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A comprehensive study of the impact of green roofs on building energy performance

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ABSTRACT

Green roofs have several environmental benefits, such as improving building energy efficiency. The present paper provides a comprehensive study of the impact of a green roof on building energy performance. A model of green roof thermal behavior was coupled with a building code to allow the evaluation of green roof foliage and soil surface temperatures. Simulations were conducted for a single-family house with conventional and green roofs in a temperate French climate. In the summer, the fluctuation amplitude of the roof slab temperature was found to be reduced by 30 °C due to the green roof. The heat flux through the roof was also evaluated. In the summer, the roof passive cooling effect was three times more efficient with the green roof. In the winter, the green roof reduced roof heat losses during cold days; however, it increased these losses during sunny days. The impact of the green roof on indoor air temperature and cooling and heating demand was analyzed. With a green roof, the summer indoor air temperature was decreased by 2 °C, and the annual energy demand was reduced by 6%. The present study shows that the thermal impact of green roofs is not functionally proportional to the leaf area index parameter. It also shows the high dependency of this impact on the roof insulation. Finally, the simulations suggest that green roofs are thermally beneficial for hot, temperate, and cold European climates.

1. Introduction

Green roofs are considered to be an effective contribution to the resolution of several environmental problems at the building and urban levels. In addition to the creation of a pleasant environment, green roofs offer several benefits in comparison to conventional roofs. They improve storm water management [1,2] as well as reduce air pollution [3,4] and noise [5]. Green roofs increase vegetal and animal biodiversity in cities [6,7], and they also reduce a city's carbon footprint by converting carbon dioxide to oxygen through photosynthesis [4,8].

Green roofs improve building energy efficiency by enhancing the heat transfer through roofs [2,9–23]. The reduction of the summer temperature around green roofs improves the efficiency of HVAC systems by providing a local free cooling effect to the fluid before it returns to the chiller. This reduced temperature also improves the efficiency of surrounding photovoltaic panels [20]. Green roofs improve the longevity of roofing membranes by limiting the thermal stress to which they are subjected [2,15,17,21,24–26]. Finally, at the city level, green roofs contribute to the mitigation of the urban heat island effect [14,21,27,28].

Two types of green roofs are generally identified: extensive (with soil thickness less than 10–15 cm) and intensive (with soil thickness more than 15–20 cm) [2,8,13,16,20,23,24,29–31]. Because of their low additional loads, extensive green roofs are suitable for building retrofitting, i.e. they do not require any additional strengthening [20]. By calculating the net present value (NPV), Carter and Keeler [31] suggest that green roofs become more economic than traditional roofs if their cost decreases by 20%.

The choice of green roof characteristics depends greatly on climate. For instance, in Australia, solutions for green roofs (plants, substrate, etc.) may be different from those used in the European climate [29]. A study on the choice of suitable plant species for green roofs in the midwestern US climate is presented in [30].

The surface temperature of conventional roofs can reach very high values in the summer. For instance, a temperature of 90 °C was recorded in Australia [29]. Green roofs have a large impact on this temperature because of several effects (foliage shading, soil thermal resistance, evapotranspiration, etc.). The heat flux through the roof is therefore affected, which influences the building energy

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demand and the indoor thermal conditions. The summer and winter temperatures on the exterior surface of the roof slab are less extreme, and their fluctuation amplitude is lower than that of a conventional roof. Thus, the thermal stress applied to roofing membranes is substantially limited, which improves their longevity [2,15,17,21,24–26].

Although there are many works dealing with the impact of green roofs on building energy performance, many aspects are still not well understood, and more studies on this subject are necessary. For instance, quantifying the impact of green roofs on indoor air temperature has not yet been examined with detailed models. In addition, the variation of the building energy demand and indoor conditions as a function of key parameters, such as the roof insulation, climate, and green roof configuration, requires further investigation.

In this study, a comprehensive analysis of the impact of green roofs on the thermal performance of buildings is presented, including consideration of the foliage and green roof soil temperatures, the indoor air temperature, and the energy demand. For this purpose, a green roof thermal model was coupled with a building model, and a comparative study was made between the energy performance of conventional and green roofs on a single-family house.

2. Green roof modeling

Modeling the thermal behavior of green roofs requires the study of several interacting phenomena, such as heat and mass transfer and plant physiology. Many green roof models are available in the literature, ranging from simple to detailed. The simplest model considers only the decrease of the roof *U*-value [9–11]. Many other studies have presented more detailed models, with a heat balance that considers additional influencing phenomena, such as solar shading by foliage and cooling by evapotranspiration [12,13,17,18,21,32,33].

Del Barrio [12] developed a thermal model for the impact of green roofs on building energy performance. She divided the green roof system into three main parts: canopy, soil, and roof slab. A heat balance calculation was performed for each part in association with boundary conditions at the canopy–soil, soil–roof slab, and roof slab–indoor air interfaces.

Frankenstein and Koenig [32] developed the FASST (Fast All-Season Soil Strength) model. Two heat balances are considered, at the roof soil surface and at the foliage surface. The main influencing parameters that affect heat transfer for a green roof were considered: foliage height, leaf area index (LAI), fractional vegetation coverage, albedo, stomatal resistance, etc. The heat and mass transfers in the canopy were studied by considering the leaf as a solid body in which air circulates.

Sailor [13] developed an energy balance model for green roofs. The model is based on the energy balance equations developed by Frankenstein and Koenig [32]. The model was linearized and integrated into the EnergyPlus program. The model was validated on a University building in Florida. Then, it was used to evaluate the energy consumption for office buildings in Chicago and Houston.

Kumar and Kaushik [19] developed a mathematical model based on the work of Del Barrio [12] to evaluate the thermal impact of green roofs and solar shading. It was validated for a green roof in Yumuna Nagar (India). The results suggest that a high value of the LAI parameter decreases the canopy air temperature, stabilizes its fluctuation and reduces the flux through the roof.

Photosynthesis was included in the thermal balance by Fenget al. [8]. A finite differences model considering several green roof levels was developed by Lazzarin et al. [23].

Alexandri and Jones [14] developed a two-dimensional model to study the impact of green roofs and walls on the microclimate in a typical canyon. The model results were analyzed for nine typical climates. For the roof surface, the results suggest that the highest decrease of the mean temperature was 12.8 °C in Riyadh (desert climate). The highest decrease of the maximum temperature was 26.1 °C in Mumbai (rain forest climate).

Generally speaking, available studies show that green roofs decrease cooling demand and improve summer thermal comfort [9–14]. Few studies have considered the impact of green roofs on heating demand. For the Mediterranean climate of Athens, this impact depends on the month and is either globally insignificant [9,16] or constitutes a decrease in the demand [11]. Winter energy consumption was also decreased by the use of green roofs in the climates of Houston and Chicago [13].

Many green roof soil parameters, such as thermal conductivity, specific heat capacity, short-wave reflectivity and albedo, vary as a function of the moisture content [34]. The optical properties and geometry of foliage vary as a function of many parameters (age, vegetation water content, soil water content, mineral deficiencies, outdoor conditions, etc.) [35]. These properties are considered to be constants in the actual green roof models. Hence, developing coupled heat and mass transfer models for green roofs and studying properties of vegetation and soil are important issues. However, these are not the objectives of this work, which focuses on coupling a green roof model with a building code and on the analysis of the impact of green roofs on building energy performance.

In fact, the model developed by Sailor [13], based on the works of Frankenstein and Koenig [32], seems to be well adapted to evaluate the performance of green roof systems. Even if many simplifications were made (foliage optical and geometric properties, mass transfer, etc.), this model considers several heat transfer phenomena in a relatively simple way. It is also well adapted to coupling with thermal software, as has been performed with EnergyPlus in the same work. Castleton et al. [20] also recommended the use of this model. Hence, the model presented for the evaluation of green roof thermal behavior in this study is based on Sailor's approach.

In addition to green roof modeling, the coupling of models with building energy programs (TRNSYS, EnergyPlus, etc.) is an important issue. Models should focus on the green roof system (canopy and substrate), thus avoiding simplifications concerning the heat transfer in the roof structure (mainly regarding its thermal mass and heat exchange between the roof and the interior). This is important not only for an accurate evaluation of the thermal impact of green roofs but also for comparison with conventional roofs.

3. Method

3.1. Mathematical model

The presented model divides the green roof heat balance into two parts: the balance at the foliage and at the soil surface. The heat balance equations are based on the models developed and validated in the works of Sailor [13] and Frankenstein and Koenig [32]. The main heat fluxes that describe the heat balance of the canopy are the following.

- The solar radiation absorption by the foliage.
- The long-wave radiation exchange between the foliage and the sky as well as between the foliage and the soil surface.
- The convection heat exchange between the foliage and the air in the canopy H_f (W m^{-2}).
- The latent heat flux by evapotranspiration in the foliage L_f (W m^{-2}).

The foliage heat balance (W m^{-2}) is given by