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Energy Procedia 30 (2012) 1233 – 1242

Energy Procedia

SHC 2012

Energy performance of greenhouse for energy saving in buildings

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Abstract

Nowadays it is necessary to reduce the energy consumptions of the built environment. This problem has led, in the last years, to a series of regulations to promote high performance systems. These can create a new way of building that is aware of the energetic consumptions. Besides the systems to use the solar radiation to produce energy (as active solar systems i.e. solar thermal collectors and photovoltaic modules) there are the passive solar systems such as the greenhouse. The greenhouse systems have a great potential to improve quality of living and energy performance of the buildings. However, it is now important to adopt a valid evaluation method to assess the project efficiency. There are already spreadsheets (for example SERRA 5000, based on *Method 5000* and *SERRA 832*, based on UNI EN 832/2001) which can evaluate energy performance and verify the effectiveness. The purpose of this research concerns the update of the existing spreadsheets for the winter (UNI EN ISO 13790/2008) and the definition of added spreadsheet for the summer period. In order to test this evaluation method, a case study has been evaluated and discuss.

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Keywords: Solar Architecture; thermal behaviour of greenhouse; energy performance; solar gains; cross ventilation; air changes

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doi:10.1016/j.egypro.2012.11.136

1. Introduction

In the past the greenhouse were used as a space for growing plants and flowers. However, its role has been changing during time for its suitability in creating a comfortable living space added to a building, provided of an aesthetic quality and an energetic function. In fact, the greenhouse is able to store heat during the winter season reducing the energy demand of the building [1].

Nomenclature

e	subscript for the outer glass of the greenhouse
j	subscript for the absorbent wall of the greenhouse
p	subscript for the wall of the greenhouse that adjoins the indoor environment
p,e	subscript for the absorbent part of the wall that adjoins the indoor environment
α	absorption coefficient [-]
ρ_a	density of air [kg/(m^3)]
A	area [m^2]
c_a	specific heat of air [J/(kgK)]
C_d	loss of load coefficient [-]
C_p	pressure differential [-]
F_F	frame factor [-]
g	acceleration of gravity [m/(s^2)]
g_{gl}	total solar energy transmittance of a transparent element [-]
I	solar radiation [kWh/(m^{2}day)]
k	sequential number [-]
t	period of time [-]

The glass used for such constructions allows the solar radiation to be transmitted inside the space and to keep inside part of the thermal radiation (infra-red and long wave radiation).

The solar radiation captured by the green house can produce a positive heat flow for the building during winter season but it must be evaluate the overheating effects in summer period. It is important to calculate the total annual thermal balance of the building in order to achieve the required comfort conditions [2]. One of the main concerns of the passive solar systems is the appropriate management of the greenhouse by the users during the day and the year. Therefore it is fundamental to evaluate correctly the real performance of the passive system [3].

Local regulations and international standards provide simplified methods to estimate the energy balance of generic buildings that can be applied to the greenhouses and have been integrated in existing spreadsheets, e.g. SERRA 5000 or SERRA 832. However, only the winter balance is considered by these tools. A new spreadsheet, called SERRA 13790, was developed to enhance the accuracy of the calculation and is presented in this paper. Among the novelties proposed in the spreadsheet, the most relevant is the calculation of the summer balance, including the contribution of the ventilation. In the paper, the structure of the new spreadsheet is presented in detail and a comparison of the results between the existing spreadsheet SERRA 832 and the new SERRA 13790 is performed for a case study in Italy, therefore the suitability of this tool in supporting the greenhouse design is shown.

2. National regulations

A strong guidance for defining the energy balance of the greenhouses is represented by the national and international standards. In Italy the most relevant ones are UNI EN 832/2001 [4] and UNI EN ISO 13790/2008 [5]. The former proposes a static method for the assessment of the energy balance of building, while the latter introduces a simplified dynamic procedure, including the summer balance. Most recently, it has been developed the UNI TS 11300-1/2008 [6], which is the Italian standard resulting by the European standard.

3. Implementation of greenhouse assessment spreadsheet: SERRA 13790

Based on the standard UNI EN ISO 13790/2008, the new spreadsheet SERRA 13790 was developed in order to update the winter balance evaluation proposed by the previous tools (e.g. SERRA 832 [9]) and to introduce the summer balance calculation with a focus on natural ventilation [3, 7, 8].

The spreadsheet SERRA 13790 is divided in two parts described in the following sections, i.e. the winter balance (Sect. 3.1), and the summer balance with the ventilation study (Sect. 3.2). A total of 32 Excel sheets were defined to link every sheet with the calculation of one of the factors influencing the energy balance.

3.1. Winter balance of the greenhouse

The structure of the first part of the spreadsheet, i.e. the winter balance of the greenhouse, is illustrated in Fig. 1. The diagram points out the main factors involved in the calculation and their correlation and hierarchy. Every box shows the correspondence between these factors and the number of the associated Excel sheet. The improvements to the former spreadsheet SERRA 832, also indicated in Fig. 1, concern the correction factor for shading ($F_{sh,ob}$), the movable shading device factor ($F_{sh,gl}$), the estimated nocturnal transmittance ($U_{w,corr}$), and the possibility to calculate the temperature inside the greenhouse (T_u related to T_i - T_e) using the correlations in UNI EN ISO 13789/2001 [10].

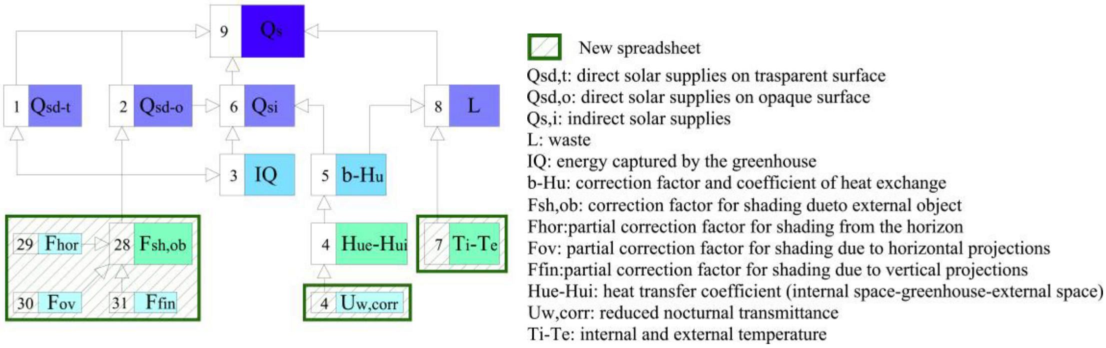

Fig. 1. Structure of the winter balance calculation of a building with greenhouse according to the spreadsheet SERRA 13790 and indication of the improvement to the former spreadsheets

As shown, the main factors involved in the calculation are the net gains Qs and are the solar gains QSs which can be estimated with Equation 1 and 2 respectively:

$$Q_S = Q_{Ss} - L = Q_{Ss} - [H_u\,(T_i - T_e)\,t] \tag{1}$$

$$Q_{Ss} = Q_{sd\text{-}t} + Q_{sd\text{-}o} + Q_{si} \tag{2}$$

The net gains Q_s (Eq. 1) are the difference between the solar gains (Q_{Ss}) transmitted in the greenhouse and the losses (L) through the envelope. The solar gains QSs (Eq. 2) are created by the direct solar gains through the transparent ($Q_{sd\text{-}t}$) and opaque ($Q_{sd\text{-}o}$) surfaces (Eq. 3, 4) and the indirect solar gains Qsi (Eq. 5). The indirect solar gains result by the difference between the energy stored in the inner walls of the greenhouse, IQ (Eq. 5), and the direct solar gains of the opaque surface, $Q_{sd\text{-}o}$ (Eq. 4). The losses, L (Eq. 1), result by the heat transfer through the envelope due to the difference of the temperatures between the internal and external side [11].

$$Q_{sd\text{-}t}=F_{sh,e}(1\text{-}F_{F,e})g_{gle}(1\text{-}F_{F,w})g_{glw}A_wI_pt \tag{3}$$

$$Q_{sd\text{-}o}=F_{sh,e}(1\text{-}F_{F,e})g_{gle}\alpha_pA_p(H_p/H_{p,e})I_pt \tag{4}$$

$$Q_{si}= (1\text{-}b)IQ\text{-}Q_{sd\text{-}o} =(1\text{-}b)[\,F_{sh,e}(1\text{-}F_{F,e})g_{gle}\textstyle\sum_j(I_j\,\alpha_j\,A_j)\,t]-Q_{sd\text{-}o} \tag{5}$$

with $F_{sh,e} = F_{sh,ob}F_{sh,gl}$. Note that generally the movable shading devices are evaluated only in the summer months as they have the function of protecting the interior space.

This procedure is not suggested by the standards, which, for the greenhouse, calculate only the solar gains Q_{Ss}. Italian regulations calculate the energy balance of the greenhouse by subtracting the losses, L (Eq. 1), using the UNI EN ISO 13789/2001 for the thermal exchanges in unheated rooms. The correction factor, b (6), includes the combined effect of the thermal transmission and solar radiation.

The evaluation of the advantage of the greenhouse is made by the comparison of the energy balance of the building with and without the effect of the greenhouse. In cold climate the solar greenhouse can work just as a buffer zone reducing the thermal losses.

The shading factors $F_{sh,ob}$ and $F_{sh,gl}$ strongly influence the evaluation of the solar gains, as can be noticed in the equations above for the direct component through the transparent (Eq. 3) and opaque (Eq. 4) envelope and the indirect component (Eq. 5).

The evaluation of the nocturnal thermal transmittance of the windows, $U_{w,corr}$, improve the estimation of the losses. This value, in fact, includes the values of thermal losses H_{iu} (i.e. the thermal flow from the heated room to the greenhouse) and H_{ue} (i.e. the thermal flow from the greenhouse to the outside) which are required for the calculation of the correction factor, b (Eq. 6), which is used for calculation of both the indirect solar gains, Q_{si} (Eq. 5), and the heat loss coefficient, H_u (Eq. 6):

$$H_u = H_{iu}\, b = H_{iu}\, H_{ue}/(H_{iu}+H_{ue}) \tag{6}$$

For the calculation of the internal monthly temperature of the greenhouse, T_u, the Equation 7 was added to the spreadsheet.

$$T_u = (\varphi+T_iH_{iu}+T_eH_{ue})/(H_{iu}+H_{ue}) = [(F_{sh,e}(1-F_{F,e})g_{gle}\,A_e\,I_e)+T_iH_{iu}+T_eH_{ue}]/(H_{iu}+H_{ue}) \tag{7}$$

Fig. 2 shows an example of the outputs obtained for the winter balance calculation and listed in the “energy balance” sheet of SERRA 13790.

GREENHOUSE ENERGY BALANCE

Direct Solar Gains - Transparent Surfaces

	OCT	NOV	DEC	JAN	FEB	MAR
Q_{sd-t} (kWh/day)	12,58	5,99	2,47	4,01	10,19	13,58

Direct Solar Gains - Opaque Surfaces

	OCT	NOV	DEC	JAN	FEB	MAR
Q_{sd-o} (kWh/day)	0,00	0,00	0,00	0,00	0,00	0,00

Indirect Solar Gains

	OCT	NOV	DEC	JAN	FEB	MAR
Q_{si} (kWh/day)	2,81	0,72	0,40	0,47	1,85	4,49

Solar gains

	OCT	NOV	DEC	JAN	FEB	MAR	TOT kWh/year
Qss (kWh/day)	15,4	6,7	2,9	4,5	12,0	18,1	1804

Waste

	OCT	NOV	DEC	JAN	FEB	MAR	TOT kWh/year
L (kWh/day)	-5,8	-10,6	-14,5	-15,7	-13,7	-9,5	-2114

Net Gain

	OCT	NOV	DEC	JAN	FEB	MAR	TOT kWh/year
Qs (kWh/day)	9,5	-3,9	-11,6	-11,2	-1,7	8,5	-311

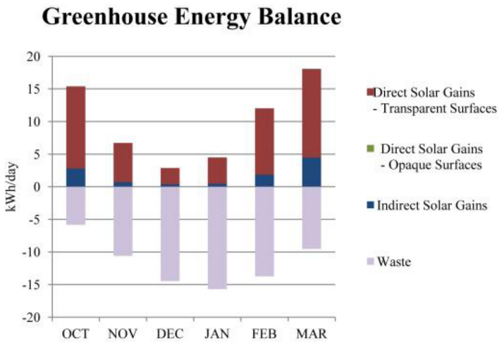

Fig. 2. Sheet of the energy balance of the greenhouse

3.2 Summer balance of the greenhouse and study of ventilation

The structure of the second part of the spreadsheet concerning the summer balance evaluation is shown in Fig. 3. At the moment this calculation is not included in regulations or standards and as can be noticed in Fig. 3 also represents a novelty of SERRA 13790.

The main concern about the summer behavior of the greenhouse is the increase of the indoor temperature due to the greenhouse effect. While in cold climates this effect is useful throughout the year, in Mediterranean climates it causes overheating and compromises the indoor thermal comfort. Thus, the role of the openings in providing natural ventilation is crucial and an accurate estimation of their efficiency was included in the spreadsheet.

The new calculation of the summer balance is similar to the winter in terms of solar radiation and shading contribution, but it includes also the evaluation of the natural ventilation effect and the effectiveness of the openings (Fig.3).

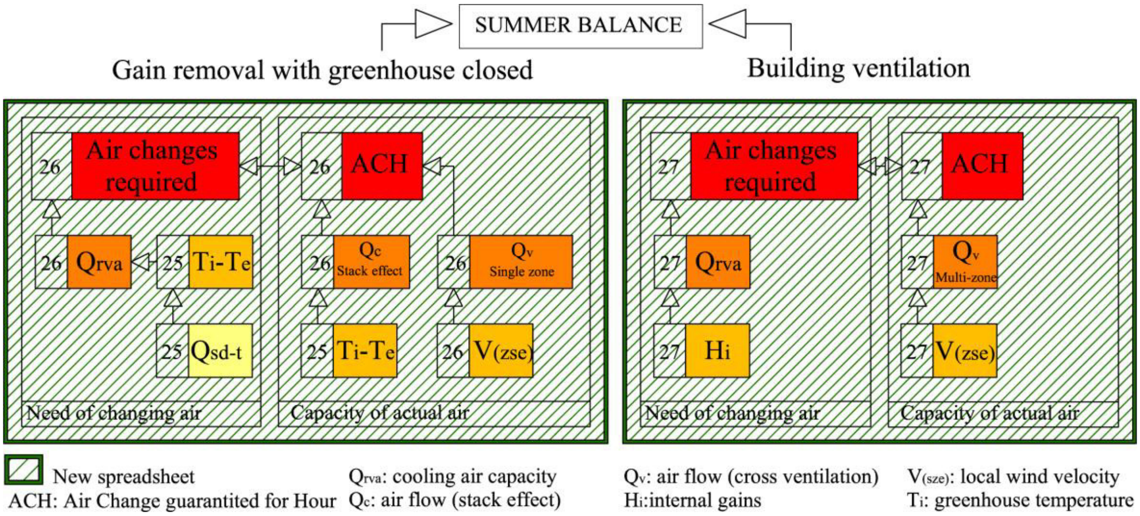

Fig. 3. Diagram of the summer balance with the ventilation analysis

In order to assess the natural ventilation efficiency, the minimum ventilation rates, Q_{rva}, to remove the internal heat gains are estimated (Eq. 8) and compared with the existing ventilation rates for stack effect, Q_c (Eq. 9), and cross ventilation, Q_v (Eq. 10, 11).

$$Q_{rva} = (H_i+Q_s)/\rho_a c_a(T_i\text{-}T_e) \tag{8}$$

$$Q_c = C_d A\sqrt{[2gH(T_i\text{-}T_e)/T]} \tag{9}$$

$$Q_{v,s} = C_d A\,\upsilon_{(zse)}\sqrt{(C_p^{\,+}\text{-}C_p^{\,-})} \tag{10}$$

$$Q_{v,m} = \upsilon_{(zse)}\sqrt{(C_p^{\,+}\text{-}C_p^{\,-})/\sum_k[1/(C_{dk}^{\,2}A_k^{\,2})]} \tag{11}$$

The term H_i in Eq. 8 includes some factors: it accounts for the metabolic heat of people, for the daily average occupational factor and for the contribution due to the equipments. Q_s (Eq. 8) refers to the direct and indirect solar radiation. The characteristics of the openings are also considered (Eq. 9, 11) in terms of pressure, C_p, and discharge, C_d, coefficients.

The monthly variation of climatic data used in winter period calculation can lead if used also in summer period to an incorrect estimation. During the summer period the temperature differences between indoor space and external air can be positive or negative. For that reason a more detailed evaluation is needed. The new spreadsheet considered the hourly time step for air temperature and solar radiation for a representative day of the summer months. The shading factors change hour by hour too, and to perform this calculation the solar mask can be used as shown in Fig. 4(b).

4. Case study

The selected case study is a building designed by the ATA office of Arona (Italy) for the Borgo Ticino Park and located in the countryside near the Solivo Woods. The building is isolated, with some trees located on the south and west sides, Fig. 4(b). The building is used mainly during the spring days for workshops and meetings. The project of the building has a greenhouse of 18 m^2 on the south side and includes some offices (60 m^2) and a meeting room for 50 people (53 m^2).

In the first project phase a greenhouse was designed with the south side made by a transparent surface and two opaque walls in the east and west sides. The surface which divides the heated indoor space from the greenhouse is made by glass. The roof of the greenhouse is opaque. At first, the winter losses and the summer overheating was minimized by choosing materials with a high thermal inertia for the opaque surfaces. Then, in order to avoid the summer overheating, ventilation and solar shading devices were analyzed to propose a modified project. Ventilation analyses showed that the only one opening on the glazed south wall of the first project could not guarantee an effective dissipation of the internal heat gains. Thus, two more openings were placed in the east and west side of the greenhouse for summer ventilation, Fig. 4(a). To avoid thermal losses through these openings in winter, opaque insulated movable systems were provided. In addition, analyses of the solar mask, Fig. 4(b), showed that the roof provided solar shading only from May to July. Therefore, a movable element was designed to block the direct radiation during April, August and September, Fig. 4. So, the modified project includes then the new east and west openings and the shading element on the south wall, Fig. 4.

The modified project was evaluated with the spreadsheet SERRA 832 and SERRA 13790 for the winter period and the results are shown in Sect. 4.1. The first and the modified projects were evaluated and compared using SERRA 13790 during the winter and summer period and the results are shown in Sect. 4.2.

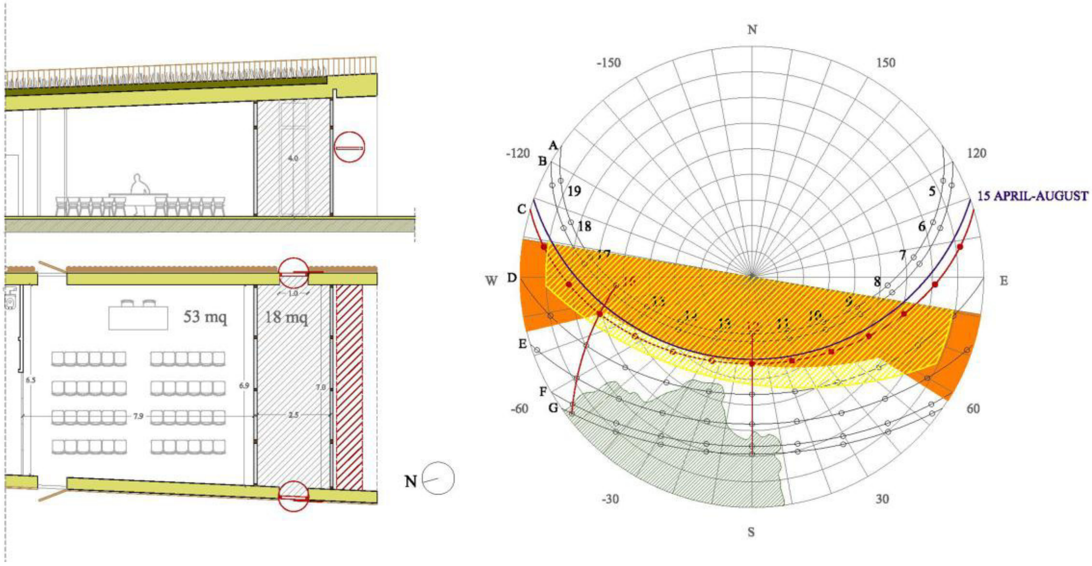

Fig. 4. (a) Plan and section view of the project, in red the proposed modifications; (b) Solar mask of the southern glazed wall

4.1 Comparison of the results of the winter period

A comparison between the winter balance results from the two spreadsheets is proposed in terms of solar gains, Fig. 5(a), and winter advantage, Fig. 5(b). Note that the winter shading factor, $F_{sh,ob}$, is the only one changing significantly within the two calculations. In the spreadsheet SERRA 832 the solar radiation changes monthly but the shading factor is a seasonal single value. In the spreadsheet SERRA 13790, instead, this value changes monthly too. It can be observed in Fig. 5(a) the use of the average annual value of the shading coefficient favors incorrectly the winter period and in contrast by modifying the shading factors, the solar gains in the colder months are strongly reduced. Note that the case study is characterized by a strong shading effect due to the trees of the park situated near the building. For that reason it is possible to observe that the detailed calculation of the monthly shading coefficients shows the major effect of shading in the winter months when the angle of the sun is lower and the solar gains are lower than in the middle seasons. Therefore, the monthly shading factor permits a more realistic results.

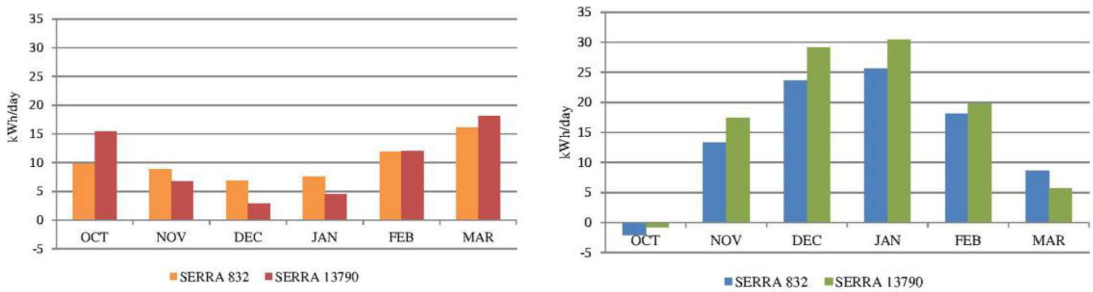

Fig. 5. Solar gains (a) and global advantage (b) in winter obtained with SERRA 832 and SERRA 1370

The global advance calculated with the spreadsheet is the result of the difference between the thermal balance of the building with and without the connected greenhouse. In these balances the gains change due to the shading factors, influencing the final global advance which represents the buffer effect of the greenhouse to reduce winter losses. During the coldest month when the difference of temperature between indoor space and external air is higher the greenhouse can reduce this gap, decreasing the losses. During the middle seasons the temperature difference is lower, thus the buffer effect of the greenhouse is not so relevant.

In Fig. 5(b) are shown the results of the case study. The global advantage of the greenhouse is higher with SERRA 13790 in comparison with SERRA 832 because the gains are reduced but the losses are lower on the final balance

4.2 Comparison of the results of the summer period

The solutions adopted in the modified project, i.e. the two new openings on the east and west sides and the solar shading on the south wall, are evaluated by comparison with the first project. Significant improvements are noticed in the summer energy balance when the solutions are applied. While in winter period, the enlarged area of the transparent surface of the envelope increases the heat losses, in summer period it is fundamental to guaranteed the correct ventilation of the greenhouse space to prevent overheating and reduce energy consumption for air conditioning of the adjacent spaces.

The effect of the movable shading is evaluated in the two projects showing a reduction of solar gains with the improvements of the modified project (Table 1).

Table 1. Solar gains in the two versions of the project with and without the new windows

Solar gains [kWh/day]	Apr	May	Jun	Jul	Aug	Sept
First project	8.9	9.3	10.0	10.7	10.9	10.5
Modify project	7.2	8.0	8.5	9.1	9.0	8.8

The summer balance calculation is performed considering the solar gains in the greenhouse space and indentifying the opening surface needed to remove the heat accumulated in the greenhouse.

As introduced above considering average monthly temperatures is not possible to highlight the daily variations of the parameters involved i.e. temperatures and solar radiation. For that reason the evaluation is improved with an hourly time step for one day for each summer month, Fig. 6.

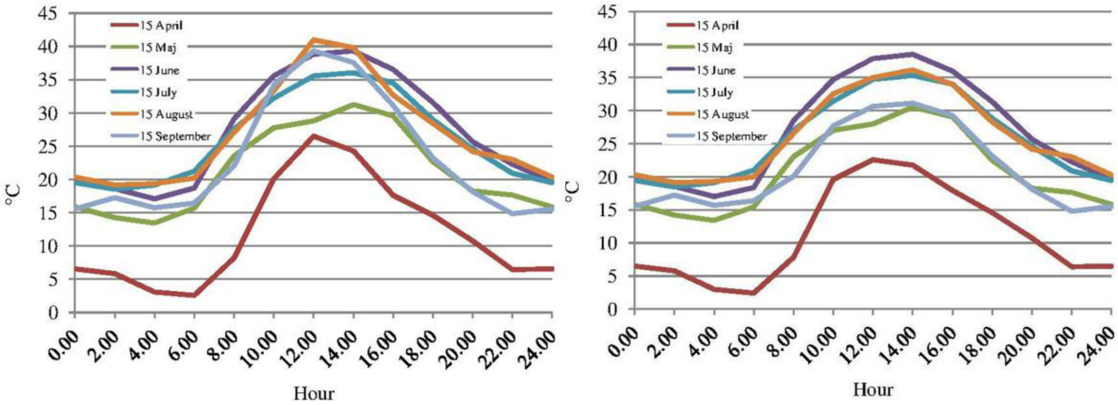

Fig. 6. Indoor temperature in the greenhouse during the summer months for the first project (a) and the modified project (b)

In Fig. 6 it is possible to appreciate the temperature reduction due to the decrease of solar radiation with the new shading system introduced in the modified project. Moreover to reach these results it has been calculated the ventilation rate obtainable with the first configuration of the openings and the new enhanced opening surfaces in the modified project. The effectiveness of the solution is verified analyzing the indoor temperatures. In the first case the temperature in the greenhouse rise up to 40.97°C and in the modified project reaches 38.51°C (at 12 am of the August 15). A comparison between the minimum ventilation rates required and the ventilation rates in the modified project is shown in Table 2.

Table 2. Air change per hour required and air changes guarantied in the modified project

Ventilation [vol/h]	15 Apr.	15 May	15 Jun.	15 Jul.	15 Aug.	15 Sept.
Air Change per Hour required	2.1	2.1	2.1	2.1	2.1	1.8
Air Change per Hour guarantied	4.4	2.9	2.7	2.5	2.9	2.7

5. Conclusion

The spreadsheet presented in this paper permits to optimize the performance of the greenhouse to reduce energy demand for buildings. Some methods are available to assess winter performance of these passive solar systems but no one is specifically realized to verify that, in summer period and in warm climate, there are no negative effects as overheating. Even the Austrian architect G. W. Reinberg, known for his low energy buildings in northern Europe and strong proponent of the greenhouse system to improve quality and energy performance of residential and commercial buildings highlights in a interview [12] the importance of the ventilation techniques to control the summer overheating in the greenhouse, even in his country. The difficulty of managing the variables such as the change of temperatures influenced by ventilation, has brought to many debates, unfortunately, without any definitive solutions. Therefore this research wants to provide a simple and efficient tool as the spreadsheet SERRA 13790, which can evaluate more precisely in comparison with the older calculation methods the winter situation of the greenhouse.

Furthermore the spreadsheet is realized to allow the control of summer behavior of the passive solar system. In this way it is possible to control the negative effect of this system which is a technical solution often introduced in the projects to improve the quality of the indoor space but at the same time can compromise the thermal comfort in summer.

Acknowledgements

The authors would like to thank Arch. Claudio Zappone for the kind availability and for all architectural materials. The authors are grateful to Rubina Ramponi for providing valuable comments and suggestions in improving the manuscript substantially.

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