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Modeling double skin green façades with traditional thermal simulation software

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Abstract

The use of plants attached to the building walls is a bioclimatic strategy that has grown in popularity due to the savings in building energy consumption. The plant is a living component of the façade that responds to the environment in a very complicated way, by regulating their transpiration levels. The simulation of this response is generally not included in the available software for transient thermal simulation of buildings, thus making difficult the simulation of green walls by architects and building designers. The aim of this paper is to present a simplified method to simulate a green wall using a traditional wall/glazing element, with fictitious properties, whose thermal model is included in transient simulation softwares. Thus, green walls can be simulated with softwares that do not provide specific modules for plant calculation. The model is more accurate under humid conditions and for low wind speeds. An application example is presented, consisting of a building prototype with a green façade that was simulated through EnergyPlus software. Inside and outside glass temperatures, plant foliage temperature, and window heat gain and losses were calculated. The results were discussed and recommendations for simulating green façades were done.
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Keywords: Green wall; Evapotranspiration; Double façades; Plants

1. Introduction

Using plants on building walls is an effective passive design strategy that has benefits at the urban, building, and human scales. At the urban scale, this strategy mitigates the heat island effect and reduces the CO_2 emissions (Alexandri and Jones, 2008; Thottathil et al., 2010; Metselaar, 2012). When compared with green roofs, green walls have larger potential surface area for greening because in tall buildings the area of the walls is always greater than the area of the roof. Thus, green walls can play an important role in urban rehabilitation and they can contribute to the insertion of vegetation in the urban context without occupying any space at street level (Manso and Castro-Gomes, 2015). At the building scale, green walls can reduce the energy demands of buildings and provide benefits related to the acoustic comfort (GhaffarianHoseini et al., 2013; Manso and Castro-Gomes, 2015). The reduction of the energy demand is due to the additional insulation layer provided by the vegetation together with the shading of building façades and the evaporative cooling effects on the surrounding air (Pérez et al., 2011; Renterghem et al., 2013). For example, reductions of around 12–32% in the cooling loads were reported for a building in Singapore with 50% and 100% of glazing coverage, respectively (Wong et al., 2009), while reductions of 28% were found by Di and Wang (1999) in a west vegetated wall in summer.

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Nomenclature

A_f	effective area, m^2
$c_{p,f}$	specific heat at constant pressure, J/(kg K)
d	characteristic length of the leaf, m
e_{air}	the actual vapor pressure, kPa
e_f	average leaf thickness, m
e_0	saturation vapor pressure at the mean air temperature, kPa
F_{ground}	view factor between the green façade and the ground, unitless
F_{sky}	view factor between the green façade and the sky, unitless
g	gravitational acceleration, m/s^2
G	heat absorbed by the soil, usually negligible when compared to the other contributions ($G \cong 0$), W/m^2
Gr	Grashoff number ($Gr_L = \beta g L^3 \Delta T / u_\infty{}^2$), unitless
h_c	reference crop or plant height, m
$h_{f,in}$	heat transfer coefficient between the foliage and the air cavity, $W/(m^2\,K)$
$h_{f,out}$	heat transfer coefficient between the foliage and the outdoor environment, $W/(m^2\,K)$
h_w	heat transfer coefficient between the outer wall/window surface and the air cavity, $W/(m^2\,K)$
I_s	solar radiation incident on the green façade, including the shortwave radiation reflected by the ground and surrounding surfaces, W/m^2
$I_{IR,f}$	radiative heat exchange between the foliage and the surrounding environment (sky, ground, and glass/wall surface), W/m^2
k	von Karman constant (equal to 0.41), unitless
LAI_{active}	active (sunlit) leaf area index, m^2 of leaf area/m^2 of soil surface, unitless
L_f	latent heat, W/m^2
Pr	Prandtl number, unitless
$qrad$	infrared net flux between the green façade and the surrounding, W/m^2
r_a	aerodynamic resistance to moisture transfer, s/m
r_l	stomatal resistance, resistance of a single leaf to the diffusion of water vapor from the leaf stomata into the atmosphere, s/m
$r_{l,min}$	minimum stomatal resistance, s/m
r_s	'bulk' surface resistance, resistance of vapor flow through the transpiring crop and evaporating soil surface, s/m
Re	Reynolds number ($Re_d = u_\infty \rho d/\mu$), unitless
T_{ground}	ground temperature (K)
T_{sky}	sky temperature (K)
$T_{w,out}$	outer surface temperature of the glass or wall (K)
u	wind speed, m/s
W	water evaporated, $g/(s\,m^2)$
x	ratio of latent heat expelled from the plant to total absorbed radiation by the plant, unitless

Greek symbols

α_f	solar absorptivity of the vegetation, unitless
β	volumetric thermal expansion coefficient, 1/K
γ	psychrometric constant ($\gamma = 665 \times 10^{-3}\,P$, with P the air pressure in kPa), kPa/°C
ΔT	in Gr number, the absolute value of the temperature difference between the surface and the fluid in the free stream, K
ε_f	infrared emissivity of the vegetation, unitless
ε_w	glass (or wall) infrared emissivity of the vegetation, unitless
λ	specific heat of water evaporation ($\lambda = 249$ KJ/kg)
Λ	slope of the saturation vapor pressure–temperature curve at the mean air temperature $\overline{T}$ in °C (kPa/°C)
ρ_f	density of the plant, kg/m^3
σ	Stephan–Boltzmann constant, $5.67 \times 10^{-8}\,W/(m^2\,K^4)$
τ_f	solar transmissivity of the vegetation, unitless

Reductions of the temperature of the external surface of building walls between 1.1 °C and 11.6 °C were found, depending on the vegetation type (Wong et al., 2010). Other studies reported reductions of 5.5 °C (Pérez et al., 2011) and 1.9–8.3 °C (Eumorfopoulou and Kontoleon, 2009). At the human scale, using plants in the built environment is recognized, beyond its aesthetic value, as a source of psychological and therapeutic benefits (Fjeld et al., 1998).

Pérez et al. (2011) proposed a detailed classification of green vertical systems. The authors make a first classification of green vertical systems into *green façades* and *living walls*. In *green façades*, climbing plants or hanging port shrubs are developed using special support structures, mainly in a directed way, to cover the desired area. The plants are mainly rooted at the base of these structures, in the ground, in intermediate planters or even on rooftops. On the other hand, *living walls* are made of panels and/or geotextile felts, sometimes pre-cultivated, which are fixed to a vertical support or on the wall structure. These panels can be made of various types of material, and support a great variety of plant species. Due to the diversity and density of plant life, *living walls* normally require more intensive maintenance and protection than green façades (Kontoleon and Eumorfopoulou, 2010). This paper focuses on the thermal simulation of green façades, where part of the incident solar radiation is transmitted through the vegetation and reaches the building envelope.

Plants are living components that respond to the environmental conditions in a very complicated way which is today an open research field. The first attempts to include plants in building simulations considered that the vegetation effect is simply the reduction of the solar radiation reaching the wall (*only-shading* model). For example, Wong et al. (2009) determined by simulation (with TAS) the effect of vertical greening systems on thermal comfort and energy consumption of buildings through shading coefficients linked to the leaf area index *LAI* (defined as the projected area of leaves on a horizontal area). The *only-shading* model is very simple to use, but its major drawback is that evapotranspiration, radiative heat exchange, and other effects are not accounted for. These are key effects that need to be considered for a more precise understanding of the thermal behavior and impact of green façades on the building energy consumption. For example, it is known that plants are thermally better than conventional shading devices, such as fins, blinds, rollers, and overhangs. In plants, the surface temperature of leaves is lower than that of the shading material. This cooling effect is caused by the transpiration of the leaves, whose quantification is not straightforward.

Significant contributions to the thermal modeling of green façades were made in the last years and only a few are cited here. Stec et al. (2005) developed a simulation model of a double skin façade with plants in the interior of a cavity that was validated with experimental data obtained in a laboratory test facility. They considered the latent heat expelled by the plant to be proportional to the absorbed radiation, and they proposed a model based on the electric-thermal analogy that was calculated with Simulink™ software. The thermal network model was used also by Kontoleon and Eumorfopoulou (2010), who investigated the thermal behavior of a building zone with a green façade. The green layer was divided into several ventilated air spaces of around 5 cm width (*multi-layer* model), each of them having a different rate of air changes, and the obtained equations were solved numerically. More recently, Scarpa et al. (2014) developed a mathematical model for two kinds of living walls, one with grass and a closed air cavity and the other one with a vertical garden and an open air cavity. The finite volume approach and the thermal–electrical analogy were used. The model showed good agreement with field measurements of surface wall temperatures and heat fluxes in summer and winter. Susorova et al. (2013) developed a mathematical model of an exterior wall with climbing vegetation and verified with experiments during summer. The authors considered the variable behavior of the plant stomatal resistance with solar radiation, which is a crucial parameter determining the transpiration level of the plant. Finally, Malys et al. (2014) developed a hydrothermal model of a living wall using SOLENE-Microclimate software, which is devoted to the simulation of urban microclimate. This model was tested and validated through experimental data for mid-season period in a temperate climate.

As shown, in order to assess the actual thermal effects of green walls, mathematical models of the plants need to be included in the available simulation software. The existing models are commonly obtained from one-dimensional dynamic thermal balances based on finite differences or finite volumes approaches, and they are solved numerically or coupled to specific simulation software. Such models are quite complex and they are not commonly included as specific modules in available commercial software, thus, making difficult their use by architects and building designers. This paper presents an alternative simplified method to simulate a green wall by using a traditional wall/glazing element, with fictitious properties, whose thermal model is usually included in transient simulation softwares. Thus, when the specific module for green wall is not included, it is still possible to simulate the effect of vegetation by using the available traditional models. The paper firstly presents the behavior of the vegetation from the thermal viewpoint, analyzing the sensible and latent heat fluxes. Then, a thermal model for the plant is derived that can be used in any thermal simulation software. Finally, an application example is described, consisting of a prototype with a glazed wall covered by a double green façade that is simulated using EnergyPlus. Inside and outside glass temperatures, plant foliage temperature, and heat gain and losses through the glazing are calculated, and comparisons of the obtained results with those of the *only-shading* model are performed. The results are discussed and recommendations for simulating green façades are done.

2. The thermal behavior of the plant

2.1. Energy balance of a green wall

Plants are living beings that suffer adaptations to the environment, which are not simple to predict. The temperature of plants depends on non-biotic (physical) parameters – for example, the boundary layer resistance for heat transfer by convection and radiation or the boundary layer resistance to water vapor-, as well as on biological parameters – for example, the actual stomatal resistance, the water content of leafs, the water content of ground, etc. (Bajons et al., 2005). The heat transfer processes involved in the energy balance of a leaf are: absorption of solar radiation, sensible heat exchange by convection between the leaf and the surrounding air, infrared energy exchange between the leaf and the surroundings, latent heat expelled by the plant by transpiration, store of energy in tissues, conduction through the leaf (usually negligible), and energy for metabolic processes necessary for photosynthetic or catabolic reaction (for most situations in nature the energy losses due to metabolic processes are relatively small and neglected in the calculations).

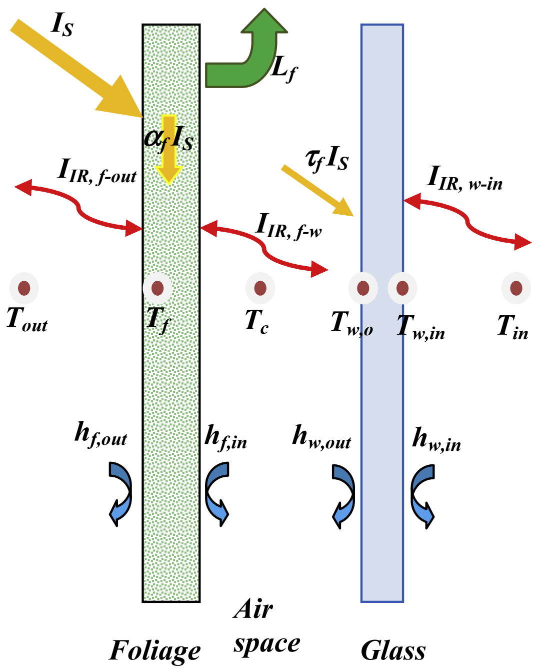

Fig. 1. Heat transfer mechanisms in the double facade with plants.

A green façade can be considered as a vertical element involved in the energy balance of a glazed or opaque wall as shown in Fig. 1 for a glazed wall. For the energy balance of the green façade, it can be thought as a unique "big leaf" of density ρ_f, specific heat at constant pressure $c_{p,f}$, thickness e_f and an effective area A_f. This area is the dimension of the vertical surface which is covered by the leaves, in accordance with the assumptions of other authors (Stec et al., 2005; Kontoleon and Eumorfopoulou, 2010). An air space is formed between the building and the green façade, with the air in the cavity being represented by a temperature T_c. The solar radiation I_s incident on the green façade is partially reflected, absorbed, and transmitted by the foliage, which are described by the solar reflectivity, absorptivity and transmissivity, respectively. The spectral properties of the leaves make the canopy highly absorbent in the visible wavelength range (photosynthetically active radiation, PAR), from 400 nm to 720 nm, and moderately reflective in the near infrared region from 720 nm to 4000 nm (Sellers et al., 1997). For a given plant specimen, these variables change during the year because the foliage is denser in summer than in winter, and because the intrinsic properties of the leaves also change (i.e., they have different colors and densities in summer and autumn). The solar transmissivity of the vegetation along a year was studied by Ip et al. (2010) for a vertical deciduous climbing plant canopy. The authors proposed the use of a dynamic Bioshading Coefficient Function representing the shading performance of the canopy over its annual growing and wilting cycle.

As explained, a fraction of the absorbed energy is transformed into latent heat, causing transpiration to appear in the leaves' surfaces, and part into sensible heat, causing an increase in the foliage temperature T_f. Because of the high thermal conductivity of leaf tissues, the temperatures of the upper and lower surfaces of a leaf can be assumed identical. Heat is transferred by convection from both sides of the foliage layer to the adjacent air, described by the heat transfer coefficients $h_{f,out}$ and $h_{f,in}$. Radiative heat exchange between the foliage and the surrounding environment (sky, ground, and glass/wall surface) is represented by $I_{IR,f}$. Thus, the energy balance in the foliage expressed per unit area of coverage is written as:

$$\alpha_f I_s - h_{f,out}(T_f - T_{out}) - h_{f,in}(T_f - T_c) - qrad - L_f = (\rho c_p)_f e_f \frac{dT_f}{dt} \quad (1)$$

where the term in the right is the energy stored in the green façade (leaves and branches), usually neglected (Zhang et al., 1997), L_f is the latent heat (estimated in the next section), and $qrad$ is the infrared net flux between the green façade and the surrounding surfaces given by:

$$qrad = \sigma\varepsilon_f F_{ground}\left(T_f^4 - T_{ground}^4\right) + \sigma\varepsilon_f F_{sky}\left(T_f^4 - T_{sky}^4\right) + \sigma\frac{\varepsilon_f\varepsilon_w}{\varepsilon_f + \varepsilon_w - \varepsilon_f\varepsilon_w}\left(T_f^4 - T_{w,in}^4\right) \quad (2)$$

where T_{ground} and T_{sky} are the ground and sky temperatures (K), $T_{w,out}$ is the outer surface temperature of the glass (or wall), ε_f and ε_w are the plant and glass/wall infrared emissivities, respectively, F_{ground} and F_{sky} are the corresponding view factors, and σ is the Stephan–Boltzmann constant.

2.1.1. Convective heat transfer coefficients

Heat transfer coefficients $h_{f,out}$ and $h_{f,in}$ in Eq. (1) are estimated by correlations depending on the type of convection regime. Thus, firstly the dominating heat transfer regime (forced, free, or mixed convection) must be determined, by inspecting the dimensionless ratio Gr/Re^2, where both adimensional numbers are based on the characteristic length of the leaf d (the length in the direction of the wind). The wind speed is an average along the height of the plant (usually estimated from a wind profile). Forced convection occurs for $Gr/Re^2 \ll 1$, while free convection for $Gr/Re^2 \gg 1$. In both cases, the boundary layer resistance is generally evaluated through the classical heat transfer equations. Under mixed conditions ($Gr/Re^2 \cong 1$) the effects of air velocity and canopy air temperature difference must be combined (Incropera and DeWitt, 1996). In vertical green walls, the dominant modes are usually mixed convection and free convection (low wind velocities, occurring in general on the inner side of the green façade). For these cases, the recommended correlations are given in Eqs. (3) and (4). The first one is valid for mixed convection and it was proposed by Stanghellini (1993) and used by Stec et al. (2005). The second one is valid for free convection in vertical plates and it was proposed by McAdams (1954):

$$Nu = 0.405(Pr\,Gr + 6.92 Pr Re^2)^{0.25} \quad \text{for mixed mode}, Gr/Re^2 \cong 1 \quad (3)$$

$$Nu = 0.59(Gr\,Pr)^{1/4} \quad \text{for free convection}, Gr/Re^2 \gg 1 \quad (4)$$

2.2. The latent heat L_f

2.2.1. Stomatal resistance

The flux of water vapor from a plant (or latent heat flux) is called *transpiration*. Some leaves transpire through both sides, while some leaves transpire through only a single side. The water vapor is released through small valve-like openings called *stomata*, which regulate the passage of water vapor from the leaf tissues to the surrounding air. The degree of aperture of these pores depends on several factors as the plant species and age, PAR flux density, leaf temperature, soil moisture content, air humidity, and ambient concentration of CO_2. The resistance r_l of a single leaf in s/m to the diffusion of water vapor from the leaf stomata into the atmosphere is called the stomatal resistance ($1/r_l$ is the stomata conductance) and it varies during the day. For example, during the day r_l is directly linked to the solar radiation level, so it usually has higher values in the morning and slightly lower around noon. During the night r_l dramatically increases, thus the transpiration is reduced to a minimum value (5–15% of daytime values, Caird et al., 2007). Moreover, in some critical situations as in extreme temperature conditions or in extremely dry environment, the plant closes its stomata to minimize the water loss. It is evident that the estimation of r_l is quite complex, so a minimum value called the *minimum stomatal resistance* is taken as the characteristic value for a given plant, that is, when the leaf or soil is at full water capacity, at full sunlight and when the vapor pressure deficit effect is negligible. Korner et al. (1979) compiled maximum stomatal conductance data for 246 plant species. Typical values of $r_{l,min}$ ranges from 25–50 s/m for crops as corn and soybeans to 200–500 s/m for many types of trees. For creepers, the values used in the literature are 80–160 (Susorova et al., 2013; Stec et al., 2005). Recently, some researchers proposed the use of infrared thermography to determine the stomatal resistance (Bajons et al., 2005).

In a canopy, well illuminated leaves on the top contribute more to transpiration than non illuminated ones. Thus, a 'bulk' surface resistance r_s is defined, which describes the resistance of vapor flow through the transpiring crop and evaporating soil surface. An acceptable approximation of the surface resistance of dense full cover vegetation as proposed by the Food and Agricultural Organization – FAO – is (Allen et al., 1998):

$$r_s = \frac{r_l}{LAI_{active}} \tag{5}$$

where LAI_{active} is the active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)], with $LAI_{active} = 0.5\ LAI$ (Malys et al., 2014). In a vertical green façade, the LAI should be estimated as the projected area of leaves per unit area of vertical wall surface.

2.2.2. Aerodynamic resistance

A second resistance that acts in series with the stomatal resistance and influences the latent heat transfer is the aerodynamic resistance to moisture and heat transfer r_a (s/m). It is the resistance to moisture and heat exchange offered by the boundary layer formed on the leaf surface; and it depends on wind speed and surface roughness. The aerodynamic resistance in s/m of a single leaf is defined as (Bonan, 2008):

$$r_{a,leaf} = 0.5\rho_{air}c_{p,air}L/(k_{air}Nu_L) \tag{6}$$

where d is the leaf characteristic length (m), k_{air} is the air conductivity in W/(m K), ρ_{air} is the air density in kg/m^3, $c_{p,air}$ is the specific heat of air in J/kg, and Nu is the Nusselt number obtained from Eqs. (3)–(5). The 0.5 factor accounts for the reduction of the boundary layer resistance r_b of a leaf with both sides transferring heat to the environment ($r_{a,leaf} = 0.5r_b$). Bonan (2008) calculated r_b (s/m) in relation to leaf sizes between 1 and 10 cm and wind speed between 1 and 10 m/s ($r_b = 200(d/u)^{1/2}$, with u the air velocity in m/s and d the leaf characteristic length in m). He found values of r_b between 8 s/m (for small leaves with $d = 0.01$ m and $u > 6$ m/s) and 60 s/m (for big leaves with $d = 0.10$ m and $u < 1.3$ m/s).

For a canopy, the aerodynamic resistance r_a, should include the contribution of all leaves. In the case of crops, several equations exist to estimate r_a (Monteith and Unsworth, 1990; Vining and Blad, 1992; Jacobs et al., 2002). FAO calculates r_a for horizontal crops by considering that the wind speed profile follows a logarithmic profile (surface similarity theory) and that the moisture transfer is performed only by the upper portion of the canopy. This logarithmic profile is valid only above the plant canopy (Bonan, 2008), but in a vertical green wall not only the upper portion of the canopy transfers moisture but all leaves along the plant height and inside the canopy. For plants with low values of LAI ($LAI < 3$) r_a is inversely proportional to LAI and it can be estimated in a similar way of Eq. (5) as:

$$r_a = \frac{r_{a,leaf}}{LAI_{active}} \tag{7}$$

It is noted that the "big leaf" model do not considers the horizontal air flow through the leaves of the canopy. In fact, in dense canopies it was found that r_a remains constant as LAI increases. The reason is that the leaves inside a deep canopy have their stomata closed due to the low light levels, so they do not contribute significantly to the moisture transfer (Bonan, 2008).

2.2.3. Evapotranspiration

Evapotranspiration is the combination of two different processes that occur simultaneously, evaporation from the soil surface or the wet vegetation and transpiration (vaporization of liquid water contained in plant tissues) from the vegetation (FAO, 2015). There is no easy way of distinguishing between the two processes. The latent heat L_f (W/m^2 of covered area) involved in the evapotranspiration process is then:

$$L_f = W \cdot \lambda \tag{8}$$

where W is the water evaporated in g/(s m^2) and λ is the specific heat of water evaporation ($\lambda = 249$ kJ/kg).

The commonly used method proposed by FAO (Allen et al., 1998) to calculate the evapotranspiration of well irrigated plants is the Penmann–Monteith equation that estimates W depending on the air properties (temperature and humidity), the plant properties (stomatal and aerodynamic resistances), the solar radiation absorbed by the plant and the radiant exchange of the plant with the environment ("big leaf" model):

$$W = \frac{\Lambda(\alpha_f I_s - qrad - G)}{\lambda[\Lambda + \gamma(1 + r_s/r_a)]} + \frac{\rho_{air} c_{p,air}(e_0 - e_{air})/r_a}{\lambda[\Lambda + \gamma(1 + r_s/r_a)]} \quad (9)$$

where

$$\Lambda = \frac{4098\left[0.618\mathrm{Exp}\left(\frac{17.27t}{t+237.3}\right)\right]}{(t + 237.3)^2} \quad (10)$$

$$e_0(t) = 610.78\mathrm{Exp}\left(\frac{17.27t}{t + 237.3}\right) \quad (11)$$

$$e_{air}(t) = (RH/100)e_0(t) \quad (12)$$

In the Penmann–Monteith equation, Eq. (9), G [W/m^2] is the heat absorbed by the soil that is negligible when compared to the other contributions ($G \cong 0$), γ is the psychrometric constant in kPa/°C ($\gamma = 665 \times 10^{-3}P$, with P the air pressure in kPa), e_0 the saturation vapor pressure at the mean air temperature (kPa), e_{air} the actual vapor pressure (kPa), r_a the aerodynamic resistance in s/m, r_s the bulk stomatal resistance in s/m, $qrad$ is the infrared net flux between the plant and the surrounding surfaces in (W/m^2) and Λ is the slope of the saturation vapor pressure–temperature curve in kPa/°C at the air temperature t (°C).

Stec et al. (2005) proposed a simplified equation to calculate L_f that is based on the observation that there is a fixed relation between the radiation absorbed by the plant and latent heat expelled from the plant:

$$L_f = x(\alpha_f I_s - qrad - G) \quad (13)$$

where x is the ratio of latent heat expelled from the plant to total absorbed radiation by the plant, which is assumed by the authors to be roughly constant ($x \cong 0.6$–0.7). We found this concept very useful in order to derive a model for the green façade, but we consider that x can be estimated in each particular situation instead of assuming a constant value for all cases. In the next section the factor x is estimated and included in the proposed thermal model of the green façade.

3. Model of the plant for building simulation

3.1. Estimation of x and applicability conditions

By comparing the Stec's expression with the Penmann–Monteith equation, we can realize that both are similar when the actual vapor pressure of the air is near the saturation vapor pressure (humid environment) or when the aerodynamic resistance is high (i.e., low air velocities near the plant). In these cases, the second term in the equation is negligible when compared with the first term and x can be estimated as:

$$x = \frac{L_f}{(\alpha_f I_s - qrad - G)} = \frac{\Lambda}{[\Lambda + \gamma(1 + r_s/r_a)]} \quad (14)$$

The graph of x versus the mean air temperature t at sea level is shown in Fig. 2 for different ratios r_s/r_a. As shown, the fraction x of latent heat increases with the mean air temperature for any ratio r_s/r_a. When $r_a \gg r_s$, x varies from 0.60 to 0.75 (at mean air temperatures between 15 and 30 °C), which is the range found by Stec et al. (2005) in their measurements ($r_a = 1300$ s/m, $r_s = 160$ s/m, air temperature below 30 °C). In this case, moisture readily travels to the leaf surfaces but is not easily evaporated; thus, around 60–70% of the absorbed total energy is expelled as latent heat and 30–40% as sensible heat. When $r_a \sim r_s$, x varies from 0.45 to 0.65 (at mean air temperatures between 15 and 30 °C) and 45–65% of the solar energy absorbed by the plant is turned into latent heat. Finally, when $r_a \ll r_s$, leaf surfaces remain dry as surface moisture is readily evaporated (i.e., for high wind speed). In this case, x can reach values of around 0.23–0.40 (at air temperatures between 15 °C and 30 °C), that is, around 23–40% of the absorbed total energy is expelled as latent heat and 60–77% as sensible heat.

The conditions of applicability of the model are related with the assumption that the second term of Eq. (9) is much lower than the first term. In the following, a contribution of the second term of around 25 W/m^2 was selected as the limiting value, which is around 10–15 times lower than the usual contribution of the first term in a sunny day. In order to verify this assumption, a set of calculations for air relative humidity between 20% and 100% and air temperature between 15 °C and 30 °C was made, for different ratios r_s/r_a. The results – not shown in this paper – indicate that, when $r_a \gg r_s$ (low wind speed), the second term is negligible (not exceeding 25 W/m^2 in the worst situation) so the assumption is always valid. When $r_a \sim r_s$ the second term does not exceed 25 W/m^2 for air relative humidity

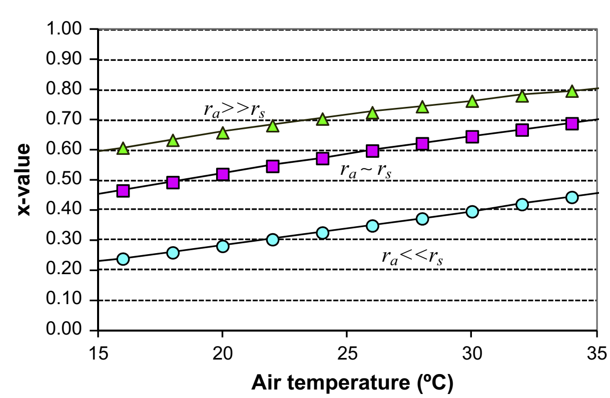

Fig. 2. x versus the mean air temperature at the sea level for $r_s = 160$ s/m and $r_a = 1300$ s/m ($r_a \gg r_s$), 160 s/m ($r_a \sim r_s$), and 35 s/m ($r_a \ll r_s$).

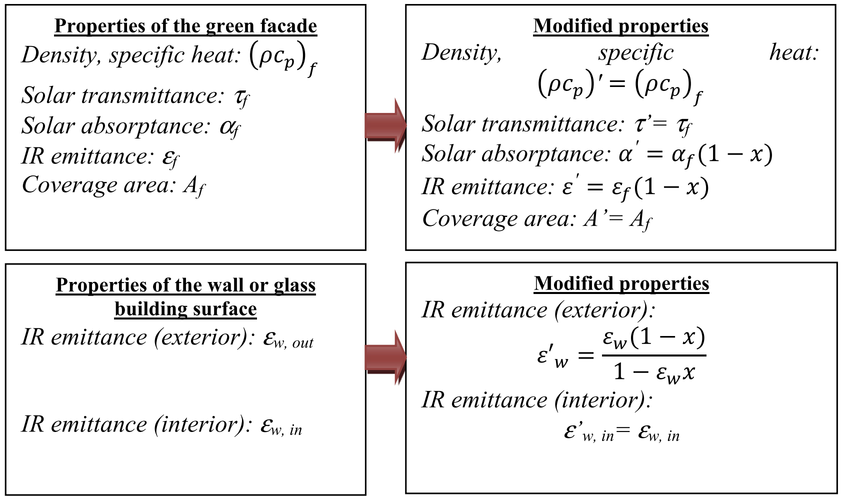

Fig. 3. A green façade defined by τ_f, α_f, ε_f, A_f, in front of a surface of emittance $\varepsilon_{w,out}$ can be simulated as a single layer slab with τ'_f, α'_f, ε'_f, A_f in front of a surface with infrared emittance $\varepsilon'_{w,out}$. x is the fraction of the total absorbed radiation (solar and infrared) turned into latent heat.

higher than 65% (at 30 °C) and must be applied with some caution for dry or dessert climates with lower relative humidity (i.e., for RH = 50%, the second term reaches 42 W/m^2). Finally, when $r_a \ll r_s$ the second term of Eq. (9) is comparable to the first one so, if it is neglected, the transpiration rate could be around half the real one. For example, at 30 °C, the contributions of the second term are around 100–160 W/m^2 (for relative humidities of 50% and 20%, respectively). The case of $r_a \ll r_s$ is not usual, because it occurs under very windy conditions or when r_s is high (the leaf transpiration is reduced by the plant due to adverse environmental conditions such as extremely dry or hot climates).

3.2. Including the latent heat L_f in the thermal model of the green façade

By including Eqs. (2) and (9) into the energy balance of the foliage, Eq. (1), we found that:

$$I_s\alpha_f(1-x) - h_{f,out}(T_f - T_{out}) - h_{f,in}(T_f - T_c) - \sigma\varepsilon_f F_{ground}(1-x) \times (T_f^4 - T_{ground}^4) - \sigma\varepsilon_f F_{sky}(1-x)(T_f^4 - T_{sky}^4) - \sigma\frac{\varepsilon_f\varepsilon_w(1-x)}{\varepsilon_f + \varepsilon_w - \varepsilon_f\varepsilon_w} \times (T_f^4 - T_{w,in}^4) = (\rho c_p)_f e_f \frac{dT_f}{dt} \quad (15)$$

Now consider a fictitious slab with the following properties: thickness e', density ρ', specific heat c'_p, solar absorption α', infrared emissivity ε'. Suppose that this fictitious slab absorbs solar energy I_s on one side, and that it exchanges heat by convection and radiation to the sky, ground, and a fictitious wall at a temperature $T_{w,in}$ and infrared emittance ε'_w. The heat balance for this fictitious slab would be:

$$I_s\alpha' - h_{f,out}(T_f - T_{out}) - h_{f,in}(T_f - T_c) - \sigma\varepsilon' F_{ground}(T_f^4 - T_{ground}^4) - \sigma\varepsilon' F_{sky}(T_f^4 - T_{sky}^4) - \sigma\frac{\varepsilon'\varepsilon'_w(1-x)}{\varepsilon' + \varepsilon'_w - \varepsilon'\varepsilon'_w}(T_f^4 - T_{w,o}^4) = (\rho c_p)' e' \frac{dT_f}{dt} \quad (16)$$

Equaling the two last equations, we obtain:

$$(\rho c_p)' = (\rho c_p)_f \quad (17)$$

$$e' = e_f \quad (18)$$

$$\alpha' = \alpha_f(1-x) \quad (19)$$

$$\varepsilon' = \varepsilon_f(1-x) \quad (20)$$

$$\varepsilon'_w = \frac{\varepsilon_w(1-x)}{1-\varepsilon_w x} \quad (21)$$

Thus, in simulation software that do not include the calculation of a green façade, it is possible to simulate it by considering the façade as a fictitious non-opaque slab with a very low thermal resistance $R_{th} = e_f/k_f$ in m^2/(W K), a solar transmissivity τ_f, a modified solar absorption α', a modified infrared emissivity ε' and a modified emissivity ε'_w of the outer glass or wall surface emissivity, defined by Eqs. (17)–(21). The emissivity of the glass (or wall) inner surface remains unchanged and equal to ε_w.

3.3. The thermal model of the green façade

Fig. 3 schematically shows the transformation needed to simulate a green façade with the proposed model. It is important to note that the value of x modifies substantially the "apparent" absorptance and emissivity of the outer foliage layer. As it was mentioned in Section 3.1, attention must be paid for low values of x, occurring at very high wind speed or for high stomatal resistance, when the applicability of the model is restricted. In this case the simulation could predict temperatures of the foliage which are too high to be realistic, so a more detailed modeling of the moisture heat transfer is needed.

4. Application: simulation of a green façade with EnergyPlus

As an application example, a prototype building with a West green wall façade was simulated with EnergyPlus

V7.1 for a summer period in Salta, a city in the Northwest region of Argentina. In the following, the prototype geometry, materials, and climate, are described. Then, the proposed model is used to derive the thermal properties of the green wall that will be included in EnergyPlus software. Because the *only-shading* is a widely used model, it was included as an additional simulation, in order to serve as a comparison "base" model.

4.1. Description of the prototype building and the local climate

4.1.1. Building geometry and materials

The building prototype is 2.4 m height, with a floor area of 5 m × 5 m. This was simulated as a single thermal zone, which was thermostatized at 20 °C. The horizontal roof consists of a galvanized iron cover with thermal insulation (expanded polystyrene, 0.05 m thick). The North, South and East walls are opaque (massive brick, 0.20 m thick). The West façade is a single-glazed wall (glazed area $A_f = 10.56\ m^2$, glass infrared emittance $\varepsilon_w = 0.84$). The glazed West façade was selected to be covered by a double skin green façade, placed at a distance of 0.30 m from the glass. A glazed façade was studied instead an opaque one in order to evidence the effect of the green wall in reducing the direct solar heat gain that reaches the internal surfaces of the prototype.

The solar and visible transmittance, absorptance and reflectance of the green façade are assumed constant for the simulation period, with average values given by the literature (Oke, 1983): $\tau_{f,solar} = 0.2$, $\alpha_{f,solar} = 0.5$ and $\rho_{f,solar} = 0.3$, $\tau_{f,vis} = 0.06$, $\alpha_{f,vis} = 0.85$, $\rho_{f,vis} = 0.09$. The thermal emissivity and reflectance of the plant were $\varepsilon_f = 0.95$ and $\rho_{f,ir} = 0.05$. Plant density and specific heat at constant pressure were assumed similar to that of water, average leaf thickness was $e_f = 0.3$ mm, *LAI* of around 2, and stomatal resistance of 160 s/m.

4.1.2. Climatic conditions

The climate of Salta (24.85°S, 65.48°W, and 1216 m over the sea level) is classified as *Cwa* by the Köppen–Geiger climate classification (temperate climate with dry winter/hot summer pattern). The prototype was simulated for an average day in summer with climate data provided by the National Meteorological Service (Table 1): mean maximum temperatures are around 28.3 °C with absolute maximum of 38.4 °C. Fig. 4 shows the hourly temperature and solar irradiance on horizontal surface and on vertical surface facing West, for an average day of December.

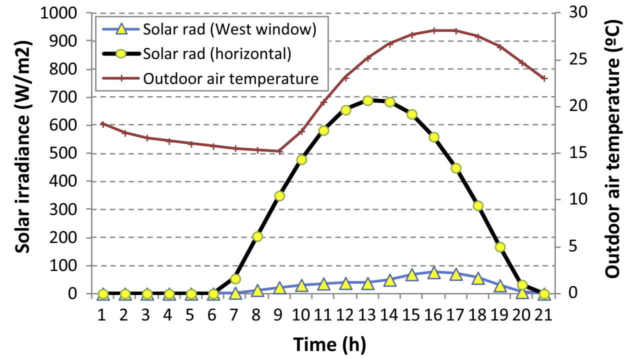

Fig. 4. Hourly outdoor air temperature (°C) and solar irradiance (W/m^2) on a horizontal surface and on a vertical surface facing West, for an average day of December in Salta city, Argentina (24.85° South latitude, 65.48° West longitude, 1216 m.o.s.l.).ç.

4.2. Modeling the green wall

The fraction x was estimated in 0.77 by using Eq. (15), for a mean maximum air temperature of 28.3 °C, an air pressure of 88,200 Pa, relative humidity of 71%, $r_s = 160$ s/m, and r_a around 1300 s/m (very low wind speed, in accordance with Stec et al., 2005). Then, the thermal properties of the fictitious slab (the modified solar absorptance and infrared emittances) were estimated through Eqs. (17)–(21).

As explained, previously extant elements can be used to simulate green walls. In the case of EnergyPlus, the software provides the element Window Shading Device (EnergyPlus, 2014). This type of shading devices affects the system transmittance and glass layer absorptance for short-wave radiation and for long-wave (thermal) radia-

Table 1
Climatic data for December, in Salta city (24.85°S, 65.48°W, 1216 m.o.s.l.) provided by the National Meteorological Service. Solar irradiance and relative heliophany data were obtained from Grossi-Gallegos and Righini (2007).

Summer (December)			
Temperature	Mean maximum	°C	28.3
	Mean		21.3
	Mean minimum		15.2
	Thermal amplitude		13.1
	Maximum absolute temperature		38.4
Mean wind speed		Km/h	6
Relative humidity	Mean Maximum	%	89
	Mean		71
	Mean Minimum		51
Relative heliophany		–	0.42
Mean daily solar irradiance on horizontal surface		MJ/m^2 day	19.2
Pressure		kPa	88.2

tion. The effect depends on the shade position (interior, exterior or between-glass), its transmittance, and the amount of inter-reflection between the shading device and the glazing. Also of interest is the amount of radiation absorbed by the shading device and its temperature. A window shading in EnergyPlus is a layer assumed to be parallel to the glazing and it is defined with the object WindowMaterial:Shade. The software calculates the natural convective air flow between the glass and the shade produced by buoyancy effects and the corresponding convective heat transfer coefficient, and the radiative heat transfer between the shade and the glass. Shades are considered to be perfect diffusers (all transmitted and reflected radiation is hemispherically-diffuse) with transmittance and reflectance independent of angle of incidence. The program calculates how much long-wave radiation is absorbed by the shade and by the adjacent glass surface. Reflectance and emissivity properties are assumed to be the same on both sides of the shade.

WindowMaterial:Shade requires the following inputs: solar and visible transmittances and reflectances, thermal hemispherical emissivity, thermal transmittance, thickness, conductivity, shade to glass distance, top/bottom and left/right opening multipliers (effective areas for air flow at the top/bottom or left/right of the shade divided by the horizontal or vertical area between glass and shade, respectively), and airflow permeability (the total area of openings in the shade surface divided by the shade area). Because inputs for the WindowMaterial:Shade element is reflectance (instead absorptance), the value to be entered is $\rho' = 1 - (1 - x)\alpha' - \tau'$.

This model allows estimating the thermal resistance of the green façade. The conductive thermal resistance $R_{cond,glass}$ (m^2 K/W) of a single glass layer is defined as e_{glass}/k_{glass} where k_{glass} is the thermal conductivity of the glass in W/(m K) and e_{glass} its thickness in m. Alternatively, it can be calculated as $R_{cond,glass} = \Delta T/q$, where ΔT is the temperature difference (K) between outside and inside glass surface temperatures and q the heat transferred (W/m^2) in steady state, that are variables available as simulation outputs. In the case of adding a green façade, the resulting equivalent thermal-electric circuit is shown in Fig. 5, where the dots represent the nodes of temperature: $T_{glass,in}$ and $T_{glass,out}$ are the indoor and outdoor glass surface temperatures, T_c the air temperature inside the cavity, and T_f the temperature of the green façade. Convective and radiative resistances are defined as usual in the literature. Thus, the effective thermal resistance of a glazing panel with a green façade can be calculated as:

$$R_{eff} = R_{cond,glass} + R_{green\_facade} = (T_f - T_{glass,in})/q \quad (19)$$

4.3. "Only-shading" model

A first approximation to the problem is to simulate a green wall is to consider the green wall as a building shading device, with the transmittance of the foliage layer. As pointed out, evapotranspiration, radiative heat exchanges, and other effects are not accounted for in this case. We named this situation "Case BS". In EnergyPlus, a Building Shading object is defined by its geometry (it can be a simple rectangular shape or a more complicated one) and a transmittance schedule (transmittance is assumed to be the same for both beam and diffuse solar radiation). The user can optionally input constant values of visible and solar reflectivities. The most important effect of shading surfaces is to reduce solar radiation reaching the shadowed surfaces. Shading surfaces also automatically shade diffuse solar radiation (and long-wave radiation) from the sky. This element does not typically have enough thermal mass to be described as part of the building's thermal makeup, that is, it is not involved in heat transfer calculations.

Because the presence of the green façade modifies the wind velocity near the covered wall, the convective heat transfer coefficient must be calculated previously from Eqs. (3) and (4). Besides, EnergyPlus assumes that shading devices are opaque to long-wave radiation no matter what the solar transmittance value is. Because plants have large long-wave absorptance (around 0.95) they can be roughly treated as opaque elements in the infrared range. The view factors to the sky and ground for thermal infrared (long-wave) radiation are not user inputs; they are calculated within the software based on surface tilt and shadowing surfaces. Shadowing surfaces are considered to have the same emissivity and temperature as the ground, so they are lumped together with the ground in calculating the ground IR view factor.

Another important observation in relation to using a Building Shading Object is that the shading of ground diffuse solar radiation is not calculated by the program (even if transmittance is set to 1). EnergyPlus Manual warns that *it is up to the user to estimate the effect of this shading and modify the input value of the surface-ground view factor accordingly*. This mean that reflected ground diffuse solar radiation will not be transmitted by the foliage layer if the user does not take the corresponding precautions. To include this transmission, the wall and window view factor must be calculated and multiplied by

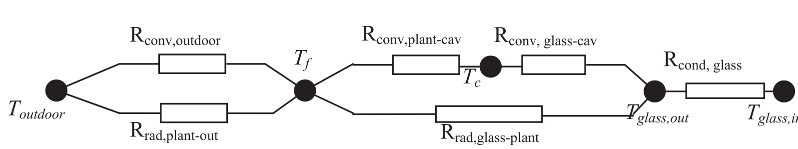

Fig. 5. Thermal-electric equivalent circuit of the green façade.

the transmittance of the plant foliage. This value must be used as a “fictitious” view factor F_{sg} to account for the transmittance of ground diffuse solar radiation (to allow the code using the user-input view factor, Full Interior And Exterior option for Solar Distribution should be used).

Thus, the BS model simulates the green façade as a building shading surface placed parallel to the wall (or window), with a solar transmittance equal to the green façade transmittance, solar and visible reflectances equal to those of the green façade, with a modified convective heat transfer coefficient h for the covered glazed surface, and with a “fictitious” view factor of the covered wall equal to the real view factor value multiplied by the solar transmittance of the green façade.

The view factor F_{sg} between the vertical glazed surface and the ground is 0.5. Because the solar transmittance of the green façade is 0.2, a “fictitious” view factor of 0.1 was used for the glazed surface.

4.4. Results

For both models (BS and WSD), the solar energy transmitted by the window, the window heat loss, outside and inside glass surface temperatures, and green façade temperature resulting from de WSD model, are shown in Figs. 6–9. The results corresponding to a bare window are also shown.

Fig. 6 shows that both models predict similar amounts of solar energy transmitted by the window to the zone, with the maximum value at 16:00 due to the West orientation of the vertical façade. The energy transmitted by a bare window is around 6.9 MJ/(m^2day) while the energy transmitted by the window covered by the green façade is around 1.4 MJ/(m^2day). Fig. 7 shows the window heat losses: for the bare window, heat loss is negligible during the sun hours, reaching a maximum value of 300 W (equivalent to 28 W/m^2) immediately after the sunrise. When comparing the heat losses predicted by both models, it is evident that modeling the green façade as a Building Shade results in 12% higher window heat losses when compared

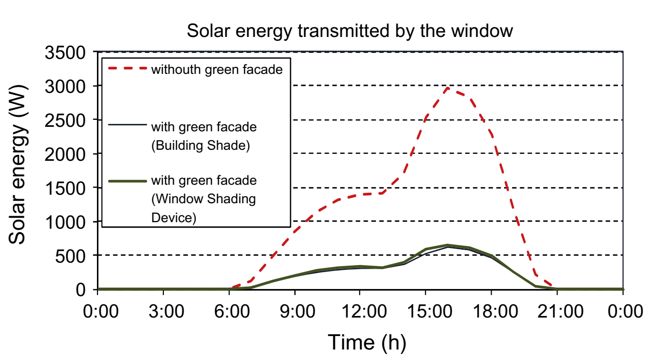

Fig. 6. Solar energy (W) transmitted by the window for both models. The solar energy transmitted by a bare window (without the green façade) is also shown.

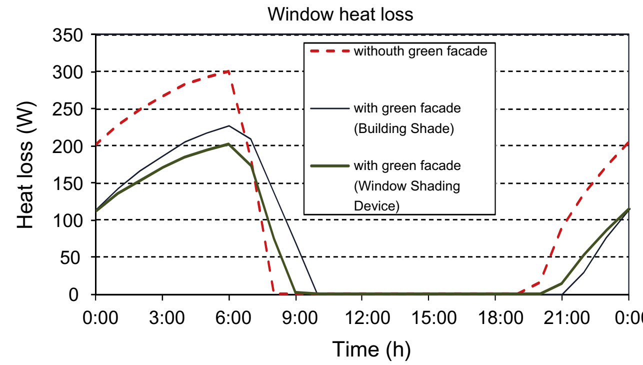

Fig. 7. Window heat loss (W) predicted by BS and WSD models. The window heat loss of a bare window (without the green façade) is also shown.

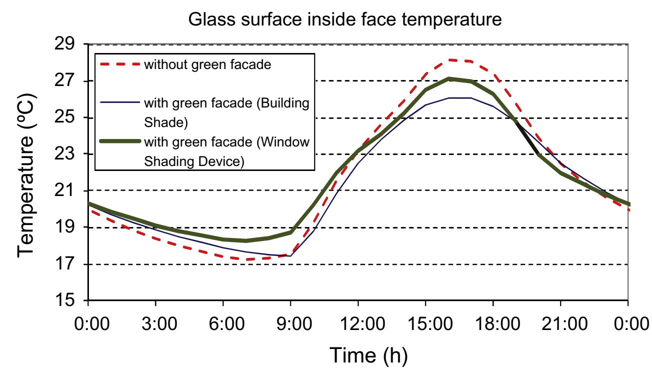

Fig. 8. Inside face temperature of the glass (°C) predicted by BS and WSD models. The behavior of a bare window (without the green façade) is also shown.

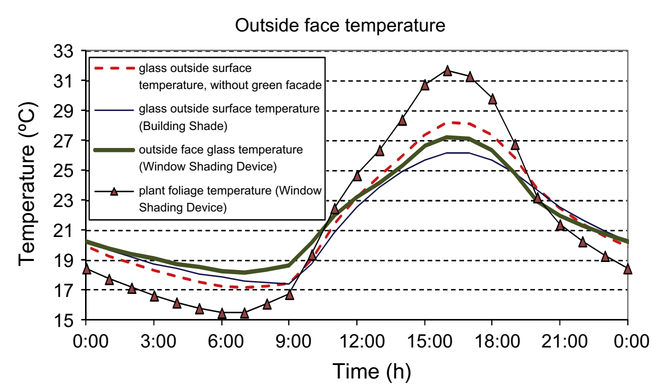

Fig. 9. Outside face temperature of the glass (°C) predicted by BS and WSD models, and plant temperature predicted by the WSD model. The behavior of a bare window (without the green façade) is also shown.

with the WSD model. The reason is that higher in the BS model the radiative exchange is calculated for the glass facing an isothermal surface with emissivity and temperature equaled to the ground emissivity and the ground temperature (assumed constant), while the real exchange is between the glass and the plant façade. In the WSD model the radiative heat transfer is calculated in a more realistic way as occurring between the glass and the shading device (the plant), where the emissivity of the plant was defined by the user, and the plant temperature is variable and calculated by the code. Also there are differences in the heat convection coefficient of the glass for each model. It can be concluded that window heat loss (0.8 MJ/m^2 day) is higher for bare window than for a plant covered window (0.5 MJ/m^2 day), and that covering a single-glazed window with plants reduces the heat losses around 37% with respect to the bare window.

Figs. 8 and 9 show the simulations of the glass surface temperatures for the bare window and for both models. In all cases the highest temperature is reached in the afternoon when the incident solar radiation is maximum. When the window is covered by the green façade, both the inside and outside glass surface temperatures in the afternoon are around 1.5 °C lower due to the shading effect of the green façade. Because the glass pane absorbs around 15% of the incident solar radiation, the decrease of the surface temperature is significantly lower in transparent materials than in opaque ones (absortances between 50% and 80%), where decreases down to 10 °C were reported in the literature. During the night, the temperature of the glass simulated by the BS model is similar to that of the bare glass and lower than the predicted by the WSD model, due to the higher radiative thermal losses of the first model. Fig. 9 shows also the plant foliage temperature that reaches the maximum values (31 °C) during the afternoon.

The estimation of the green façade thermal resistance gives values of $R_{green\_façade}$ around 0.15 m^2 K/W, which is a value equivalent to the thermal resistance of a 6 mm thick layer of expanded polystyrene or 89 mm of a quiet air layer. This value is in accordance with other values found in the literature: Kontoleon and Eumorfopoulou (2010) estimated the thermal resistance of a 25 cm width plant foliage in 0.5 m^2 K/W (thermal conductance of 2 W/m^2 K), while Perini et al. (2011) estimated an additional resistance of 0.09 m^2 K/W.

5. Conclusions

This paper presents an alternative simplified method to simulate a green wall. The method can be used in available software for transient thermal simulation of buildings, where a specific module for the calculation of green walls is not included. The model is more accurate under humid conditions and for low wind speeds. The method replaces the green wall with a fictitious layer with modified optical properties. It considers the radiative heat transfer between the green façade and the surroundings, and provides a rough estimation of the plant temperature and the equivalent thermal resistance of the green façade.

The proposed model was used to predict the thermal behavior of a prototype with a glazed West wall that was covered with a double skin green façade, placed in the climate of Salta, a city in the North West of Argentina. It was shown that the heat gain of a bare window oriented to West is around 6.8 MJ/m^2 day and its heat loss is 0.8 MJ/m^2 day. Covering the window with a plant façade lowers the window heat gain down to 2.1 MJ/m^2 day and the heat loss down to 0.5 MJ/m^2 day. That is, heat gain and heat loss are reduced to a 30% and 63%, respectively, of the values for the bare window. The proposed model was compared with the *only-shading* model of the green façade, and it was found a mean difference of 10–12% between the window heat gains and heat losses predicted by them. Also a maximum difference of 1.3 °C was found between surface glass temperatures predicted by both models, with the *only-shading* model resulting in lower glass temperatures.

In this simplified model, we consider that r_s is constant during the day, while in fact this value is a response of the plant to the environmental changes such as the solar irradiance level, the CO_2 concentration, the soil irrigation, and other factors. A future challenge is to include in simulations a dynamic model of the plant parameters under variable environmental conditions.

In accordance with Perini et al. (2011), it is evident that modeling is an abstraction of reality and it will always have some shortcomings. Nevertheless, we can use simulations to anticipate future implications of current decisions. It is still crucial that the results of the scientific research could reach the architects, engineers and building designers, in order to develop efficient energy solutions toward a greener, smarter and more ecological urban environment.

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