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Abstract

This study is interested in the evaluation of the development of extensive green walls (GWs) on the energy balance of buildings with a global code of dynamic thermal simulation of buildings under TRNSYS. In fact, green walls are not integrated into the thermal simulation during thermal calculations. For, the "Type" developed was used to make a new contribution to the prediction of the thermal behavior of green walls. The first part presents the equations integrated in the model. A description of the dynamic thermal simulation software is carried out as well as the methods of integration of the developed model. Then, the modeling of the influence of GW (Ivy or Virginia Creeper) on a more global scale is detailed. It highlights the thermal and energy impact of GWs in winter and summer on a brick house located in Lille in France. This is a concrete case of representation of an existing residential building in an urban environment to help thermal design offices to take them into account in the simulations. It has been shown that the presence of vegetation protects the facades against summer overheating and therefore reduces the energy requirements for air conditioning. In winter, the use of deciduous plants on facades exposed to the sun makes it possible to benefit from solar radiation

and limit the demand for energy for heating. Finally, the GWs technique is more suitable for the thermal renovation of weakly insulated buildings.

Keywords: extensive green walls, dynamic simulation, building, TRNSYS, thermal behavior

Nomenclature

Symbols :

T	temperature, K
GW	Green wall
GWs	Green walls
$Is^{\downarrow}$	incident solar radiation, W/m²
F	leaf cover index
W_{CC}	Cellular Concrete Wall

Greek letters :

α	solar absorption coefficient
β_{zen}	solar zenith angle
φ	flux density, W/m²
σ	constant of Stefan-Boltzmann
σ_{occ}	coverage rate, [0,1]
ε	emissivity, [0,1]
τ	transmissivity, [0,1]
σ_{GW}	coverage rate, [0,1]
μ^*	solar extinction coefficient

Indices / Exponents :

CC	cellular concrete
Eq	equivalent
sol	solar
R_{env}	infrared exchanges with the environment
R_{occ}	infrared exchanges with the GW
R_{env}	infrared exchanges with the environment
R_{occ}	infrared exchanges with the GW
R_{env-CC}	infrared exchanges with the environment
R_{GW-CC}	infrared exchanges with the GW
cv	convection

I. Introduction

The use of green walls came mainly from Germany in the early 1970s. The aesthetic aspect and the desire to bring originality to buildings was often the main reason for creating a green wall [1]. Its usefulness was subsequently oriented to mainly counter the phenomenon of urban heat island which results in a temperature difference between a rural and urban area in the same region [2-4]. Most of the experiments in in-situ conditions on the thermal benefits of green walls make comparisons between buildings with or without green walls [5-11]. The results cannot be generalized, unless all the parameters that can influence the building's energy balance have been considered or measured, which is very complicated to achieve. It is also recognized that interior temperatures are strongly influenced by the occupants and their behavior (cooling and heating system, opening / closing of doors and windows, manipulation of window curtains, etc.) and it is very difficult to obtain precise technical information throughout the year unless the building is pre-equipped with a set of sensors capable of collecting the necessary data [12-16]. In addition, it is not possible to ask for the same scenarios or modes of use for all the occupants of the different buildings studied and this can therefore generate significant differences and affect the comparisons.

Green walls can also have very positive effects on improving sound insulation [17-19]. Green walls are used more and more as a means of fighting against urban climate warming, especially in the case of tropical climates [20-22] or to reduce consumption of heating or air conditioning [23]. Moreover, many studies, green walls contribute to the improvement of air quality [24,25] and bring biodiversity to urban centers [3]. The integration of green walls in dynamic thermal simulation codes is little used for the calculation of the energy balance [26-28] or for special cases, such as the study of solar greenhouses [29]. Numerical simulation has been used more to study green roofs to reduce heat islands and overheating in summer [30-35] or to improve the energy efficiency of an entire building [36,37]. Experimental research done on radiative

occultation by extensive green walls (ivy and Virginia creeper) has shown good conclusions [8]. Three boxes had been instrumented to collect all the information necessary for the creation of the numerical model. In addition, this model for the prediction of the thermal influence of extensive green walls was validated at the scale of the experimental model [38]. The results are very encouraging. To finalize the study, the quantitative analysis must be extrapolated to a real scale of a building. Various software can be used for the dynamic simulation of greenhouses [39]. In our case, the coupling of the green wall model focused on the use of the global dynamic thermal building simulation code TRNSYS. This software was used in our laboratory for the study of solar walls [40, 41]. TRNSYS is often used for estimating energy consumption in buildings [42,43]. Modeling the influence of GWs on a more global scale will highlight, through several scenarios, the thermal influence of GWs on the thermal balance of an old brick house located in Lille (France). A first study on the thermal conductivity of the materials composing green walls (intensive and extensive) had shown that green walls could be used as an additional insulation [44]. It is therefore an application to a representative study of an existing residential building in an urban environment in the north of France in a degraded oceanic climate. That is, these regions have more mixed characteristics, with less rain in winter, and more thunderstorms in summer. These climates average roughly the same amount of rain each month of the year. The temperature contrasts are also more important there [45]. The aim of this study is to show the advantages and disadvantages of green walls in winter and summer. This tool would also allow construction companies to better use this technique in the construction and integration of the energy balance. The first part is introduced by the description of the simulation software used, and the integration of the model developed in this same software. The second part will focus on modeling the influence of GWs on a more global scale and quantifying the heating or air conditioning needs.

II. Materials and Method

2.1. Equations to the case of vegetation

As explained in a previous publication [38], the digital model has been described and validated. To provide a better understanding of the simulations that will be developed in this research, the modifications of the equations with the presence of a green wall (GW) are recalled. The energy balance at a wall obscured by vegetation is based on the balance equations of solar radiation exchanges, infrared exchanges, and convective exchanges (Equation 1).

$$\varphi_{cc} = \varphi_{sol} - \varphi_{R_{env-CC}} - \varphi_{R_{GW-CC}} - \varphi_{cv} \quad (1)$$

Figure 1 shows the differences in parameters between an artificial occultation and a vegetated occultation.

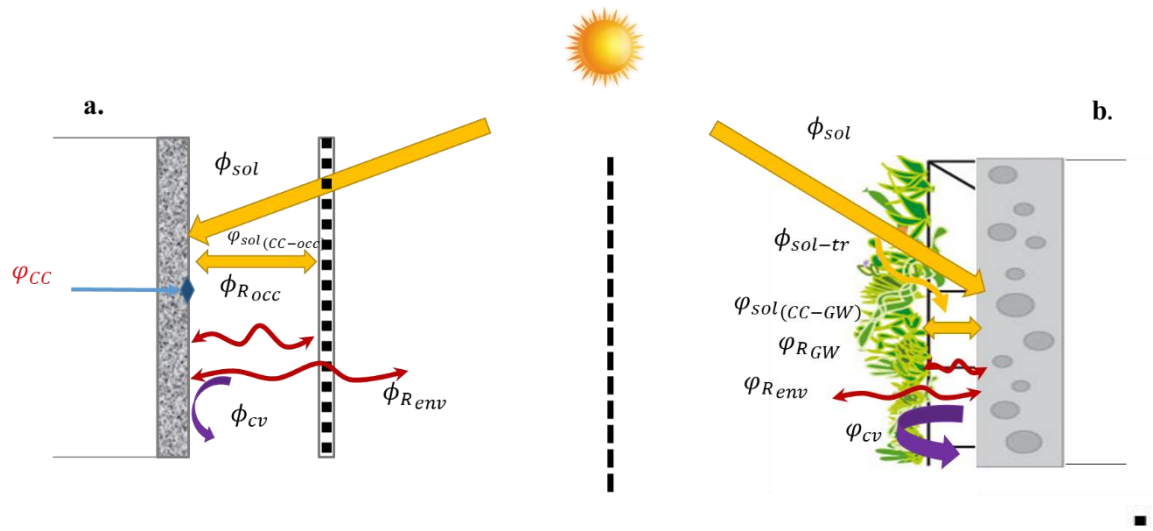


Fig. 1: Elements of the energy balance ;(a) case of artificial obscuration ; (b) case of masking by the vegetation [30]

As explained [38], the second important difference is related to the geometry of the occultation. The thickness of the leaf layer, the density and the number of leaves are new parameters to be integrated into the energy balance equations. This last aspect requires modification of the transmitted and absorbed solar radiation and an adaptation of the equations of convective exchanges. These convective exchanges are considered in the case of the artificial occultation

to be similar to exchanges between two flat surfaces. They are more complex in the case of plants, and it is then necessary to consider an aerodynamic resistance in the external surface area of the leaf layer and a resistance to the sensible heat transfer within the canopy layer, following its thickness, and the density of leaves.

The radiative exchanges balance was also adapted according to the characteristics of the plants, no change was made to the infrared radiation equations on one hand and between the GW and the cellular concrete wall (W_{CC}) on the other hand (Equation 2):

$$\varphi_{R_{GW-CC}} = \frac{\sigma \times \left(T_{CC}^4 - T_{GW}^4\right)}{\frac{1-\varepsilon_{CC}}{\varepsilon_{CC}} + \frac{1}{\sigma_{GW}} + \frac{1-\varepsilon_{GW}}{\varepsilon_{GW}} \times \frac{1}{\sigma_{GW}}} \quad (2)$$

Since the leaf layer of plants is considered semi-transparent to solar radiation, a transmitted flux term has been added (φ_{sol-tr}). This adds to the direct solar flux and to those exchanged between the masking and the WCC have been expressed respectively by ($\varphi_{sol_{(GW-CC)}}$) in equations (3).

$$\varphi_{sol_{(GW-CC)}} = Is^{\downarrow} \times \alpha_{CC}\left(1-\sigma_{GW}\right) \times \sum_{n=2}^{\infty} r_{CC}^{n}\left(\sigma_{GW} \times r_{GW}\right)^{n-1} \quad (3)$$

The radiative flux transmitted by the foliar layer of plants (φ_{sol-tr}), is obtained as a function of the incident solar radiation, the WCC absorption coefficient, the coverage rate of the plant layer and the solar transmission coefficient of the leaf layer (Equation 4).

$$\varphi_{sol-tr} = Is^{\downarrow} \times \alpha_{CC} \times \sigma_{CC} \times \tau_{GW} \quad (4)$$

Thus, the coefficient (τ_{GW}) is calculated as a function of the solar zenith angle (β_{zen}), the leaf coverage index (F) and a solar extinction coefficient (μ*) which vary according to the radiative properties of the leaves and their mean inclination (Equation 5).

$$\tau_{GW} = \exp(-\mu^{*} \times \beta_{zen} \times F) \quad (5)$$

The inclination of the leaves and the radiative properties of the plants (μ *) determine the depth up to which direct solar radiation (of β zenith angle) can penetrate in the leaf layer without

being intercepted. The foliar cover index (F), for its part, is a dimensionless quantity, representing the spatial distribution of the leaf structure in three dimensions. In other words, the index F is taken to be equal to the coverage rate in the case of a spatial distribution in 2D only (case of artificial occultation). It is defined as the ratio between half of the total surface area of the leaves (up and down seeds) and the total surface area (W_{CC}). Unlike the coverage rate, which is limited to the ratio between the covered area and the total area, the index F is calculated taking into account the total number of leaves, even if they are superimposed (Equation 6).

$$F = \frac{1/2 \; Total \; leaf \; area}{W_{cc} \; area} \tag{6}$$

The numerical model equations have been validated allow a modeling of the thermal effect of vegetation on buildings on a real scale [38]. This developed digital tool provides more precision on the effects of vegetation in regions with a temperate climate. It can now be integrated into thermal building simulation software (TRNSYS). It will also make it possible to study the thermal effects of simple green walls in other climates and for different types of constructions.

2.2. Building modeling using TRNSYS

The theoretical study developed in this research focused on the thermal exchanges between building facades and the external environment in the presence of green walls. For the model to be validated, it was necessary to introduce a junction temperature (or heat flow) to the modeled surface (instrumented wall). On the real scale of the building, it will be necessary to consider all the thermal phenomena influencing this junction temperature, hence the interest of coupling the model developed with a global code for dynamic thermal simulation of buildings. The model developed predicts the thermal behavior of green walls.

By integrating it into the overall code, it will be possible to assess the influence of the presence of green walls on the building's energy balance.

The choice of simulation software was the "TRNSYS" simulation environment [26, 46], which stands for "Transient System Simulation Program" (TRaNsient SYstem Simulation program). The strong point of TRNSYS is its modularity. Indeed, simulations under TRNSYS are based on links between several dynamic systems created through the graphical interface (TRNStudio). Each system is represented by an open component (TYPE) containing a pre-implemented code for modeling it. This flexibility allows TRNSYS to integrate all the characteristics of the building (geometry, construction materials, overall architecture ...), equipment (heating or air conditioning system, ventilation, ...) and user behavior. The simulation of buildings under TRNSYS is carried out with a multi-zone building code. This is the "Type 56" which uses an external "TRNBuild" program during simulations.

The "TRNBuild" allows the user to define the geometry of the building (the geometry can also be imported from a 3D drawing), the number of thermal zones to be modeled, and the different characteristics of the materials. It is used to manage occupancy scenarios, define the air infiltration rate, and control the set point temperatures for the heating and air conditioning systems. Using the "TRNBuild" software environment the walls should be defined as either external walls (with orientation specification) or internal walls adjacent to a defined thermal zone. The program can take into account several layers of materials for each type of wall (multilayer walls), the characteristics of most conventional materials being listed in a database accessible from TRNBuild. External thermal stresses are applied through a link with a weather file (Type 99: data defined by the user or Type 15: typical files and historical data by city) according to the geographical position of the building and the orientation of each of the walls exterior. Solar masks can be interposed between the outputs of the weather file and the “Type 56” inputs by adding a “Type 67” component dedicated to the projection of incident solar

radiation on the building envelope in the presence of a distant solar mask (immediate environment of the construction). In addition, local thermal excitations can also be applied to a wall, if the boundary conditions thereof are known.

When the “Type 56” is configured via the “TRNBuild” interface and linked with the meteorological data on the “TRNStudio”, it allows annual simulations to be carried out for different thermal zones (room, floor, etc.) or for the whole building. Thus, the user will be able to analyze the variations in the temperatures of the exterior and interior surfaces of each wall, and the variations of the air temperatures at the level of each thermal zone. It will also be able to assess the heating and / or air conditioning energy needs and establish detailed energy balances for the building as a whole or only part of it. The calculations made with the "Type 56" are based on establishing the energy balance equations in each of the thermal zones. Regarding the convective heat flow, the equations used by the "Type 56" consider the sum of the following terms to perform an aeraulic heat balance:

- Convective exchanges with the interior surfaces of the walls ($Q_{surf,\ i}$),
- The contributions of infiltration of outside air ($Q_{inf,\ i}$),
- The contributions of ventilation,
- Thermal gains from internal convective exchanges "occupants, equipment, lighting, heaters, etc.",
- Convective exchanges with the adjacent zone.

In addition, the convective heat flow in a thermal zone considers the fraction of solar gains transmitted by any glazing, which immediately transforms into significant internal convective gains. The solar flux absorbed by interior solar masking devices "interior curtains" which directly transforms into sensible convective gains in the interior air is also considered.

Regarding the radiative energy balance inside a thermal zone, the equation under TRNSYS considers the:

- Internal radiative contributions,
- Radiative flux transmitted by the glazing,
- Infrared exchanges with the internal surfaces of the area,
- Possible radiative thermal gains defined by the user.

Each thermal zone is then considered as an air node whose temperature is approximated either by the standard method (by default on TRNSYS) by combining the radiative and convective flows according to a star network [47], or by using a model of detailed transfer [48, 49], with which radiative and convective fluxes are treated separately.

The standard model, unlike the detailed one, uses a fictitious temperature called (Tstar) which combines the convective and radiative exchanges between the walls of the zone. While the detailed one, treats convective and radiative exchanges separately. In terms of results, the energy balances evaluated with the standard model are very similar to those evaluated by the detailed calculation method [50]. The similarity is all the more confirmed in the case of multi-zone buildings. For a study case with a single thermal zone, the detailed method is preferred [51]. With regard to heat transfer by conduction, the heat flux at the walls is modeled in TRNBuild by the method of weighting factors in the form of time series of surface temperatures and heat fluxes [52, 53].

The digital study of the thermal interest of green walls [38] has shown the impact of occultation by vegetation on the superficial energy exchanges at the level of the walls of prototypes. The briefly presented TRNSYS code makes it possible to establish annual simulations at the real scale of a building. The link between the two programs then allows the estimation of the annual energy needs of a building in the presence of green walls. This involves modifying the initial link between the meteorological data file "Type 99 or Type 15" and the multi-zone building code "Type 56". It is necessary to create a new component, which models the links between the weather file and the green walls. In other words, the new component must provide continuity

between the heat flow that passes through a green wall, and the heat flow to the exterior surface of the building's facade.

The TRNSYS program offers several options for developers to implement new components. The most classic is to program the new component under the same language used by TRNSYS (FORTRAN or C ++), then to define the links between the new component and the other "Types" on the TRNStudio. For codes created in other languages, TRNSYS offers the possibility of calling the code developed by an external program from specific toolboxes. Codes like ours on the heat transfer of green walls, developed under Matlab, can be called through "Type 155".

Figure 2 illustrates the principle of coupling between the green wall model and the multi-zone building model. The links shown schematically in green and orange are the iterative calculations between the two programs. They pass through the "Type 155".

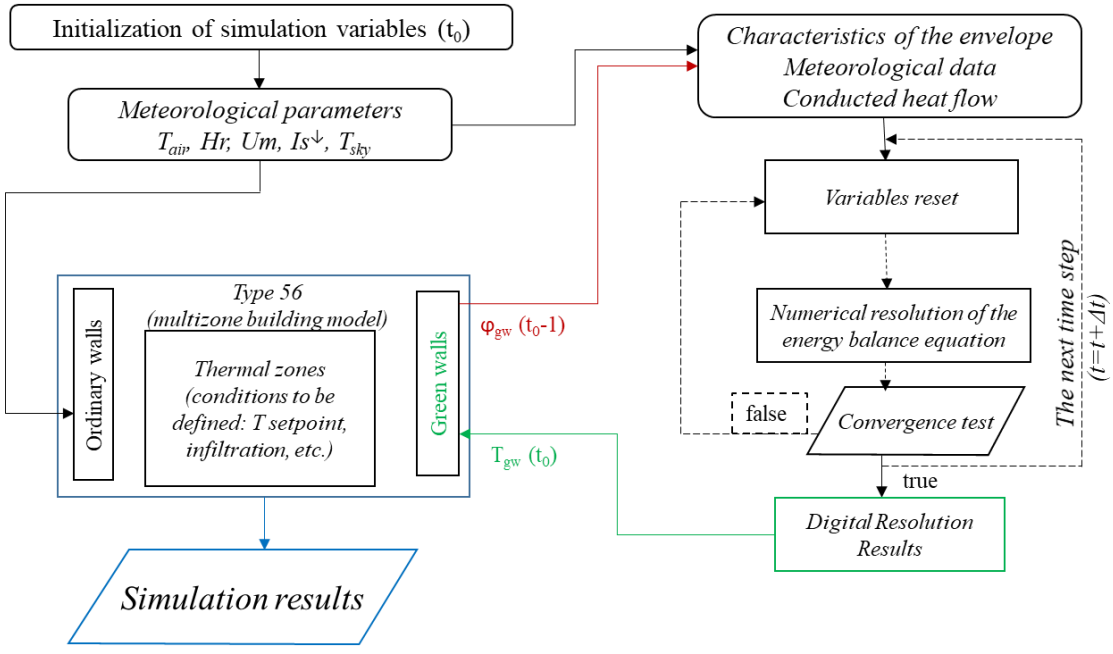


Fig. 2 : Principle of the coupling between the green wall model and the multizone building mode

The definition of green walls on "Type 56" is limited to specifying the orientation in which you the green wall will be installed. Then, at each time step, the heat flow of the surface indicated

as vegetated is connected to "Type 155". It will be added to the other boundary conditions from the weather file, and then the program solves the equations [48]. The results are used as an entrance to the green wall of the "Type 56". In other words, for the operation of the program, at each time step (t_0) the green wall model recovers the surface heat flux (provided by the "Type 56") in the previous time step (t_{0-1}), solves the GW equations, then returns the determined temperature to "Type 56". The program will then take care of carrying out the energy balances of the building.

2.3. Study and analysis of a detached house

As shown previously, few numerical studies have focused on the evaluation of the thermal interest of green walls on buildings. To this end, the new component developed on TRNSYS was used to bring a new contribution to the prediction of the thermal behavior of green walls. These are simulations carried out on a typical brick masonry house located in Lille, France. These houses were built in the years 1960-70. Studies have already been carried out on this type of construction. [54, 55]. This type of house has low insulation and in some cases no insulation. For our case study, the house consists of two floors (ground floor + one floor) with a total area of 100 m2. The one floor is only added to limit the influence of the roof on the energy balance of the ground floor (Fig. 3). Its outer envelope is constructed in solid red bricks (6 * 12 * 24 cm) (transmission coefficient U = 2.273 W/m²/K). The study focuses on the analysis of the concealment of the green walls, they were placed on the South and West side of the house. They are considered without vegetation when it comes to simulations on the reference house. In terms of insulation, it has been assumed that the South and West walls do not have any additional insulation. While the North and East walls have an interior insulation layer of 10 cm (U_{global} = 0.335 W/m²/K). It was considered that the percentage of glazing is 20% on each of the facades. As for the internal thermal gains, they were assumed to be zero and the air infiltration was set at 0.6 vol/h. The influence of the vegetation on the microclimatic scale was not addressed in

this study, the numerical study case is considered without any joint ownership in the surroundings. In addition, the simulations presented relate only to the ground floor (DRC).

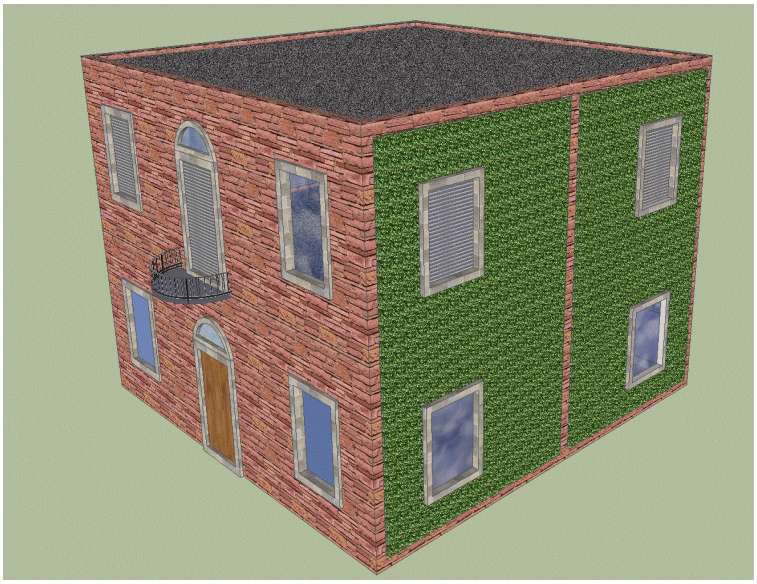


Fig. 3 : Numerical case study

Given the absence of historical meteorological data specific to the city of Lille in TRNSYS, a standard file in "user" format was used (TYPE 99). It was created on the basis of data recorded by the weather station between September 01, 2014 and August 31, 2015.

2.4. Definition of scenarios

The hypotheses of the scenarios are based on the French Energy code with articles R.241-25 to R.241-29 [56]. It establishes the obligation to limit the heating temperature in buildings. For example, article R.241-26 specifies that in premises for residential use, the upper heating temperature limits are set on average at 19°C. For all the simulations, the set temperature in winter (heating period: October to April) is set at 19°C during the day and at 15°C at night. While the set temperature for air conditioning is set at 25°C (May to September). Likewise, blackout curtains are supposed to be drawn on the windows when the incident solar radiation exceeds 600 W/m² (only during summer to limit overheating by the glazing). Regarding the type of vegetation, the west and south walls are considered, covered either by ivy or by Virginia

creeper during simulations on the green house. The leaf area index (F) considered for the two plants is 4, while their average thicknesses are set at 12 cm. As for the coverage rate (σ_{gw}), it is 100% for ivy (persistent plant) throughout the year. Depending on the season, this fluctuates between 0 and 100% for Virginia creeper (deciduous plant) (Fig. 4).

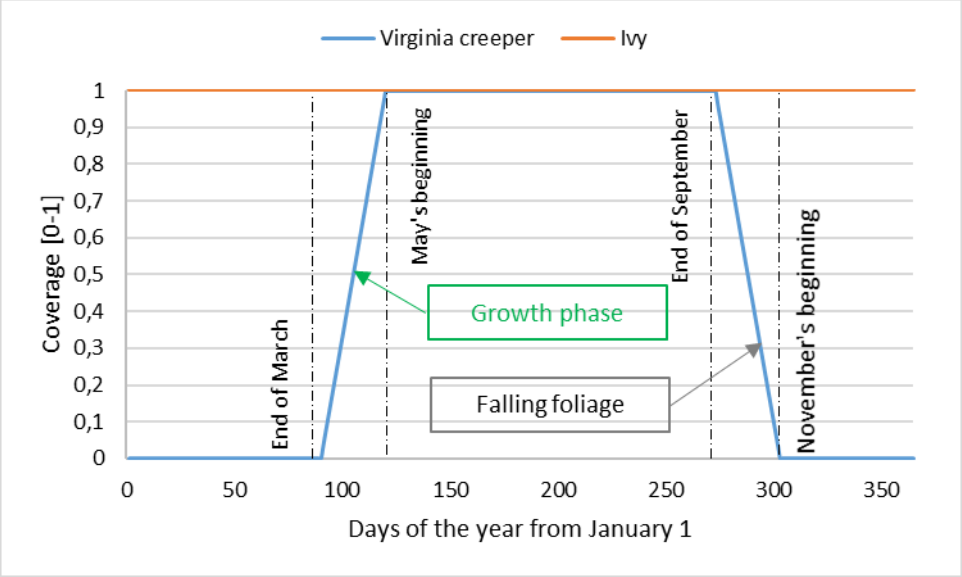


Figure 4 : Plant growth cycle (model assumption)

For both types of plants as well, GWs are considered directly related to facades (without the intermediary of an air gap).

III. Results and discussion

The first simulations were carried out on the green house (ivy) and the reference house in order to verify the influence of permanent vegetation. The results are presented through comparisons between variations in Outside Surface Temperature (TSO) and Interior Surface Temperature (TSI) of southern walls and Operating Temperatures (TOP) in winter and summer and incident solar radiation (IS). The winter period was studied with two cases of sunshine (weak and strong) Then, some analyzes are approached on the variation of the energy needs in terms of heating and air conditioning, in the cases of the presence of GW of the persistent type (ivy) and GWs of the deciduous type (Virginia creeper).

3.1. Winter period

During periods of winter with little sunlight, the exterior surface (south wall) temperatures of the green house were nearly identical to the ambient air temperatures. They varied between 7.5°C and 19.5°C. While the exterior surface temperatures of the reference house (south wall) fluctuated between 8 °C and 34 °C. The difference between the two temperatures corresponding to a minimum peak of incident solar radiation (144 W/m² at 7356 hours) during this sequence was 4°C. This difference is even more amplified with levels of sunshine approaching 200 W/m². It reached 14.5°C as a maximum value during a peak of incident solar radiation of 336 W/m² (Fig. 5).

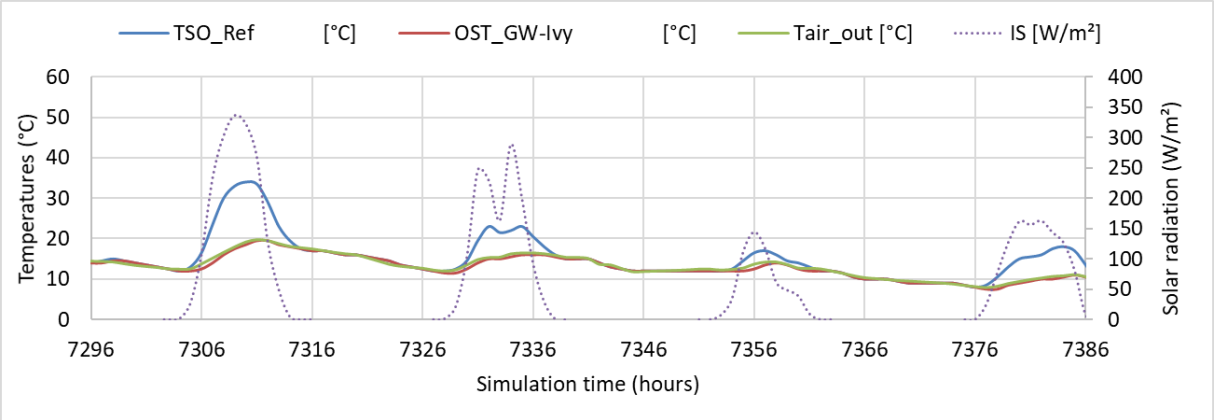
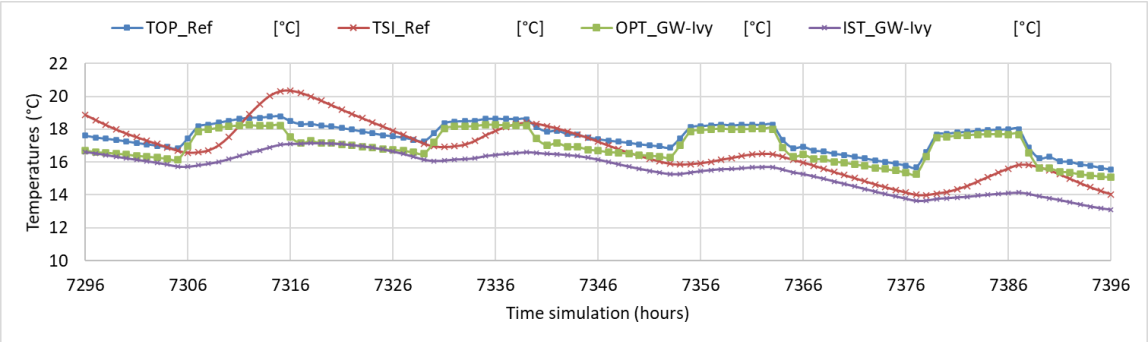


Fig. 5 : Comparison between the temperatures of the exterior surfaces of the southern walls of the two houses (winter sequence with weak sunshine)

As for the interior surface temperatures, they were between 14°C and 20°C for the south wall of the reference house. At the level of the vegetated house, these varied between 13.6°C and 17.2°C. Because of these low interior surface temperatures, operating temperatures were greatly influenced by heating. They practically closely followed the setpoint temperature variations in the case of the green house and were slightly higher for the reference house (Fig. 6).



311

312 ***Fig. 6 : Comparison between the interior surface temperatures and the operative***

313 ***temperatures of the two houses (winter sequence with low sunshine)***

314 These slight differences in terms of operating temperatures, caused mainly by the differences

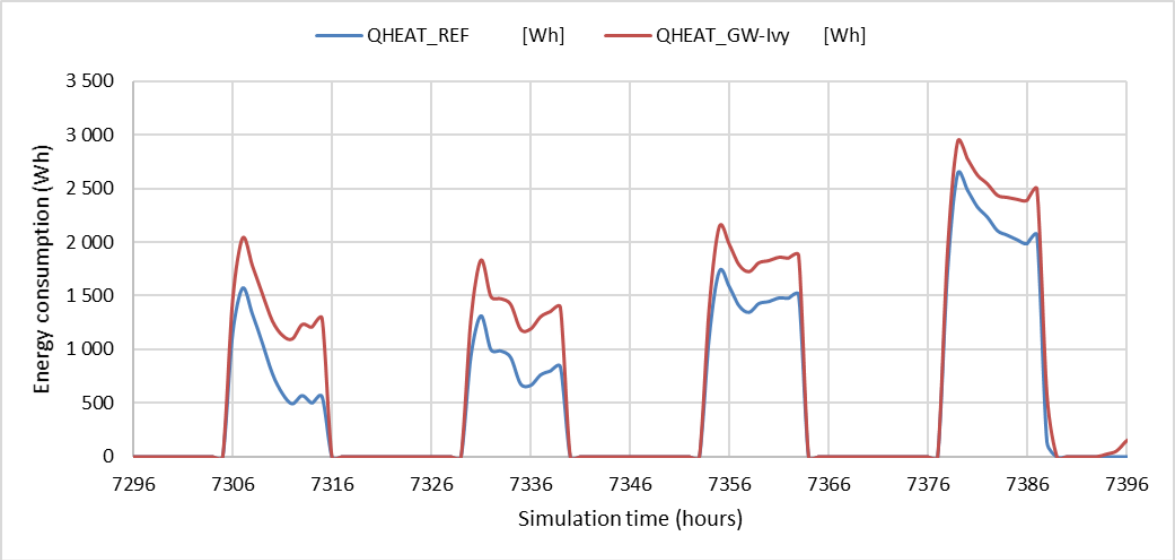
315 in temperature of the exterior and interior surfaces, resulted in a greater energy demand in the

316 case of the presence of plants. Indeed, the presence of vegetation on the south and west walls

317 has slightly limited the solar energy contributions on these facades. This led to heating energy

318 requirements on average 180 Wh higher in the green house than those of the reference house

319 (Fig. 7).



320

321 ***Fig. 7 : The variation in the energy demand for heating in the two houses (winter sequence***

322 ***with little sunshine)***

323 Figure 8 illustrates the temperature fluctuations of the exterior surfaces of the south walls of the

324 two houses (with or without GW) during the winter period. This second sequence of the winter

period is characterized by very high levels of sunshine compared to the average incident solar radiation usually recorded in Lille. Indeed, the incident solar radiation peaks oscillated between 574 W/m² and 809 Wm². The differences between the surface temperatures of the vegetated wall and those of the reference wall corresponding to these two solar radiation peaks were 14.5°C and 22°C respectively. During this winter sequence with very high levels of sunshine, the reference wall gained 22°C on average compared to the ambient air temperatures. However, the surface temperature gains of the vegetated wall were limited by only 4°C on average.

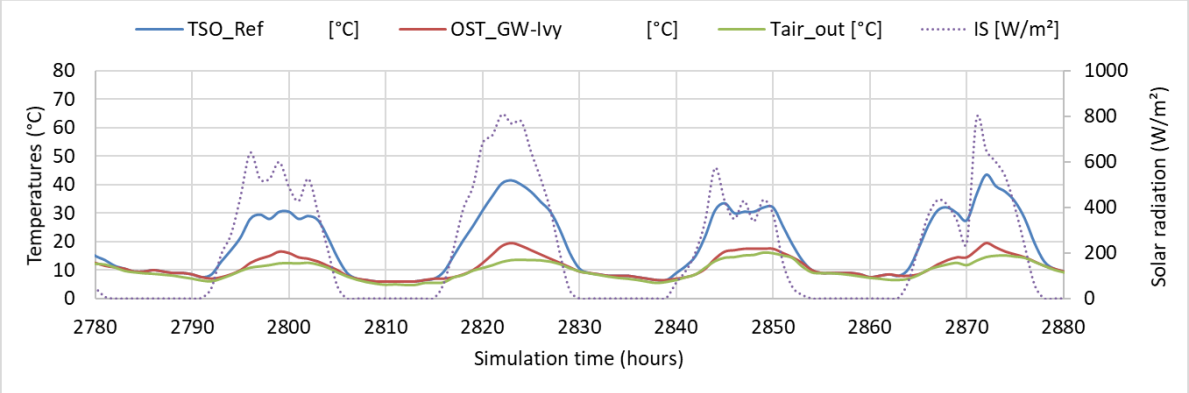
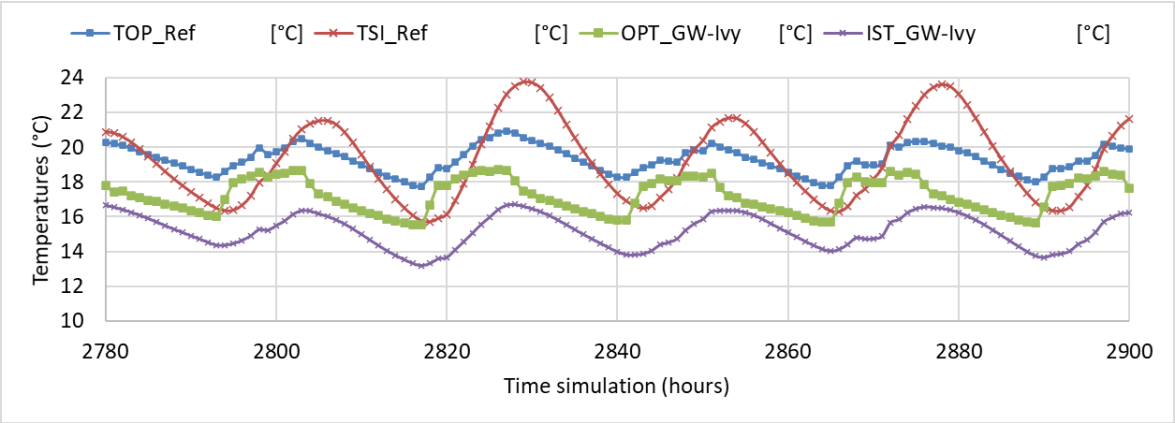


Fig. 8 : Comparison between the temperatures of the exterior surfaces of the south walls of the two houses (winter sequence with sunshine)

These large differences between the surface temperatures of the south wall of the reference house and that of the green house had direct repercussions on variations in interior surface temperatures and operating temperatures. Indeed, the (TSI_Ref) had values between 15.7°C and 23.8°C. These values significantly increased the operating temperatures. This allowed the reference house to limit the use of heating. With regard to the green house, the limitation of solar energy inputs has resulted in interior surface temperatures well below the set point temperatures. They were between 13.2°C and 16.7°C. As a result, the operating temperatures were more influenced by the heating, and nearly matched the set point temperatures (Fig. 9).



343

344 ***Fig. 9 : Comparison between the interior surface temperatures and the operating***

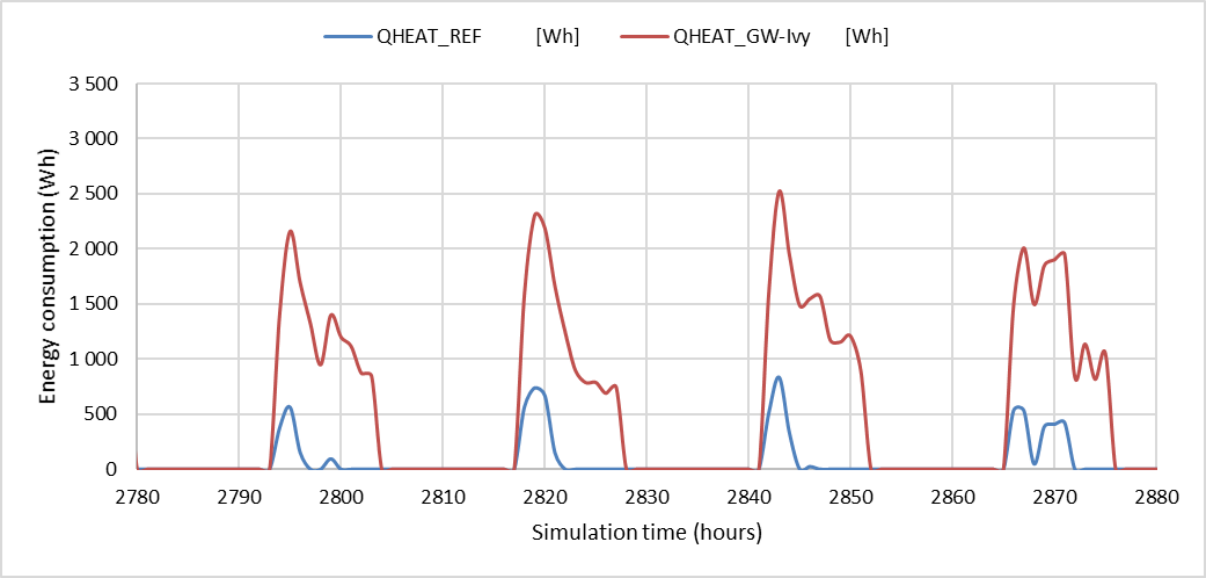
345 ***temperatures of the two houses (winter sequence with sunshine)***

346 Figure 10 illustrates the impact of limiting solar energy gains on the energy demand of the two

347 houses. During the very sunny winter period, the presence of green walls on the west and south

348 facades had a negative influence on the energy needs for heating. These were on average 478

349 Wh higher in the green house than those in the reference house.



350

351 ***Fig. 10 : The variation in energy demand for heating in the two houses (winter sequence***

352 ***with sunshine)***

353 It is important to emphasize that the presence of plants under other winter weather conditions

354 (very cold day, strong gusts of wind, etc.) could provide buildings with positive effects in terms

355 of limiting energy needs [57-59]. However, for a better optimization of the benefits which could

be brought by the plants, the results obtained led us to recommend the use of deciduous plants (which lose their foliage in winter) on the South and West facades so as not to limit the solar energy gains in winter. Evergreen plants, on the other hand, can be used on facades that receive less solar radiation during winter (North and East).

3.2. Summer period

In summer, the comparison between the temperatures of the exterior surfaces of the green house and those of the reference house shows spectacular results. For the sequence chosen, the surface temperatures of the south wall of the ordinary house reached 65°C and 67°C during the solar radiation photos (813 to 850 W/m²). While those of the green house did not exceed 37°C and 45°C under solar radiations of 813 W / m² and 850 W/m² respectively (Fig. 11).

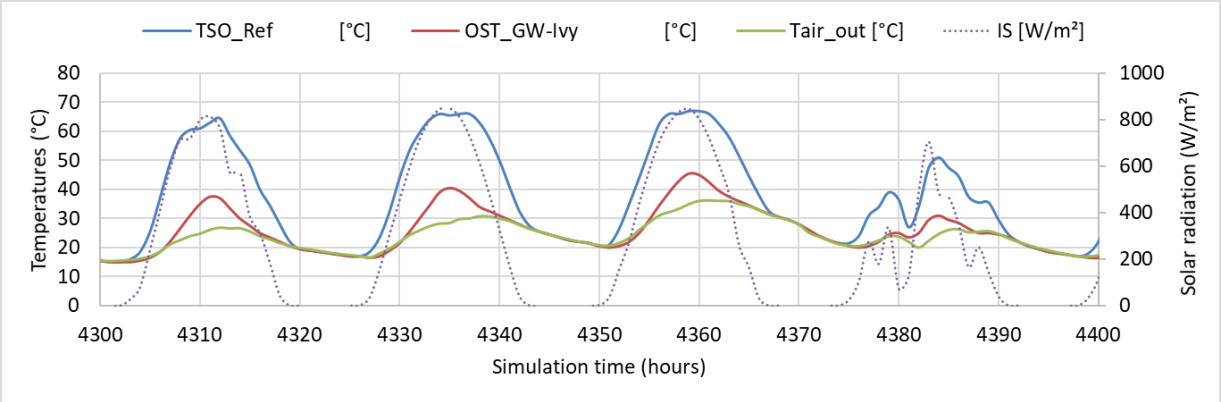


Fig. 11 : Comparison between the temperatures of the exterior surfaces of the south walls of the two houses (summer sequence)

Inside both houses, the interior surface temperatures of the regular house were much higher than those of the green house. They reached 38°C as the maximum value while those of the green house were limited to 30.5°C. Beyond reducing energy needs, reducing interior surface temperatures contributes to improving thermal comfort for users. Indeed, the results obtained showed that the operating temperatures were 1.3°C higher on average in the reference house than those of the green house (Fig. 12).

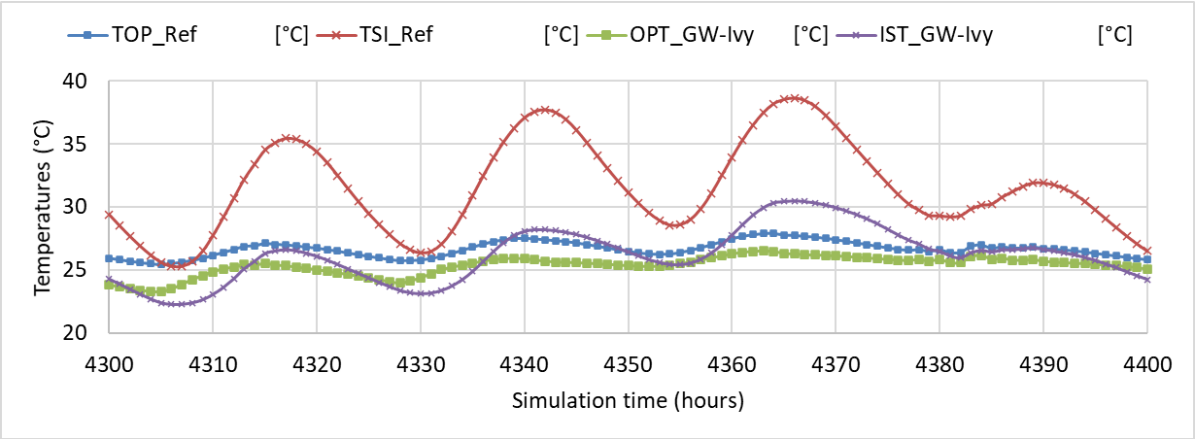


Figure 12 : Comparison between the interior surface temperatures and the operating temperatures of the two houses (summer sequence)

The differences in terms of interior surface temperatures, caused by the limitation of summer overheating by plants, resulted in a higher energy demand for air conditioning in ordinary houses than in green houses. The reduction in energy requirements was proportional to the reduction in surface temperatures. These were 1463 Wh higher on average in the reference house than the green house (Fig. 13).

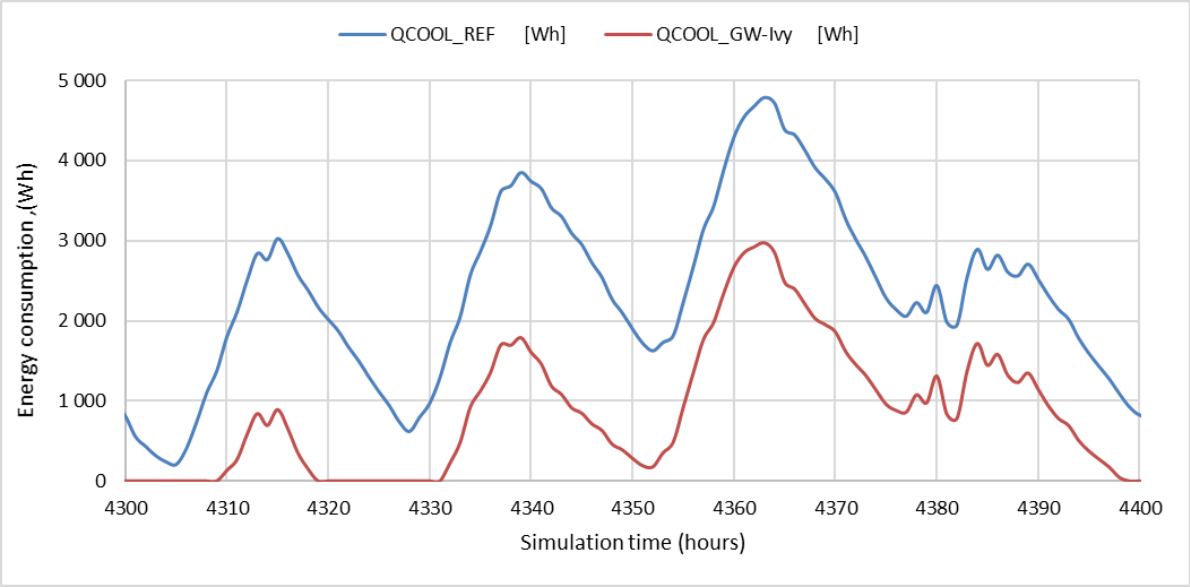


Fig. 13 : The variation in energy demand for air conditioning in the two houses

Furthermore, since air conditioning is not commonly used in single-family homes in Lille, other simulations were carried out to illustrate the influence of vegetation on improving indoor

thermal comfort in summer. These are the same criteria used for the simulations presented above with the deactivation of the air conditioning.

Figure 14 compares the number of hours during which the indoor air temperatures of the two houses were either 25°C or 26°C higher. It shows that the air temperature in the ordinary house exceeds 25°C for 1,629 hours, or 55.63% of the total number of hours in the summer period. Unlike the green house, the number of hours during which the air temperature exceeded 25°C was limited to 325 hours, representing only 11.09% of the total number of hours during the summer period.

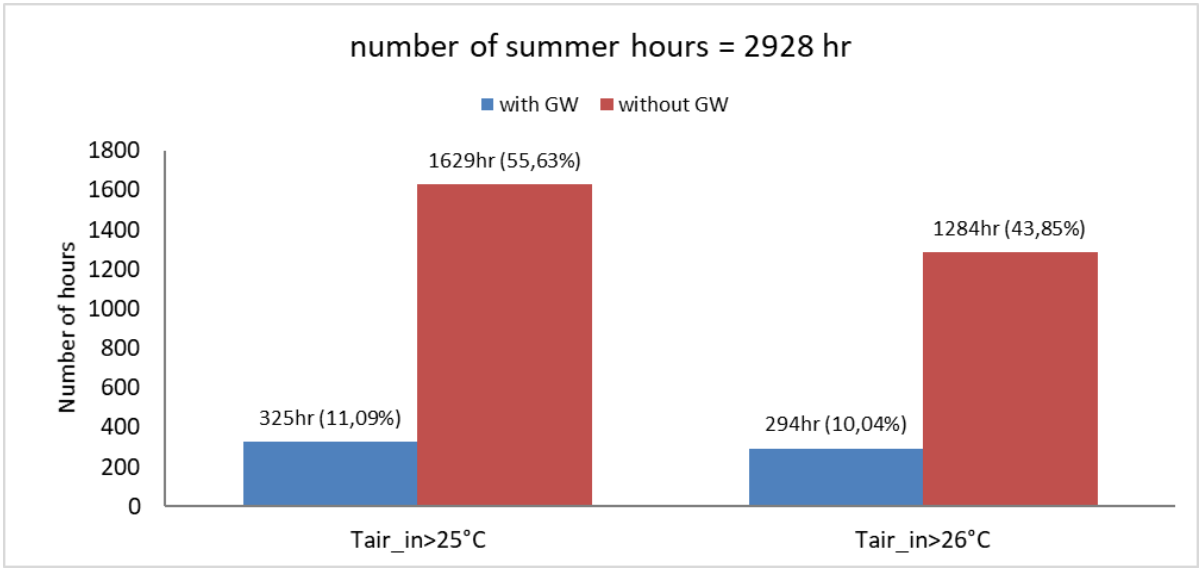


Fig. 14 : Number of hours in a situation of thermal discomfort

By taking 26°C as a comfort threshold, the number of hours during which the ordinary house is estimated in a situation of discomfort is 990 hours higher than in the green house, i.e. a total of 1284 hours during which the temperature air inside the ordinary house has exceeded 26°C. This represents 43.85% of the total number of hours in the summer period, unlike the green house where the percentage of time spent in a situation of thermal discomfort was only 10.04% (294 hours).

3.3. *Influence of vegetation on annual energy demand*

In order to assess the impact of green walls on the annual energy demand of the house studied, the results of simulations of energy demands for heating and air conditioning for each type of vegetation (ivy or Virginia creeper) are compared with those of the reference house.

3.3.1. *Influence on energy demand during winter*

In the case of using ivy (evergreen plant), the energy demand for heating was greater than that of the ordinary house. Indeed, as was explained during the comparisons of surface temperatures, the presence of plants prevented the facades from benefiting from solar energy inputs. These were found with interior surface temperatures well below the defined comfort threshold (15°C at night and 19°C during the day). This induces the use of greater heating power with longer periods than in the ordinary house (Fig. 15).

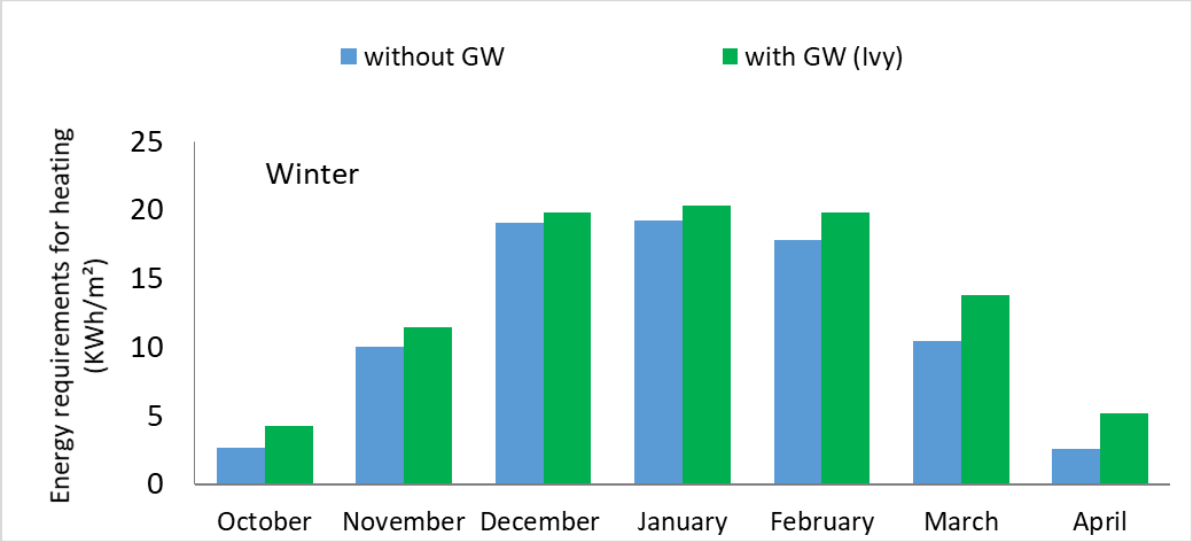


Fig. 15 : Comparison of the heating needs between an ordinary house and a house with green walls (Ivy)

The differences were more accentuated during the months of March and April which were particularly marked by sunny days. The green house consumed during these two months approximately 3 kWh/m² in heating more than the ordinary house. During the rest of the winter

period, the energy demand for heating of the ordinary house was lower by 1.37 kWh/m² on average than that of the house equipped with GW with evergreen leaves (ivy).

The house equipped with Virginia creeper thanks to the loss of foliage during winter allowed the facades to benefit from solar energy input, the energy consumption in terms of heating was similar to that of the ordinary house. It reached a maximum of 19.24 kWh/m² during the coldest month (January) and 10.22 kWh/m² on average during the months of March and November. In addition, slight deviations were noted during the beginning of the growth phases of the plants and the fall of the foliage. They are of the order of 0.31, and 0.13 kWh/m² for the months of October and April respectively (Fig. 16).

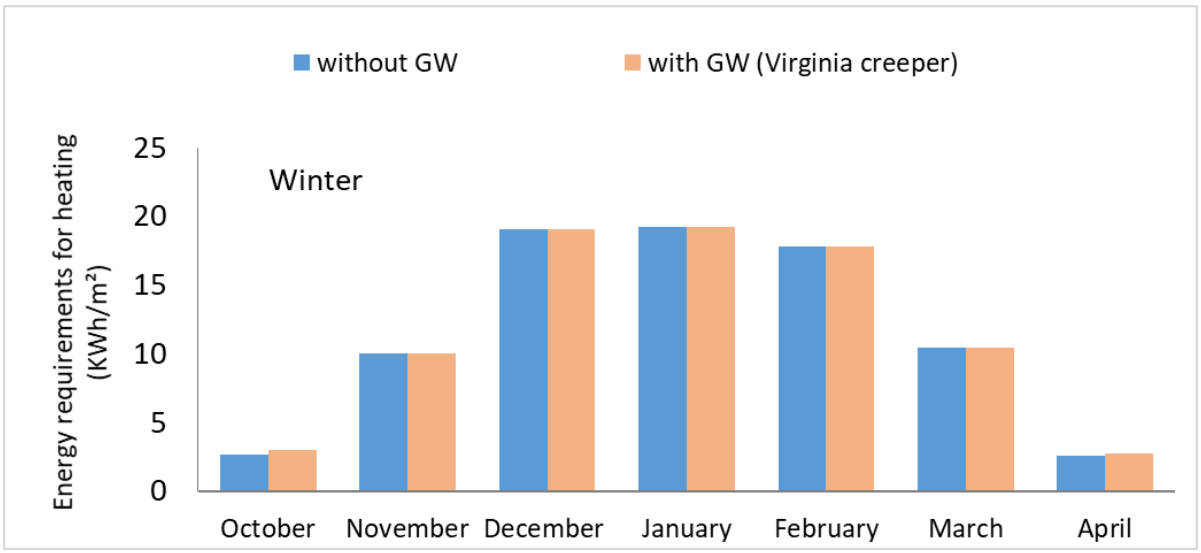


Fig. 16 : Comparison of the heating needs between an ordinary house and a house with green walls (Virginia creeper)

In terms of annual energy consumption, the simulations showed that the heating requirements for the ordinary house were 81.86 kWh/m^2/year. The presence of ivy has increased these by 18.14%, or an annual consumption of 96.87 kWh.m^{-2}/year. Unlike the Virginia creeper which amplified the energy demand for heating by only 0.45 kWh/m^2/year, i.e. an excess consumption of only 0.54% compared to the reference house (Fig. 17).

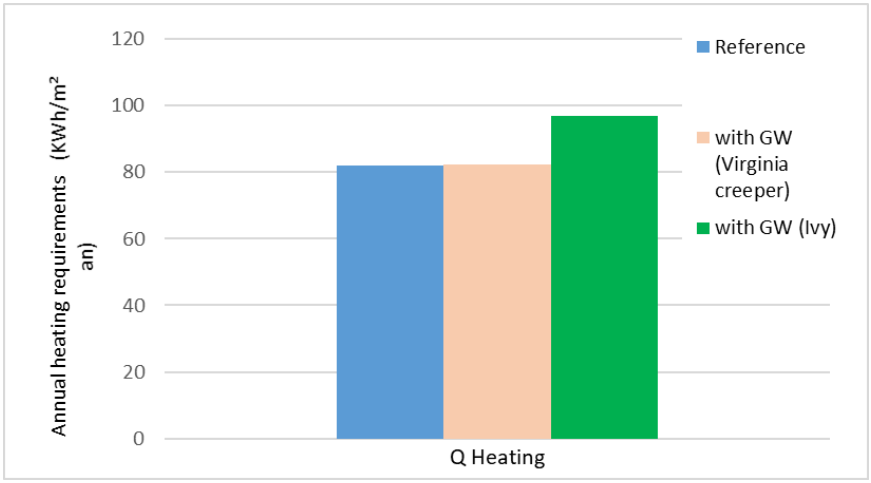


Fig. 17 : Annual report on energy needs for heating

The choice of the type of plants is therefore of great importance, it must be made according to the climatic conditions of the region. Thus, the use of GW with evergreen leaves is strongly discouraged on facades that capture more solar radiation because of their negative influence on the energy balance in winter.

3.3.2. Influence on energy demand in summer

In summer, the presence of green walls significantly reduced the air conditioning load. Virginia creeper and ivy reduced energy demand for air conditioning by 4.16 kWh/m² for the hottest month (July). During the months of June, August and September the reduction in air conditioning load was 2.76, 3.15 and 1.76 kWh/m² respectively by GW compared to the ordinary house (Fig. 18).

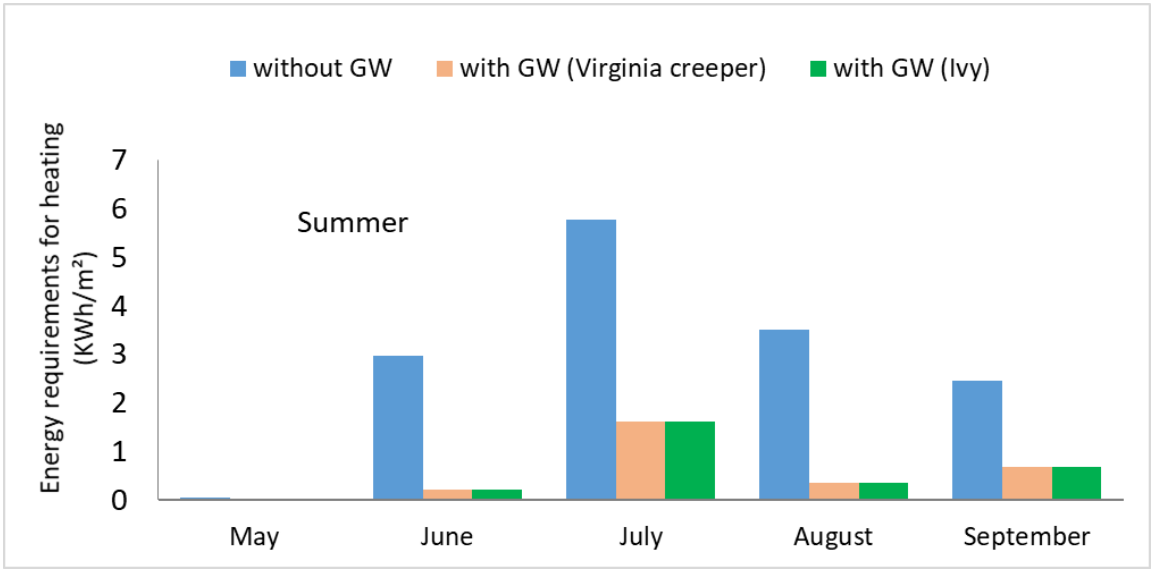


Fig. 18 : Comparison of air conditioning needs between an ordinary house and a house with green walls (Ivy and Virginia creeper)

The reduction in the air conditioning load is linked to the cooling provided by the plants, which by their presence reduce the heat flow received by the green facades. The reduction in summer overheating by the presence of vegetation was estimated at 11.89 kWh/m^2/year, ie a decrease of 80.56% relative to the reference house (Fig. 19).

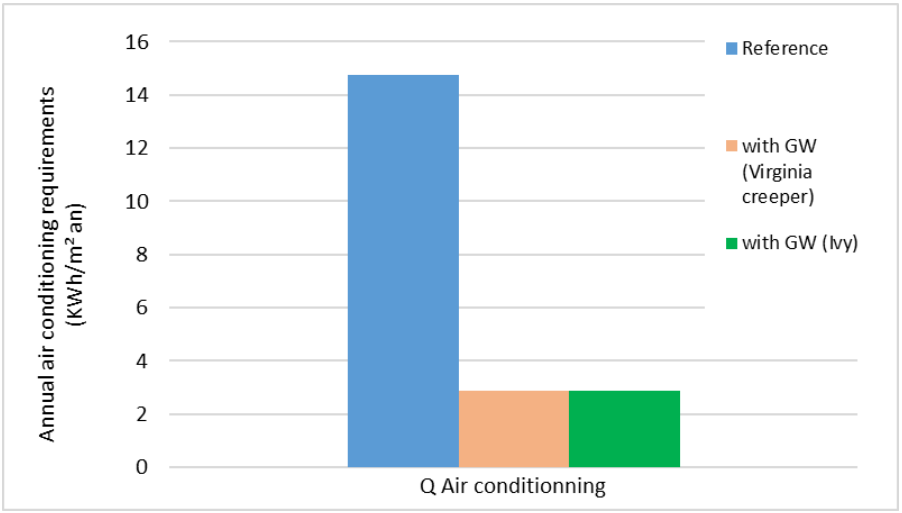


Fig. 19 : Annual review of air conditioning energy needs

In terms of quantitative results related to energy consumption, it is important to emphasize that the latter are very sensitive to the performance of the devices used (air conditioning or heating)

462 and to the set point temperatures. Note also that depending on the insulation of the walls, the
463 degree of influence of the vegetation is very different (paragraph 3.4).

464 *3.4.Influence of GW a function of the thermal resistance of the building envelope*

465 Other simulations were carried out with the objective of evaluating the impact of GWs based
466 on the thermal resistance of the facades. The thermal resistance of the south and west walls of
467 the green house was gradually increased by increasing the thickness of the added insulation
468 layer (Table 1).

469 The GW with ivy placed on the south facade made it possible to reduce the average and
470 maximum interior surface temperature by 2.85°C and 8.16°C in the case of the uninsulated
471 wall. However, these reductions were limited to 0.23°C (average TSI) and 0.35°C (maximum
472 TSI) in the case of 30 cm insulation. In terms of air conditioning load, the table shows a
473 reduction of only 13.85% for an insulation of 30cm. Unlike the uninsulated configuration where
474 the reduction in energy needs for air conditioning was estimated at 80.56% relative to the
475 ordinary house.

476 ***Table 1 : Influence of vegetation depending on the level of insulation of the wall***

	Average TSI		**Maximum TSI**		**Minimum TSI**		**Heating requirements (kWh/m²/year)**		**Air conditioning requirements (kWh/m²/year)**		**Total requirements (kWh/m²/year)**	
Insulation (cm)	**Ref**	**GW**	**Ref**	**GW**	**Ref**	**GW**	**Ref**	**GW**	**Ref**	**GW**	**Ref**	**GW**
0	18.86	16.01	38.64	30.48	8.29	8.12	82.00	96.87	14.76	2.87	96.76	99.74
5	19.82	18.84	29.20	27.53	13.52	13.34	56.94	60.55	8.95	4.74	65.89	65.28
10	19.99	19.39	28.50	27.51	14.28	14.17	52.96	54.99	8.18	5.56	61.14	60.54
15	20.05	19.62	28.22	27.54	14.59	14.51	51.34	52.75	7.86	5.97	59.20	58.72
20	20.09	19.76	28.07	27.55	14.76	14.70	50.46	51.54	7.69	6.21	58.15	57.75
25	20.11	19.84	27.98	27.56	14.87	14.81	49.90	50.78	7.59	6.36	57.49	57.14
30	20.13	19.90	27.92	27.57	14.94	14.89	49.52	50.26	7.51	6.47	57.03	56.73

477

Below an insulation thickness of 5 cm, the influence of plants in reducing air conditioning needs becomes less important, it goes from 11.89 kWh/m^2/year (0 cm of insulation) to 4.21 kWh/m^2/year (5 cm of insulation) to decrease further progressively to 1.04 kWh/m^2/year for an insulation of 30 cm.

These results confirm the positive role that vegetation can make, if they are used on old houses with little insulation. Other studies done on ivy [60] (*Boston Ivy*) or different evergreen-type plants (*Pandorea jasminoides* variegated and *Rhyncospernum jasminoides*) [61] or on decidous Chinese wisteria [62] show methodologies and results similar to ours on the interest of green walls. Thus, vegetation can contribute significantly for the thermal renovation of old buildings. In the case of new constructions, the use of GWs cannot be considered for the thermal criterion alone. Finally, although GWs are not suitable for new constructions from a thermal point of view, the use of this technique could be recommended based on the other advantages of vegetation (urban heat island, air pollution control, biodiversity, aesthetics, etc.).

IV. Conclusions

The integration of a model developed in a TRNSYS environment made it possible to assess the thermal impact of the use of Green Walls on buildings. The main conclusions are:

1. The simulations show that it is not necessary to have a great thickness of green walls to obtain good performance, the ideal is to be between 5 and 20cm. The GW on the south facade made it possible to reduce overheating in rooms in the South.
2. the evaluation of the thermal impact of the use of GWs on buildings. The various simulations carried out on the brick house highlighted the thermal advantages that GWs can provide during the summer. Indeed, the comparisons between the variations in the surface temperatures of the green house and the ordinary one has shown great differences. These reached up to 37.5°C as a maximum value during the summer. Thus, the presence of vegetation protected the facades against summer overheating. This

consequently reduced the energy requirements for air conditioning which were 80.56% lower than those of the non-vegetated house.

3. the impact of the presence of plants on heating consumption in winter was negative. The increase in energy needs for heating was very important during sunny days because of the limitation of solar energy inputs by plants. We must therefore recommend the use of deciduous plants on facades exposed to the sun so that they take advantage of solar radiation (in winter) and limit energy demand for heating. The simulations carried out on the green house with deciduous plants showed that the energy demand in winter was similar to the non-green house and the energy gains in the summer period were very important.
4. the study of the influence of vegetation as a function of the thermal resistance of the facades. It made it possible to underline that the GWs technique is more suitable for the thermal renovation of uninsulated or poorly insulated buildings than well-insulated new constructions.
5. It is therefore possible for design offices to integrate the performance of green walls in the calculations of energy balances. This work also makes it possible to promote SMI-SMEs (small and medium-sized industries/enterprises) in the implementation of green walls.

Acknowledgement

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