetition of street canyons (ratio W/H=1) formed by rectangular buildings without windows. The platform consists of 15 buildings forming 5 rows and therefore 4 street canyons, the first 3 were used to study the impact of the treatments surface by paintings with selective optical properties on the energy efficiency of buildings. The facades of these building were also painted with a standard color. The last two rows are equipped with green roof complex. Two different plants are used (sedum and grass) (Fig. 2). Recently, a green wall was put in place to achieve the same study performed for green roofs.

Fig. 2: Photography of the experimental platform

Two types of green roofs were selected to cover the last two rows of the studied experimental platform. The vegetation used for the first row is sedum and the type of the green roof is called Toundra. The second row is covered with grass and various plants; this type of green roof is called Pampa.

The experimental program took place at the level of green roof components, inside and outside the buildings. A weather station was installed on the site to track the metrological data of the site (air temperature, relative humidity, incident short and long-wave radiations, wind speed and precipitation). Thermocouples measuring temperatures at different levels of green roof components were installed. TDR (Time Domain Reflectometry) sensors were used to measure the volumetric water content at the substrate layers. Moreover, heat fluxes sensors were installed at the sealing membrane to measure the conducted heat flux. Finally, two rain gauges were installed under the eaves to measure the amount of water drained. The Figure 3 represents the disposition of these sensors on three buildings of the platform (The two buildings with green roofs and the building with conventional roof).

The incident long and short wave radiations were measured using a radiometer grouping a pyranometer CMP3 and a pyrgemeter CGR3. Furthermore, we were interested in measuring the radiative fluxes of long and short wave radiation reflected by the two green roofs. For this, we set up for each green roof a pyranometer and a pyrgeometer directed downward (Figure 3). Using the measurement values of the incident and the reflected radiative fluxes, the albedo characterizing each type of green roof instrumented was deduced. This term is defined by the ratio of the reflected radiative flux and the incident radiative flux.

Fig. 3: Pyranometer CMP3 and Pyrgeometer CGR3 used to measure the reflected flux of long and short wave radiation

An important consideration was given to the hydrodynamic characterization of the substrate; indeed, the dynamics central of water has an important role in the functioning and the sustainability of green roofs. Thus, gutters equipped with rain gauges were fixed on the lower slope of green roof and at the weather station to collect rain and drained water. This allows undertaking the water balance of green roof.

4 EXPERIMENTAL RESULTS

The figure 4 shows the experimental data of the temperature recorded by the sensors for two different periods; a hot summer period of July from and a cold winter period of December. The acquisition of the experimental data is recorded every 5 minutes. The data recorded by the sensors is displayed directly on the lab computers via an Ethernet connection.

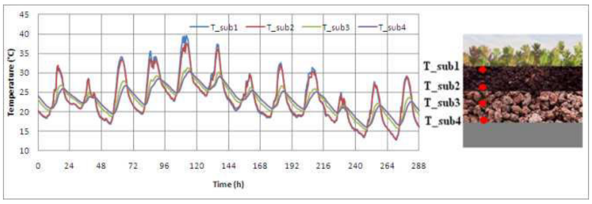

Fig. 4: Temperatures profiles at different levels of green roof components.

The temperature difference between the exterior surface (T_sub1) and the sealing membrane (T_sub4) can reach 10°C during a hot day of summer. These results provide the role of green roof thermal resistance to limit the heat flux conducted through the roof. Furthermore, the temperature variation at the sealing membrane (T_sub4) is relatively moderate for a hot period of summer. This temperature variation is more important in the case of a conventional roof. The moderate levels of temperatures and low temperature fluctuations will have a significant impact on the surface temperature of green roof supporting structure; hence, the roof longevity is increased.

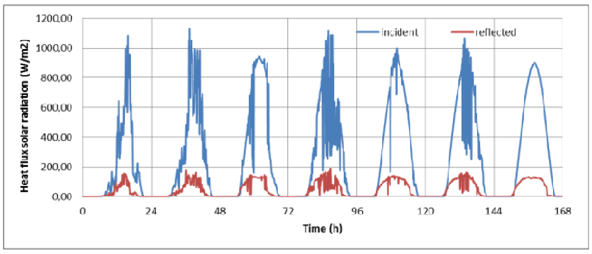

Fig. 5: Measurments of incident and reflected heat flux solar radiations for a period of week

Figure 5 shows the measurements of the incident and reflected solar radiation for a hot summer period. Through these measures, the albedo is derived by dividing the reflected flux of solar radiation on the incident flux of solar radiation. The value of albedo for this period is 0.24, this value is given by the average ratio of the radiative fluxes calculated for each day of the period studied. This value is less important compared with conventional roofs. This is explained by the role of the vegetation witch consist to absorb a part of the incident radiation for the photosynthesis process and by the inter-reflection phenomenon between the leaves of the plants. This means that less radiation flux is reflected by the green roof. The decrease of the thermal heat gained by the building is due to the reflection of solar radiation and to the evapotranspiration phenomenon.

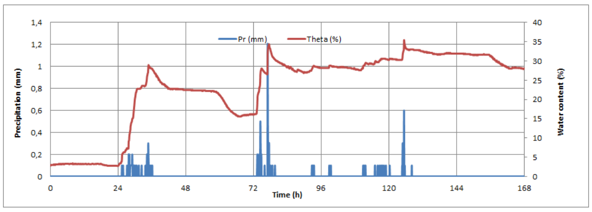

Fig. 6: Precipitation and water content evolution of the growing media for a period of week

Figure 6 shows the rainfall data recorded by the rain gauge for a period of week. In the same figure, shown in red, the variation of the water content in the green roof substrate was presented. This quantity was given by the average of the measurements recorded by the TDR sensors positioned at different levels of the green roof components.

It is noticed through the presented results that the water content starts to decrease significantly after the second day of rain but after the 4th day, we notice that the water content becomes relatively stable, this is can be explained by the high water retention of the green roof substrate. This water retention can be beneficial to the vegetation and can also minimize the risk of flooding.

We are interested in comparing the experimental and numerical results to validate the numerical model developed. For this comparison, the weather data that was recorded as the air temperature Ta, relative humidity RH, short-wave radiation Is, long-wave radiation Iir and precipitation P are similar to the inputs data that we use to calculate the outputs Tf and Tg values with the numerical model. During the same period, the soil surface temperature Tg was measured and calculated with the numerical model. The validation was performed for two different periods; a hot period of summer (17/08/2011-11/09/2011) and a cold period of winter with recorded precipitation (01/12/2011-31/12/2011).

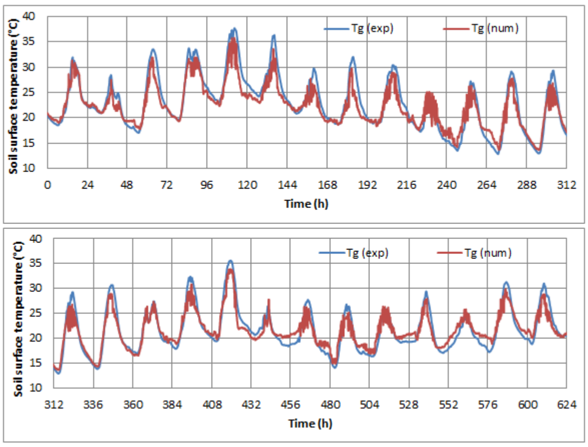

Fig. 7: Comparison between experimental and numerical results for summer period

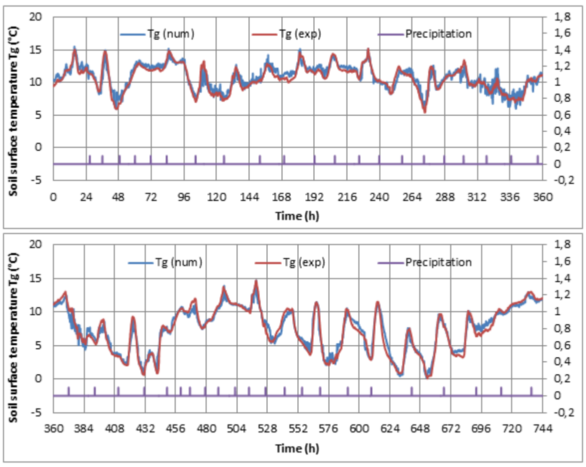

Fig. 8: Comparison between experimental and numerical results for cold winter period

Both of Figures represent the variation of the soil surface temperature Tg for a period of one month of simulation. This variation is compared to the results of the soil surface temperatures obtained experimentally. For one month of confrontation, the temperature profiles obtained experimentally and numerically are close. Indeed, differences do not exceed 1°C were observed. The results show that the temperature variations at the soil surface obtained with the coupled proposed model allows us to say that the developed model can reproduce the overall trends under the influence of the green roof.

5 APPLICATION ON BUILDING THERMAL SIMULATION

5.1 Case study

The method is applied to evaluate the impact of a green roof on the energy performance of a single family house of 96 m². The house is located in La Rochelle France where the climate is considered as temperate oceanic. The mean value of the internal heat gain is 5 W/m². For the winter period, the heating set point temperature is equal to 19 °C. For the summer period, two cases were studied, cooling demand (set point temperature of 28 °C) and the indoor air temperature (without cooling). Comparisons were made for the house energy performance between conventional and green roofs. Simulations where conducted using TRNSYS software.

For the green roof case, we first show the soil and foliage temperatures (Tg and Tf) based on the soil and foliage heat balance. Then, for both conventional and green roofs, we compare the following parameters:

• The Temperature of the exterior surface of the roof support (Tr);

• The heat flux through the roof to the inside of the building (qri);

• The indoor air temperature (Ti);

• The heating and cooling demand (Qh and Qc).

Temperature profiles, flux through the roof and the energy demand are shown for three typical days of La Rochelle climatic data. For the winter season, we consider the day with the minimum yearly temperature (13th of January) and the day with the maximum solar irradiation (7th of April). For the summer season, we consider the day with the maximum yearly temperature (21st of July).

5.2 Results and discussions

Energy performance of the studied house for conventional and green roofs has been presented in Figs. (9-13). These figures suggest that the impact of the process of heat transfer through a green roof which is different from the one encountered in a conventional roof. Temperature profiles and thus the heat flux through the roof changed in a significant way because of the presence of vegetation and soil on the roof.

For the temperature of the foliage (Tf), Fig. 10 shows that it is highly influenced by the solar radiation. For the three studied days, it appears hotter than the outside temperature during the day and colder during the night. The foliage temperature is higher than the soil temperature during the sunny winter and the hot summer days. This is mainly due to the fact that, during the day, solar radiation are largely absorbed by the vegetation, and during the night, it is directly exposed to the cold air temperature and has a high infrared radiative exchange with the cold sky compared with the soil one.

Concerning the soil temperature (Tg), in the cold winter day (Fig. 9 (a)), it appears warmer than the outside temperature. This is because of the foliage that plays an insulating role and limits the heat transfer between the roof and the outside. For the sunny winter day (Fig. 9 (b)), it is colder than the outside temperature, that is mainly due to the effects of transpiration and solar shading of the foliage. On the hot summer day (Fig. 9 (c)), the soil temperature is colder than the outside temperature for the same reason. It is worth saying, that, for the three cases, Tg varies in a relatively moderate range, 2-10 °C for the cold winter day, 7-17 °C during the sunny winter day and 9-19 °C during the hot summer day. These moderate temperature levels and ranges will have an impact on the roof support surface temperature in comparison with a conventional roof.

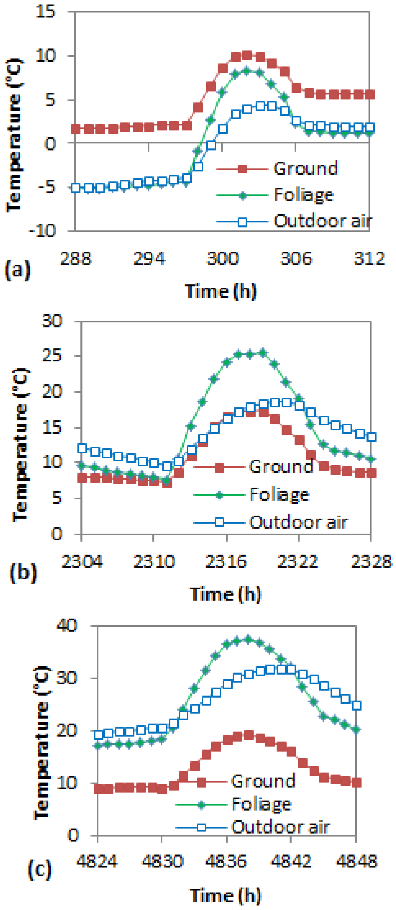

Fig. 9: Soil and foliage surface temperatures during three typical days in La Rochelle (cold winter (a) and sunny winter (b) and hot summer (c)).

The comparison of the outside roof support temperature (Tr), between standard and green roofs is shown in Fig. 10. As expected, the range of variation of Tr is clearly lowest for the green roof each day and in between these days. Where Tr reaches –6°C in winter and +58°C in summer for the conventional roof, it is still between –4 °C and 20 °C for the green roof. The reduction of the variation range of Tr due to the green roof reaches 30 °C on the hot summer day.

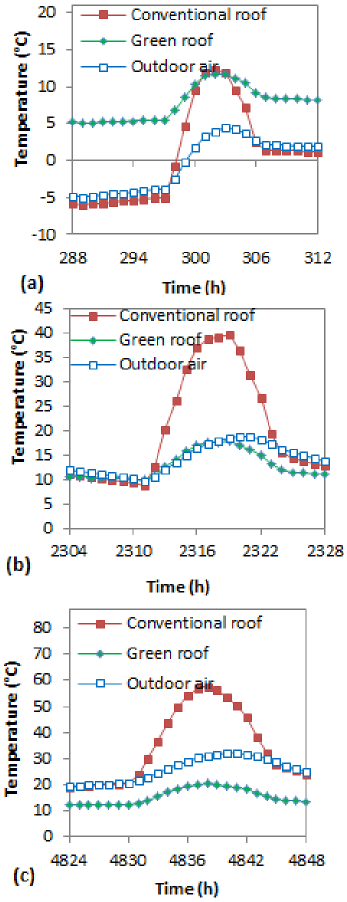

Fig. 10: Temperature of the exterior surface of the roof support during three typical days in La Rochelle (cold winter (a) and sunny winter (b) and hot summer (c))

This important effect of the green roof on the roof support outside temperature will have an impact on the heat flux exchanged between the roof support and the inside. For the winter season, Fig. 11 (a) and (b) show, that the heat losses are lower on the cold day but greater on the sunny day in the case of a green roof. Thus the green roof could increase or decrease the building heating demand depending on the winter outside conditions and mainly the solar radiation. During the hot summer day (Fig. 11 (c)), the free cooling effect of green roof is clear; total heat loss through the roof was 5.5 kWh/day for conventional roof and 15.2 kWh/day for green roof.

Indoor conditions and energy demand are directly affected by the variation of the heat flux through the roof due to the green roof usage. For the indoor temperatures, Fig. 12 illustrates a constant value of 19 °C maintained by the heating system during the cold winter day. During the sunny winter day, this temperature, when it exceeds 19 °C, is slightly higher for the conventional roof, due to its lower heat losses. During the hot summer day, indoor air temperature is lower by 2 °C due to the usage of the green roof; hence green roof contributes effectively to the summer comfort.

For the energy demand, there is a similar heating demand for houses with a green and a conventional roof (Fig. 13). This means that for the temperate climate of La Rochelle, decreasing the heating demand due to green roof during cold winter days is equal to its increase during the sunny winter days.

Fig. 7 shows also that the cooling demand was highly reduced due to green roof free cooling effect and was almost equal to zero. Finally, due to the cooling demand reduction, the total energy demand was reduced by 6 %.

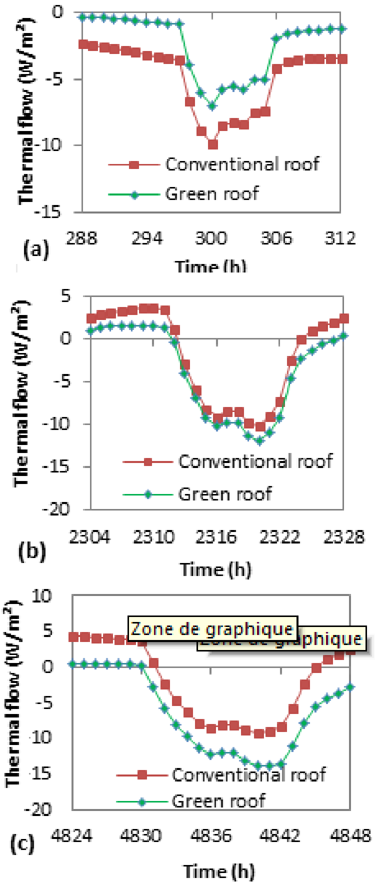

Fig. 11: Thermal flow through the roof during three typical days in La Rochelle (cold winter (a) and sunny winter (b) and hot summer (c)).

6 CONCLUSION

In this work, a study of the incidence of green roof on the building energy performance was presented. Integrating the roof model to a building thermal model was in a simple way that limits estimation to the green roof model. The impact of green roof on the energy performance of the experimental platform was evaluated with an experimental validation where a detailed implementation of different sensors in the platform is presented. Temperatures profiles of the foliage, the ground and the exterior surface of the roof support were studied for cold and hot days of the year with a climate of La Rochelle. A comparison between green and conventional roof was undertaken and simulations were performed to evaluate the cooling and the heating energy demand.

The temperature of the green roof soil is moderate by comparison to the outside air temperature, especially in summer. This is due to the different thermal phenomena that occur in the green roof, as shading, evapotranspiration and thermal resistance. The presence of green roof prevents roof support extreme temperature and high temperature fluctuations. Thus, it increases the longevity of the roof.

A free cooling effect was observed in summer, the daily heat losses were almost three times more with a green roof. This makes green roofs an effective solution in enhancing the thermal comfort and reducing the cooling demand.

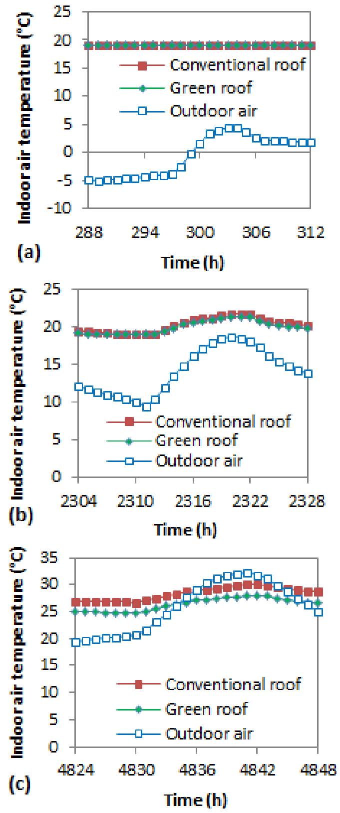

Fig. 12: Indoor air temperature for three typical days in La Rochelle (cold winter (a) and sunny winter (b) and hot summer (c)).

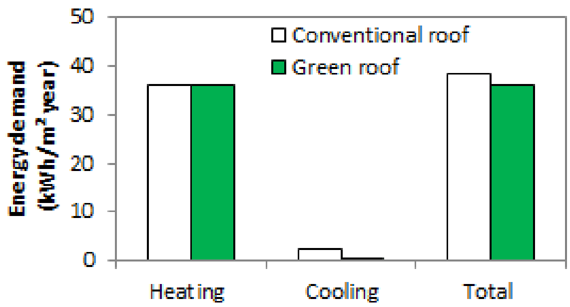

Fig. 13: Energy demand for conventional and green roofs in La Rochelle

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