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

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A B S T R A C T

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 ($\mathrm{W\,m^{-2}}$).
- The latent heat flux by evapotranspiration in the foliage L_f ($\mathrm{W\,m^{-2}}$).

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

$$F_{\mathrm{f}} = \sigma_{\mathrm{f}}\left[I_{\mathrm{s}}(1-\alpha_{\mathrm{f}})+\varepsilon_{\mathrm{f}}I_{\mathrm{ir}}-\varepsilon_{\mathrm{f}}\sigma T_{\mathrm{f}}^4\right]+\frac{\sigma_{\mathrm{f}}\varepsilon_{\mathrm{f}}\varepsilon_{\mathrm{g}}\sigma}{\varepsilon_1}\left(T_{\mathrm{g}}^4-T_{\mathrm{f}}^4\right) + H_{\mathrm{f}}+L_{\mathrm{f}} \qquad (1)$$

where ε_{g} and ε_{f} are the soil and foliage emissivity, respectively, T_{g} and T_{f} (Fig. 1) are the soil and foliage temperatures (Kelvin), respectively, I_{s} and I_{ir} are the short- and long-wave radiations ($\mathrm{W\,m^{-2}}$), α_{f} is the canopy albedo, σ is the Stefan–Boltzmann constant ($5.6710 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$) and σ_{f} is the density of the foliage.

ε_1 is expressed as

$$\varepsilon_1 = \varepsilon_{\mathrm{f}}+\varepsilon_{\mathrm{g}}-\varepsilon_{\mathrm{f}}\varepsilon_{\mathrm{g}} \qquad (2)$$

The term of the sensible heat flux H_{f} is given by Deardoff [36]:

$$H_{\mathrm{f}} = \left(e_0+1.1\mathrm{LAI}\rho_{\mathrm{af}}\mathrm{Cp_a}C_{\mathrm{f}}W_{\mathrm{af}}\right)\left(T_{\mathrm{af}}-T_{\mathrm{f}}\right) \qquad (3)$$

where e_0 is the windless exchange coefficient, C_{f} is the bulk transfer coefficient, T_{af} is the air temperature within the foliage (Kelvin), W_{af} is the wind speed at the air–foliage interface ($\mathrm{m\,s^{-1}}$), Cp_a is the specific heat of air at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$), and ρ_{af} is the air density within the foliage ($\mathrm{kg\,m^{-3}}$).

The latent heat flux exchanged between the vegetation and the atmosphere near the surface of the vegetation is given by [36]:

$$L_{\mathrm{f}} = \mathrm{LAI}\rho_{\mathrm{af}}C_{\mathrm{f}}lW_{\mathrm{af}}r''\left(q_{\mathrm{af}}-q_{\mathrm{f,sat}}\right) \qquad (4)$$

where l is the latent heat of evaporation ($\mathrm{J\,kg^{-1}}$), q_{af} is the mixing ratio of the air at the foliage interface, and $q_{\mathrm{f,sat}}$ is the saturation mixing ratio at the foliage temperature.

The main heat fluxes that describe the heat balance of the soil surface level are the following.

- The absorption of solar radiation by the soil.
- The exchange of long-wave radiation between the soil and the sky as well as between the soil and the foliage.
- The sensible heat flux exchange with the air in the canopy H_{g} ($\mathrm{W\,m^{-2}}$).
- The latent heat flux L_{g} ($\mathrm{W\,m^{-2}}$).
- The heat flux conducted through the soil q''_{sg} ($\mathrm{W\,m^{-2}}$).

The soil energy balance ($\mathrm{W\,m^{-2}}$) is given by

$$F_{\mathrm{g}} = (1-\sigma_{\mathrm{f}})\left[I_{\mathrm{s}}(1-\alpha_{\mathrm{g}})+\varepsilon_{\mathrm{g}}I_{\mathrm{ir}}-\varepsilon_{\mathrm{g}}\sigma T_{\mathrm{g}}^4\right]-\frac{\sigma_{\mathrm{f}}\varepsilon_{\mathrm{f}}\varepsilon_{\mathrm{g}}\sigma}{\varepsilon_1}\left(T_{\mathrm{g}}^4-T_{\mathrm{f}}^4\right) + H_{\mathrm{g}}+L_{\mathrm{g}}+q''_{\mathrm{sg}} \qquad (5)$$

For the soil, the sensible heat flux is given by [36]:

$$H_{\mathrm{g}} = \left(e_0+\rho_{\mathrm{ag}}\mathrm{Cp_a}C_{\mathrm{h}}^{\mathrm{g}}W_{\mathrm{af}}\right)\left(T_{\mathrm{af}}-T_{\mathrm{g}}\right) \qquad (6)$$

where ρ_{ag} is the air density near the ground ($\mathrm{kg\,m^{-3}}$) and $C_{\mathrm{h}}^{\mathrm{g}}$ is the bulk transfer coefficient for the sensible heat.

The latent heat flux is given by [36]:

$$L_{\mathrm{g}} = C_{\mathrm{e}}^{\mathrm{g}}l\,W_{\mathrm{af}}\rho_{\mathrm{ag}}\left(q_{\mathrm{af}}-q_{\mathrm{g}}\right) \qquad (7)$$

Where $C_{\mathrm{e}}^{\mathrm{g}}$ is the bulk transfer coefficient for the latent heat and q_{g} is the mixing ratio of the air at the ground surface.

A detailed expression of the heat flux through the soil q''_{sg} is presented in [12]. The boundary conditions at the canopy–soil and soil–roof slab interfaces are

$$\begin{cases} T_{\mathrm{s}}(0) = T_{\mathrm{g}} \\ T_{\mathrm{s}}(L) = T_{\mathrm{r}} \end{cases} \qquad (8)$$

where $T_{\mathrm{s}}(0)$ is the temperature at the top level of the soil (Kelvin), $T_{\mathrm{s}}(L)$ is the temperature at the bottom level of the soil (Kelvin), and T_{r} (Fig. 1) is the temperature at the top level of the roof slab (Kelvin).

Eqs. (1), and (5) are fourth-order functions in which the temperatures at the foliage and the soil surfaces are unknown. In order to solve these equations, the fourth-order terms T_{f}^4 and T_{g}^4 are linearized as follows:

$$T_{\mathrm{g}}^4 = (T_{\mathrm{g}})_{m-1}^4+4(T_{\mathrm{g}})_{m-1}^3\left[T_{\mathrm{g}}-(T_{\mathrm{g}})_{m-1}\right] \qquad (9)$$

$$T_{\mathrm{f}}^4 = (T_{\mathrm{f}})_{m-1}^4+4(T_{\mathrm{f}})_{m-1}^3\left[T_{\mathrm{f}}-(T_{\mathrm{f}})_{m-1}\right] \qquad (10)$$

The index $(m-1)$ indicates the temperature obtained in the previous time step.

It results in two linear equations with two unknowns give the temperatures at the foliage (T_{f}) and soil surfaces (T_{g}). The assessment of these temperatures is necessary to evaluate the heat exchange with the outside environment, and thus to evaluate the impact of green roofs on the mitigation of the urban heat island effect. Finding the temperature at the soil surface (T_{g}) is essential to evaluate the impact of a green roof on building energy performance.

3.2. Integration to building thermal modeling

A schematic presentation of the coupling of the green roof model with the building model is illustrated in Fig. 2. This approach allows us to limit the simplification to the green roof system (substrate and canopy). In fact, a detailed calculation of the building thermal behavior is carried out in the building block (Fig. 2) using building simulation software, such as TRNSYS or EnergyPlus. This detailed calculation includes the heat transfer through the roof slab (considering its thermal mass) and the heat transfer between the inside surface of the roof and the interior of the building.

In this work, the proposed model is coupled with TRNSYS software by creating a new component. The model source code was developed using the C++ programming language. 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 building energy performance.

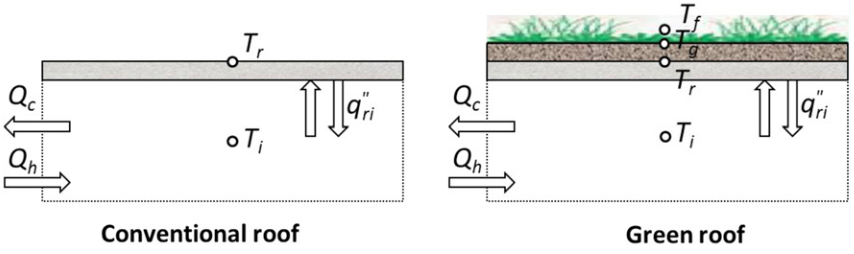

Fig. 1. The studied parameters for conventional and green roofs.

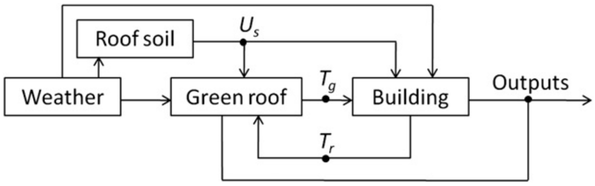

Fig. 2. Coupling of the green roof model with the building thermal model.

4. Case study

The developed approach is applied to the evaluation of the impact of a green roof on the energy performance of a single-family house with an area of 96 m^2. The window-to-wall ratio is 0.18. The mean value of the internal heat gain is 5 $W\,m^{-2}$. The house is located in La Rochelle (France), where the climate is considered to be temperate oceanic. Comparisons were made for the energy performance of the house with a conventional roof and an irrigated extensive green roof. The green roof considered in this case is sedum planted and has a soil composed of a mixture of 40% organic materials (compost) and 60% volcanic materials (pozzolan). Dynamic simulations were conducted using TRNSYS software for a one-year period using the standard TM2 meteorological file for La Rochelle. For the winter period, the heating set-point temperature was equal to 19 °C. For the summer period, two cases are presented, for the cooling demand (for a set-point temperature of 28 °C) and the indoor air temperature (free-floating, without cooling).

For the green roof case, the soil and foliage temperatures are first shown (T_g and T_f, respectively). These values were assessed based on the soil and foliage heat balance (Section 3.1), enabling the comparison of the following parameters for both conventional and green roofs (Fig. 1).

- The temperature of the exterior surface of the roof slab (T_r).
- The heat flux through the roof to the inside of the building (q''_{sg}).
- The indoor air temperature (T_i).
- The heating and cooling demand (Q_h and Q_c, respectively).

The evolution of the temperatures and of the flux through the roof are presented for three typical days of La Rochelle climatic data. For the winter season, the day with the minimum yearly temperature (the 13th of January) and the day with the maximum solar radiation (the 7th of April) are considered. For the summer season, the day with the maximum yearly temperature is considered (the 21st of July).

A detailed parametric study of the effects of different green roof system configurations is not one of the objectives of this study. However, this work presents the variation of the summer indoor air temperature and the cooling and heating demand first as a function of two of the most influential parameters: the leaf area index [12,18,19,21] and the level of roof insulation [9,11,20], and then for two additional typical European climates: Athens (Greece), which represents the hot Mediterranean climate, and Stockholm (Sweden), which represents the cold climate.

5. Results and discussion

5.1. Description of the impact of the green roof

The energy performance of the studied house with both conventional and green roofs is presented in Figs. 3–5 and Tables 1 and 2. The summer results are presented with a free-floating temperature (Figs. 3–5 and Table 1) and with a set-point temperature of 28 °C (Table 2). The results suggest that the roof temperature (and thus, the heat flux through the roof, the indoor air temperature, and the cooling and heating demand) changed in a significant way because of the presence of the vegetation and the soil on the roof.

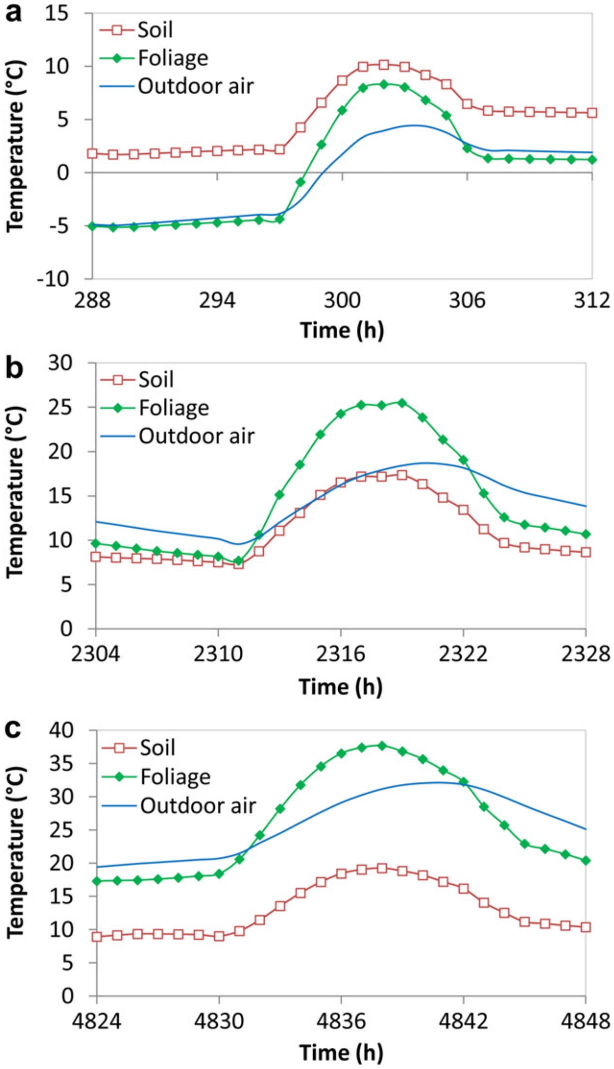

Fig. 3. Soil and foliage surface temperatures during three typical days in La Rochelle: (a) cold winter, (b) sunny winter, and (c) hot summer.

On the cold winter day (Fig. 3a), the soil temperature (T_g) is warmer than the outside temperature by 5.6 °C. This difference occurs because of the foliage, which plays an insulating role and limits the heat transfer between the roof and the outside. For the sunny winter day (Fig. 3b), the soil is colder than the outside temperature by 2.9 °C, an effect that is mainly due to evapotranspiration and solar shading by the foliage. On the hot summer day (Fig. 3c), the soil temperature is colder than the outside temperature by 12.8 °C for the same reason. For the three cases, T_g varies over a relatively moderate range: 2–10 °C during the cold winter day, 7–17 °C during the sunny winterday and 9–19 °C during the hot summer day.

The foliage temperature (T_f) is lower than the soil temperature by 4.9 °C during the cold winter day (Fig. 3a). This effect is observed because the foliage is more exposed to the cold air and has a substantial infrared radiative exchange with the cold sky compared with the exchange between the soil and the sky.

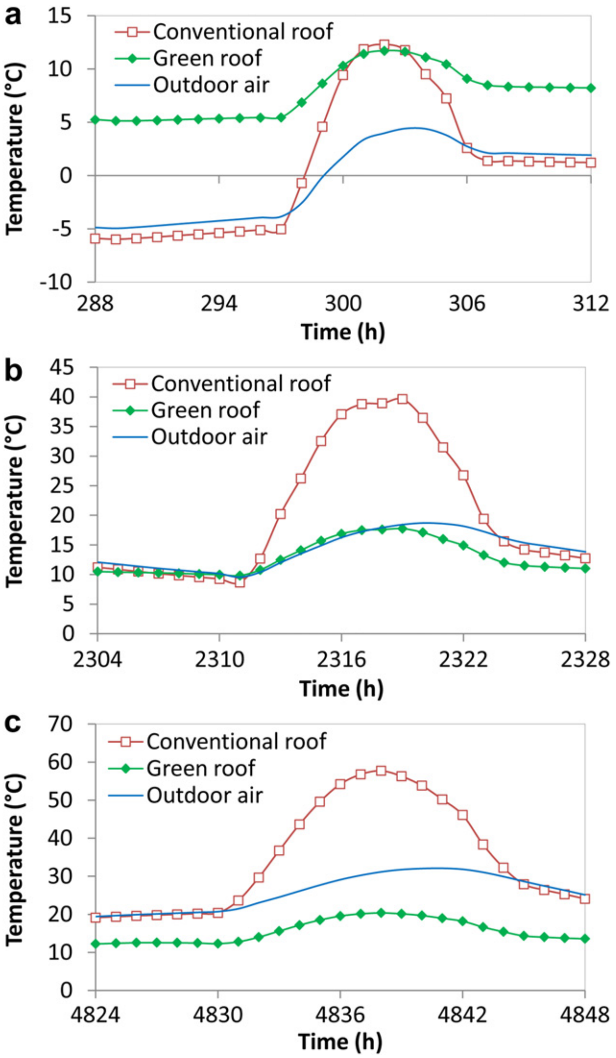

Fig. 4. Temperature of the exterior surface of the roof slab during three typical days in La Rochelle: (a) cold winter, (b) sunny winter, and (c) hot summer.

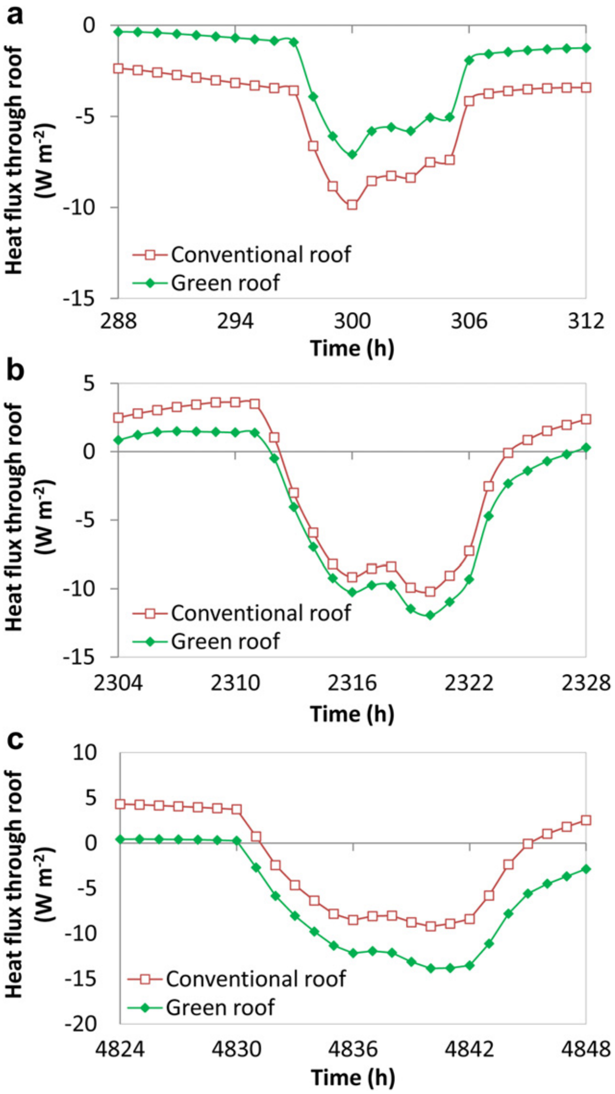

Fig. 5. Heat flux through the roof during three typical days in La Rochelle: (a) cold winter, (b) sunny winter, and (c) hot summer.

However, the foliage temperature is higher than the soil temperature by 3.8 °C during the sunny winter and by 13.2 °C during the hot summer days (Fig. 3b and c), because during the day, the solar radiation is largely absorbed by the vegetation. The significant influence of the solar radiation on the temperature of the foliage is confirmed by the fact that, for the three studied days, the foliage is hotter than the outside temperature during the day and colder during the night (Fig. 3).

The comparison of the roof slab temperature (T_r) between the conventional and green roofs is shown in Fig. 4. As expected, the range of variation of T_r is clearly lowest for the green roof during each day and between these days. While T_r reaches −6 °C in the winter and +58 °C in the summer for the conventional roof, it remains between −4 and 20 °C for the green roof. The fluctuation amplitude of T_r is reduced by as much as 30 °C on the hot summer day due to the green roof.

Previous studies confirm that green roofs protect the roof structure from extreme temperatures and large temperature fluctuations. From measurements taken during a hot and humid summer in Osaka, Japan, the maximum temperature of a concrete roof slab decreased by approximately 30 °C for the case of a green roof [17]. In the tropical summer of Taiwan, the measured temperature on the surface of a bare roof had fluctuation amplitude of 32.7 °C (23.4–56.1 °C), this amplitude is always less than 9 °C for differently vegetated roof configurations [15]. In the tropical climate of Singapore, measurements suggest a decrease of the maximum roof surface temperature by as much as 30 °C because of green roofs [21].

In Mediterranean climate of Marche, Italy, the measured temperature on a conventional roof surface reached 60 °C and showed large fluctuations in the summer. For green roofs, it was relatively stable and remained below 30 °C [2]. In the cold winter of Tartu, Estonia, the measured temperature under the substrate

Table 1
Indoor air temperature for three typical days in La Rochelle.

Day	Mean indoor air temperature (°C)		Maximum indoor air temperature (°C)	
	Conventional roof	Green roof	Conventional roof	Green roof
Cold winter	19.0	19.0	19.0	19.0
Sunny winter	20.3	20.0	21.8	21.4
Hot summer	28.4	26.4	30.1	28.0

Table 2
Heating, cooling, and total energy demand for conventional and green roofs in La Rochelle.

Roof type	Heating demand (kWh m^{-2} year^{-1})	Cooling demand (kWh m^{-2} year^{-1})	Total demand (kWh m^{-2} year^{-1})
Conventional	36.0	2.5	38.5
Green	36.1	0.1	36.2

layers of vegetated roofs did not fall below 10 °C, while it reached −20 °C for a steel sheet roof. In the summer, the same measurements indicated that the green roofs reduced the temperature fluctutation by 20 °C [26].

The important effect of the green roof on the roof slab temperature impacts the heat flux exchanged between the roof and the interior (q''_{ri}). For the winter season, Fig. 5a and b shows that, in the case of the green roof, the heat losses are lower by 5.5 kWh day^{-1} on the cold day but greater by 4.0 kWh day^{-1} on the sunny day. Thus, the green roof can increase or decrease the building heating demand, depending on the winter outdoor conditions and, more importantly, the solar radiation. During the hot summer day (Fig. 5c), the passive cooling effect of the green roof is clear. The total heat losses through the roof were 5.5 kWh day^{-1} for the conventional roof and 15.2 kWh day^{-1} for the green roof.

In the literature, many studies have concluded that green roofs have a considerable passive cooling effect. This effect was demonstrated by measuring the roof heat flux for a University building in Marche, Italy [2]. Another approach to evaluate this flux is by measuring the roof surface temperature and by performing a simplified calculation of the roof heat flux. Using this approach, different authors have found that green roofs reduce the heat gain through the roof during the summer by 50% in Osaka, Japan [17], and by 91.6% in Kaohsiung, Taiwan [15].

The indoor air conditions and the energy demand are directly affected by the variation of the heat flux through the roof as a result of green roof usage. Table 1 illustrates a constant indoor air temperature of 19 °C maintained by the heating system during the cold winter day. During the sunny winter day, when this temperature exceeds 19 °C, it is slightly higher for the conventional roof because of its lower heat losses. During the hot summer day, the indoor air temperature is lower by 2 °C as a result of the usage of the green roof. Hence, the green roof contributes effectively to summer thermal comfort.

A similar heating demand is observed for houses with green and conventional roofs (Table 2). This similarity means that, for the temperate climate of La Rochelle, the decrease of the heating demand by the green roof during cold winter days is equal to its increase during sunny winter days. However, Table 2 shows that the cooling demand was greatly reduced, nearly to zero, by the passive cooling effect of the green roof. Finally, because of the reduction of the cooling demand, the total energy demand was reduced by 2.3 kWh m^{-2} year^{-1} (6%).

The effects of green roofs on the indoor air temperature as well as the heating and cooling demand have been studied in many works. In a simulation of a nursery school in Athens, the indoor air temperature with a green roof has a frequency distribution that is higher in the 15–25 °C range and lower in the 25–35 °C range than with a conventional roof. Simulations also indicated a monthly cooling energy savings of 15–49% for the whole non-insulated building, and 27–87% for its top floor. For the insulated building, these values were 6–33% and 12–76%. The global impact on the heating demand was found to be insignificant [9].

In Athens also, simulations indicated that the monthly cooling demand for an office building was reduced due to the use of a green roof, by15–39% for the whole building and 27–58% for its top floor. The annual cooling demand reduction for the same building was approximately 40%. The monthly effect on the heating demand ranged from a decrease of 8% to an increase of 7% for the whole building, and from a decrease of 14% to an increase of 15% for its top floor. The global heating demand variation during the winter was also insignificant [16]. For a hotel, the measured indoor air temperature was reduced by 2 °C, and the average daily temperature fluctuation was reduced from 7 to 4 °C with a green roof [11].

During the summer in Yumuna Nagar, India, a mathematical model indicates that the use of a green roof combined with solar thermal shading, decreased the indoor air temperature by 5.1 °C [19]. In Brasilia (savanna climate) and Hong Kong (humid subtropical climate), the cooling demand, given by a two-dimensional canyon model and a simplified steady-state assumption of the roof heat gain, was reduced to zero due to the combined use of green walls and a green roof [14].

5.2. *Impact of the leaf area index*

The considered values of the LAI are 0.5, 2.0, 3.5 and 5.0. Table 3 shows that increasing the LAI reduces the summer indoor air temperature and the cooling demand, but increases the heating demand. This effect is mainly due to increasing transpiration and solar shading by the foliage. Table 3 also indicates that the impact of the variation of this parameter decreases at high levels. For instance, varying the LAI from 0.5 to 2.0 produced a reduction of the mean indoor air temperature by 0.3 °C. The corresponding value produced by changing the LAI from 1.5 to 3.5 is 0.1 °C, and the change produced by varying it from 3.5 to 5.0 is less than 0.1 °C. However, the LAI is one of several parameters of a green roof that has an important effect on its thermal performance, such as the foliage height, the leaf stomatal resistance, and the fractional vegetation coverage. The last parameter has a significant influence on the absorption of solar radiation by the foliage and thus on the solar shading effect (see Eqs. (1)).

5.3. *Impact of roof insulation*

The summer indoor air temperature and the energy demand were evaluated for different insulation depths (Table 4). The green roof reduced the mean and maximum indoor air temperature by 6.5 and 9.3 °C, respectively, for the uninsulated roof. However, these reductions are both less than 1.0 °C in the case of the 30 cm insulated roof.

Table 4 shows a heating demand reduction of 48% for the uninsulated green roof; this reduction is mainly caused by the additional thermal resistance of the green roof. For thicknesses greater than 10 cm, the relative importance of this additional insulation, and thus the effect of the green roof on the heating demand, becomes negligible.

Table 4 also indicates that the impact of a green roof on the cooling demand decreases as the insulation level increases. For the conventional roof, the insulation level does not impact the cooling

Table 3
Mean and maximum indoor air temperature and heating, cooling, and total energy demand in La Rochelle for different LAI levels.

Roof type	Indoor air temperature (°C)		Energy demand (kWh m^{-2} year^{-1})		
	Mean	Maximum	Heating	Cooling	Total
Conventional	28.3	30.1	36.0	2.5	38.5
Green (LAI = 0.5)	26.6	28.3	35.4	0.2	35.6
Green (LAI = 2.0)	26.3	28.0	36.1	0.1	36.2
Green (LAI = 3.5)	26.2	27.9	36.2	0.1	36.3
Green (LAI = 5.0)	26.2	27.9	36.3	0.1	36.4

Table 4
Mean and maximum indoor air temperature and heating, cooling, and total energy demand in La Rochelle for different insulation levels.

Insulation level (cm)	Mean indoor air temperature (°C)		Maximum indoor air temperature (°C)		Heating demand (kWh m^{-2} year^{-1})		Cooling demand (kWh m^{-2} year^{-1})		Total energy demand (kWh m^{-2} year^{-1})	
	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof
0	29.3	22.8	33.8	24.5	133.6	69.8	7.0	0.0	140.6	69.8
5	28.4	25.4	30.1	27.1	45.6	43.0	2.5	0.0	48.1	43.0
10	28.4	26.4	30.1	28.0	36.0	36.1	2.5	0.1	38.5	36.2
15	28.4	26.9	30.0	28.5	32.4	32.8	2.5	0.4	34.9	33.2
20	28.4	27.1	30.0	28.8	30.5	31.0	2.5	0.7	33.0	31.7
25	28.4	27.4	30.0	29.0	29.3	29.8	2.5	0.9	31.8	30.7
30	28.4	27.5	30.0	29.1	28.5	29.0	2.5	1.1	31.0	30.1

Table 5
Mean and maximum indoor air temperature and heating, cooling, and total energy demand in Athens, La Rochelle and Stockholm.

City	Mean indoor air temperature (°C)		Maximum indoor air temperature (°C)		Heating demand (kWh m^{-2} year^{-1})		Cooling demand (kWh m^{-2} year^{-1})		Total energy demand (kWh m^{-2} year^{-1})	
	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof	Conventional roof	Green roof
Athens	33.9	31.3	35.4	32.7	14.1	15.2	26.4	12.5	40.5	27.7
La Rochelle	28.4	26.4	30.1	28.0	36.0	36.1	2.5	0.1	38.5	36.2
Stockholm	25.6	24.2	27.2	25.8	131.0	120.3	0.0	0.0	131.0	120.3

demand when the insulation thickness exceeds 5 cm. For the green roof, any additional insulation limits the passive cooling effect. Thus, the reduction of the cooling demand due to the green roof fell from 7.0 kWh m^{-2} year^{-1} for the uninsulated roof to 1.4 kWh m^{-2} year^{-1} for the 30 cm insulated one.

Finally, it is logical that the effect of the green roof on the total energy demand decreases with the increase of the insulation level. The energy demand reduction decreases from 70.8 kWh m^{-2} year^{-1} (50%) for the non-insulated building to 0.9 kWh m^{-2} year^{-1} (3%) for the building with 30 cm of insulation.

The main conclusion of this section is that, considering energy savings and thermal comfort, green roofs are more suitable for retrofitting non- or poorly insulated old buildings than for use in well-insulated new buildings.

5.4. Impact of the green roof in three different climates

The mean and maximum indoor air temperatures on the hot summer day as well as the heating, cooling, and total energy demand are presented in Table 5 for Athens, La Rochelle, and Stockholm. The impact of green roofs on the indoor air temperature is more significant in hot climates. The mean indoor air temperature was reduced by 2.6, 2.0, and 1.4 °C for Athens, La Rochelle, and Stockholm, respectively.

While the green roof does not impact the heating demand in the temperate climate of La Rochelle, an increase of 1.1 kWh m^{-2} year^{-1} (8%) is observed in the Mediterranean climate of Athens; this increase occurs because of the important shading and evapotranspiration effects that increase the heating demand in this climate. A decrease of 10.7 kWh m^{-2} year^{-1} (8%) is observed in the cold climate of Stockholm, which is caused by the additional insulation effect of the green roof.

Table 5 also indicates that the cooling demand was dramatically reduced in Athens by 13.9 kWh m^{-2} year^{-1} (52%). In La Rochelle, this reduction was less significant in absolute value (2.4 kWh m^{-2} year^{-1}), but it was higher in relative value (96%). In Stockholm, the cooling demand with a conventional roof is negligible, thus the green roof has no impact on the cooling demand.

Finally, the green roof reduces the total energy demand in all three studied climates. Reductions of 12.8 kWh m^{-2} year^{-1} (32%) for the Mediterranean climate of Athens, 2.3 kWh m^{-2} year^{-1} (6%) for the temperate climate of La Rochelle, and 10.7 kWh m^{-2} year^{-1} (8%) for the cold climate of Stockholm were observed.

6. Conclusions

In this paper, a study of the impact of green roofs on building energy performance is described. A green roof model is presented and integrated into a building thermal program in a way that allows an objective comparison with conventional roofs. The impact of a green roof on the energy performance of a single-family house was analyzed. The temperatures of the foliage, the soil, the roof slab, and the indoor air were evaluated. The heat flux through the roof, the cooling demand, and the heating demand were studied.

The results show that the presence of a green roof protects the roof slab from extreme temperatures and high temperature fluctuations. This protection is afforded by a number of thermal phenomena that occur in the green roof, such as solar shading, evapotranspiration, and thermal resistance. Thus, green roofs increase the longevity of roofing membranes.

A passive cooling effect was observed in the summer, and the daily heat losses through the roof were increased by nearly a factor of three with a green roof. This cooling makes green roofs an effective solution for the enhancement of thermal comfort and the reduction of cooling demand.

The impact of the LAI parameter on the reduction of indoor air temperature and energy demand is not proportional. In order for green roofs to have a significant impact on energy performance, an optimal LAI level should be found with consideration of interacting parameters, such as the foliage density.

The effect of a green roof on the reduction of the summer indoor air temperature, the cooling demand and the heating demand strongly depends on the roof insulation level. Green roofs only exhibit significant effects for uninsulated or moderately insulated buildings, which makes the use of green roofs more thermally advantageous for retrofitting than for new building construction. However, for retrofitting, extensive green roofs are more suitable than intensive ones because their smaller load does not require additional strengthening.

The effectiveness of green roofs also depends greatly on the climate. The enhancement of thermal comfort and reduction of cooling demand are more effective when the climate is hot. However, a significant reduction of the heating demand can be observed in cold climates. For hot climates, green roofs can increase the heating demand, but this increase is still minor when compared with the cooling demand reduction. The total energy demand decreases with green roofs in hot, temperate and cold climates. This general improvement makes them an energy-efficient solution for a wide range of European climates.

The impact of green roofs on the environmental performance of buildings and cities (water management, energy, acoustic, biodiversity, etc.) remains an interesting subject for research. However, evaluating and understanding the effect of green roofs on building energy performance requires further study on the following topics.

- Finding suitable solutions for green roofs, such as well-adapted vegetation and high performance soils and drainage layers. These solutions may differ significantly from one climate to another.
- Developing more detailed green roof models that precisely consider plant physiology in addition to heat and mass transfer phenomena.
- Detailed parametric studies of different green roof configurations for both new construction and retrofit projects in different climates. These studies should also consider building use, morphology, and thermal performance level, especially regarding roof insulation.

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