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Performance of Passive Solar Systems in a Case of Retrofitted Buildings

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Abstract

Passive solar systems can be an efficient strategy to save energy both in new and retrofitted buildings, above all in the Mediterranean climatic zone. Over the last decades many passive solar applications have, indeed, taken place in this area. Contrariwise, there are still few data about the actual performances of passive solar systems; scientific literature shows that studies are limited and often they refer to very peculiar climatic conditions. That happens, basically, because passive solar systems are components of the building envelope, therefore they are dependant on specific environment, operating conditions and budget, hardly replicable and difficult to standardize; so that their performances are hard to evaluate.

However, in spite of difficulties to obtain fair operational data it may be useful, for whoever intends to adopt passive solar strategies, to acquire data about their potential performances.

The authors are actually involved in monitoring actions on passive solar systems, in particular on glasshouses and Trombe-Michel walls, applied in retrofitting of residential buildings. This study is supported by a research convention linking the Department of Sciences for Architecture, of the University of Genoa, and the Regional Territory Agency for Buildings in the Province of Savona.

The winter monitoring campaign has been carried out using temperature data loggers, a thermal photo camera and an anemometer to measure low air velocities. Those monitoring actions are producing significant data concerning: the operation/efficiency of the checked systems, their performances according to solar radiation absorption, the mode/efficiency of heat transfer, the effect of the users' behaviour, the validation of information in the literature. The research outputs may be significant in the design and research fields, particularly in order to build up databases able to lead to more reliable simulation systems.

Keywords: Monitoring; Passive solar systems; Passive retrofitting; Solar glasshouses; Trombe-Michel walls.

Introduction

This work was carried out in accordance with an agreement between the Department of Sciences for Architecture (DSA), University of Genoa, under the supervision of Prof. Andrea Giachetta, assistant professor at DSA, with Dr Chiara Piccardo and Professor Adriano Magliocco, and the Agenzia Regionale Territoriale per l'Edilizia (Territorial Regional Building Department) (ARTE) in Savona.

Data on the real winter working principles of passive solar technologies were collected through monitoring.

We should remember that although passive solar systems have been used for several years (albeit not widely), there is little research available on their effective performance and operation in the Mediterranean climate.

A collection of 151 examples (D'Errico & Funaro, 1992) was issued by ENEA (Agency for New Technologies, Energy and the Environment), demonstrating that passive solar systems have been used in Italy since the 1980s. Since then, other construction work using passive solar systems has been documented (Scudo, 2013; Rogora, 2012; Zappone, 2009). Nonetheless there are still very few data concerning the actual performance of these systems: the tests carried out in this context are limited and often concern particular climatic situations (Rempel et al., 2013; Zhu & Chen, 2013; Chandel & Aggarwal, 2008; Flores Larsen et al., 2008; Krüger & Givoni, 2008; Pfafferott et al., 2004). There are two reasons for this:

- passive solar systems are components of the building envelope, depending on local climatic and operative conditions which are not easily replicable or standardised and are therefore difficult to study;
- these systems have rarely been subjected to performance analysis which could have been used as a base for the development of simulation systems and as a guide for designers.

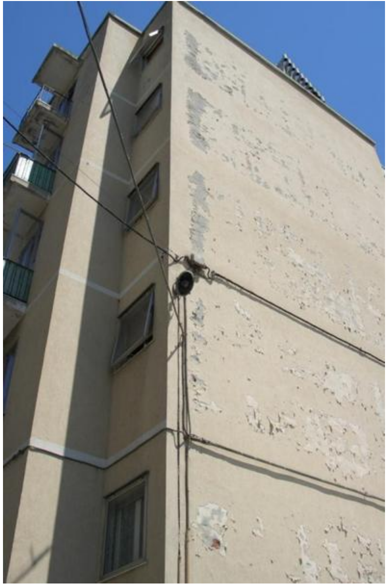
Arte Buildings in Savona

The monitoring project was carried out on three buildings owned by ARTE; these are situated in an urban area in Savona, Piazzale Moroni, and have been the object of recent sustainable renewal. This work was promoted by ARTE and the town of Savona for the urban innovation programme called Contratto di Quartiere II (District II Contract, Ministerial Decree 2522/2001 and 30/2002). Modifications were proposed with regard to open spaces, green areas and path walks to improve the quality of this area and living standards. In 2008 work was subcontracted and completed in 2013. Several papers have been published on this subject (Serafino, 2013; Giachetta, 2012; Giachetta & Magliocco, 2007, 2011; Magliocco, 2005).

The following considerations are based on the monitoring of the three buildings: we will call the buildings A, B and C.

Building A was built around the end of the 1950s and the beginning of the 1960s; it has 5 floors and 20 apartments. The building (see Figure 1) had the typical characteristics of social buildings of the period in which it was built: low cost, indoor comfort problems and premature disrepair over time. The building was made of reinforced concrete structures and double-layered brick walls with no insulation. The absence of insulation and the presence of thermal bridges caused serious problems such as the formation of dark humidity spots because of condensation and mould. The façades were heavily deteriorated, with plaster loss uncovering the structural reinforcement bars. The flat roof had no insulation and suffered from water penetration. There was a ventilated façade in concrete and asbestos to the north that had to be removed as soon as possible.

Figure 1. *Building A, South Façade before Renovation*



In the light of the situation and given good conditions of solar exposure, the project mainly focused on the building envelope, providing: an external insulation layer in expanded cork with a thickness of 4 cm, the insufflation of thermal-acoustic cellulose flake insulation in the wall cavities (approximately 15 cm), roof insulation and waterproofing, passive solar heating systems. Solar glasshouse systems were realised on the southern side of the building, in correspondence with the kitchen and the hallway (see Figure 2). Photovoltaic systems were also planned and a system with nominal power of 20 kWp was installed outside on the roof.

Figure 2. *Building A, South Façade with Solar Glasshouse*

Now there is one solar glasshouse on each of the four storeys of the building; the cellars and the mezzanine are excluded. Each glasshouse has a surface of approximately 5 m^2 and a total volume of 15 m^3. The inside space next to each glasshouse has a volume of 27 m^3. The entire space heated by the glasshouse has an internal surface of approximately 50 m^2. The glasshouses were created with their own structure in galvanized steel; they can be accessed through the apartments by a new opening placed near the hallway. The windows of the glasshouses are in aluminium with single-pane glass and they are equipped with mobile sunscreens comprising roller blinds.

Adjustable air vents were installed on the perimeter wall to guarantee the necessary thermal transfer by convection between the glasshouse and the inside of the building. There are only two air vents per glasshouse although four air vents had been planned in the project phase (this created some functional problems, as will be demonstrated). The air vents measure approximately 20x20 cm but, if one takes into account the fixed chassis for the accommodation of the closing valve, the net dimension of the opening is 16x16 cm approximately. The air vents are closed internally by a metal valve with adjustable opening and externally with a fixed plastic grid, different from the one foreseen for this project and significantly reducing the air flow from the glasshouse to the inside space and vice versa. High and low aerators were installed on the Frech-window that connects the glasshouse with the accommodation (dimensions of 80x0.5 cm), in addition to the air vents installed on the perimeter wall.

Buildings B and C (number 2 via Roveda and number 2 via Grandi) are practically identical. The monitoring campaign was carried out on accommodation in building B and its results considered valid for building C as well. The pre-recovery characteristics of the buildings' construction, degradation and inefficiency regarding thermal control and consequent excessive energy consumption were completely similar to those described above for building A (see Figure 3 and Figure 4), as were the renewal works. On the right side of the south façade (as one looks at the building) solar glasshouses were constructed with the installation of verandas to close the existing balconies; Trombe-Michel walls were installed on the left side of the façade with the addition of a glass enclosure approximately 10 cm from the perimeter wall and the addition to this last of air vents for the operation of the system (see Figure 5 and Figure 6).

Figure 3. *Building C, South Façade before Renovation*

Figure 4. *Balconies of Building C before the Recovery Operations*

Figure 5. *Building C, South Façade after the Retrofitting*

Figure 6. *Building B, South Façade after the Retrofitting*

Methodology

The winter monitoring campaign evaluated the thermal benefits of the solar glasshouse and Trombe-Michel wall systems for the relevant dwellings, taking into account eventual interference deriving from user behaviour and its effect on the normal working operations of this technology. On the basis of the obtained results, a user guide to the correct use of the passive solar systems will be supplied. We also wanted to verify the correspondence between the project forecast and the practical results.

The general goal of the surveys, even though they are based on a specific case, was to provide data concerning the actual performance of the passive solar systems in the Mediterranean climate. The limited research produced in this field (for Italy, among others, Berizzi, 2012; Allesina & Di Croce, 2009) was also a motivating factor.

The analysis method used to obtain these goals was based on the following criteria:

- reliability and significance of the temperature parameter for an initial evaluation of the indoor comfort of the buildings, explaining the thermal exchange between passive solar systems and the heated space; the greater part of the long winter campaign (111 days) is based on the use of mini data loggers installed inside and outside the buildings and inside the passive solar systems;

- the necessity to carry out non-invasive studies that would have caused problems for the users and excessive costs for the client (ARTE); the possibility of installing heat meters near the existing independent heating systems of the concerned building units was excluded. There were empty lodgings available in building A, in which it was possible to estimate the thermal contribution of the solar systems by turning off the heating for the whole survey period;
- changes in the survey conditions and the use of new instruments according to the emerging data; the data readings during the monitoring campaign refined the research, producing more significant results and interpreting them better; the use of a thermo-anemometer for understanding the convection heat transmission between the solar systems and interior spaces.

Monitoring

A winter monitoring phase was carried out from 4 December 2013 to 24 March 2014.

Climatic Data

To verify weather conditions in situ to understand the working of the passive solar systems, we used the weather station recordings of the Nautical Institute in Savona, located in the town a few miles away from the site where the monitoring was carried out. This station is part of the OMIRL network (Regional Weather Observatory) composed of 200 stations and managed by ARPAL (Regional Agency for the Protection of the Environment of Liguria). We considered solar radiation data and external temperature, as they are the main indicators of the useful days of operation of the passive solar systems. External temperatures were also recorded during the monitoring phase by a mini data logger placed outside building A. The results confirmed lower values for the monitoring site. This area is considerably colder and windier than the reference weather station location.

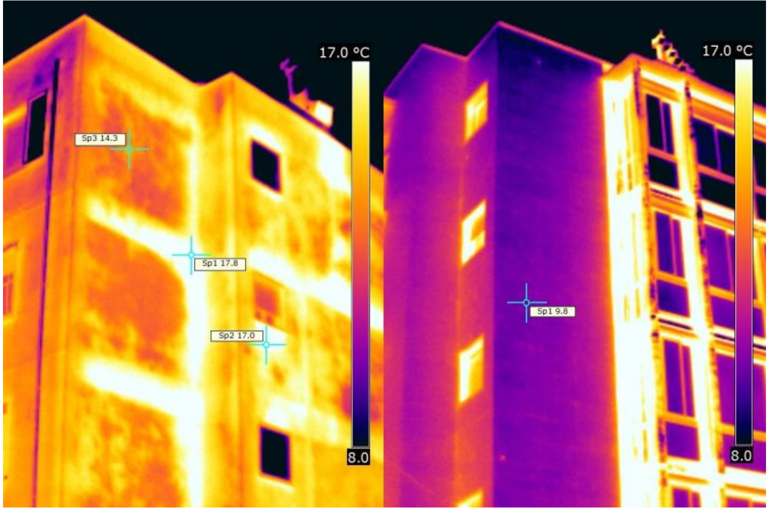
The climatic data of the survey period (winter 2013-14) were used for comparison with average winter data of the town of Savona for previous years, with particular attention to the temperatures and the number of clear days. This was very important in terms of assessing and validating our monitoring phase data. The meteorological data provided by the database of DBT-ENEA and ARPAL were therefore used as reference. Considering the higher average temperatures in this period, and a greater number of rainy days, we assumed a decrease in useful operation time of the passive solar systems compared with an ‘average’ year.

Preliminary Phase

Two lodgings directly involved in the tests are here named A1 and A2 in building A and an interior room, B1, in building B; they all have one south-facing wall where passive solar systems were placed: one glasshouse for A1 and A2 and two Trombe-Michel walls for B1. A1 is on the first floor and A2 is on the second; they were chosen because during the monitoring period they were empty while waiting to be assigned to new tenants by ARTE. Lodging B2 was occupied by a tenant who, understanding the purpose of the study, diligently supplied precise time periods in which the heating system was in use.

Thermographic images were taken inside and outside and compared with those of neighbouring buildings that were not subject to insulation and solarisation work. These thermographic surveys mainly highlight the effectiveness of the outside thermal insulation layer used for the renovation of the buildings and the reduction of the ‘thermal bridges’ in correspondence with the structures (see Figure 7).

Figure 7. *Thermo-camera Image of Building A to the Right and a Similar Building not under Renovation on the Left*



Six mini data loggers were used initially from 4 December to 27 January, and their position and specific functions are described below:

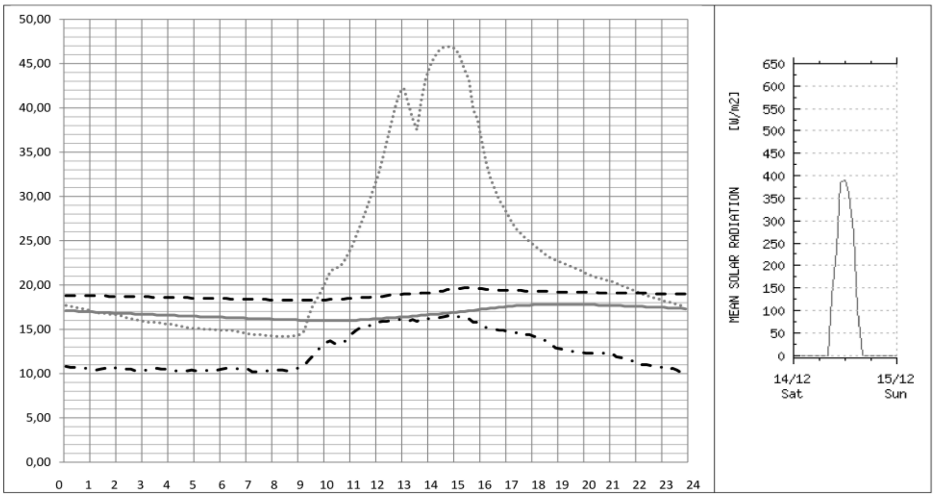
- mini data logger 1 was placed in a cellar (not insulated) facing south in building A. In relation to the interior temperatures during the monitored months, the trend is very similar to that which would have been recorded in the rooms facing south of the apartments of the same building if the above-described operations had not been completed;
- mini data logger 2 was placed outside, in the shade, on the terrace on the western side of lodging A1;
- mini data logger 3 was placed inside the solar glasshouse of lodging A1;
- mini data logger 4 was placed inside the inhabitable kitchen of lodging A1, heated by the glasshouse by convection through two

air vents with adjustable grills that connect these rooms with the glasshouse;
- mini data logger 5 was placed in the cavity of the collector of one of the Trombe-Michel walls of lodging B1;
- mini data logger 6 was placed inside the room of lodging B1 heated by convection through air vents in the Trombe-Michel wall.

Reading of Data on 14 December 2013

The diagram (see Figure 8) refers to the temperature recordings by mini data loggers 1, 2, 3 and 4 for lodging A1 and its glasshouse. The day was sunny with maximum radiation intensity just below 400 W/m^2. We can observe that the insulation and solarisation work have a substantial effect in maintaining the temperature of the space (mini data logger 4) constantly above 18 °C, even at night, with a maximum of 20 °C approximately around 3.30 p.m., without the help of any other heating system. External temperatures went from approximately 10 °C to a maximum of 16 °C. The test demonstrates that the lodging is constantly in a comfort range without use of the heating system on a sunny December day with outside temperatures which are not particularly low. The solar glasshouse can reach particularly elevated temperatures such as 47 °C and it has only a minor influence on the interior temperatures, as can be deduced from the temperature curve of the rooms heated by the glasshouse by convection (mini data logger 4) which is slightly bell-shaped. The glasshouse was never shielded by the exterior sun screen curtains during the whole winter period. Other records in December with similar or even colder solarisation show similar temperature curves.

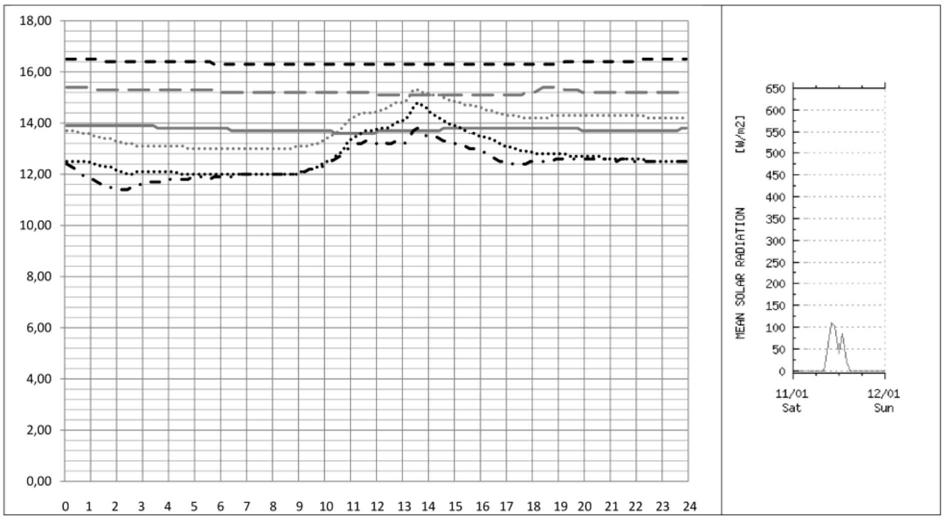
Figure 8. *Building A: Continuous Grey Line = Room without Passive Solar Systems; Dash Dot Black Line = Outside Temperature; Dotted Grey Line = Temperature Inside Glasshouse; Broken Black Line = Temperature Inside the Room Heated by Solar Glasshouse*



Reading of Data on 11 January 2014

Temperatures reported by the six mini data loggers, during a cloudy day with very little sun but not too cold, can be observed (see Figure 9). According to the graphic, with a constant temperature just below 14 °C in the test room (mini data logger 1), the interior room temperature of lodging B1 is constantly between 15 and 16 °C and inside lodging A1 it is constantly between 16 and 17 °C, close to comfort range even during the night. The temperatures in the collector space of the passive solar systems follow the trend of the external temperatures and are lower than the temperatures of the relevant interior spaces; the purpose of these systems during such days is to act as a thermal buffer space.

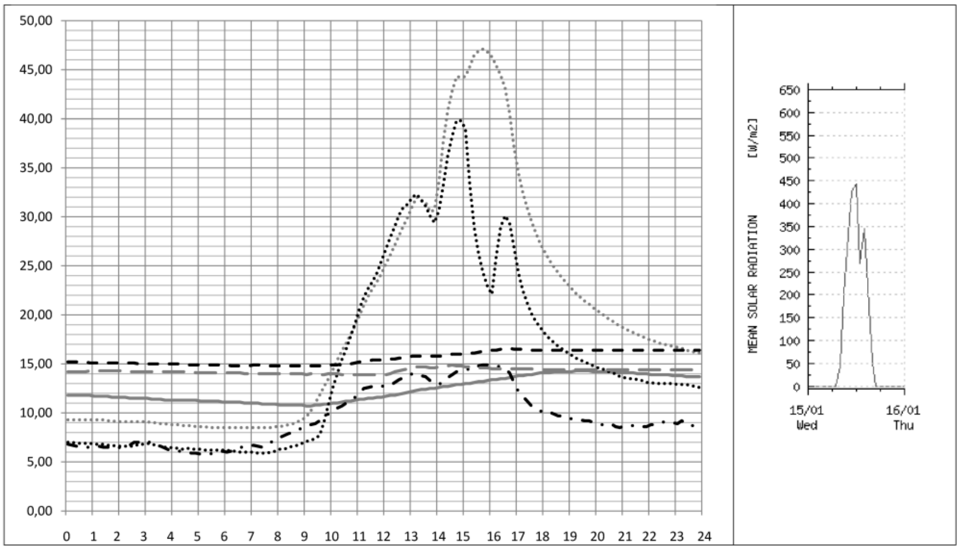
Figure 9. *11 January 2014, Buildings A and B; Same Line Code as Figure 8 Except: Dotted Black Line = Temperature Inside the Trombe-Michel Wall; Broken Grey Line (Long Dash) = Temperature Inside the Room Heated by the Trombe-Michel Wall*



Reading of Data on 15 January 2014

The diagram (see Figure 10) refers to a sunny day with a maximum solar radiation intensity value just below 450 W/m^2; the outside recorded temperatures show a minimum value just above 5 °C, with a maximum of approximately 15 °C. The temperatures inside the test room go from a minimum just below 11 °C to a maximum of approximately 14 °C; the interior temperatures of lodging A1 (with glasshouse) are considerably higher, with a minimum of approximately 15 °C and a maximum just below 17 °C. The temperatures of B1 (with a Trombe-Michel wall) are lower, but always constantly higher than those of the test room. Even with more harsh external winter temperatures, the conditions of indoor comfort in the solarised lodgings are good (although the test lodgings are not really in a comfort range and are therefore in need of heating). The temperature curves of the rooms heated by passive solar systems have a slight ‘bell’ trend compared with the temperature trend in the cavity of the Trombe-Michel wall and inside the glasshouse. This seems to be attributable to inefficient convective heat transfer through the valves, between the solar collectors and the interior rooms.

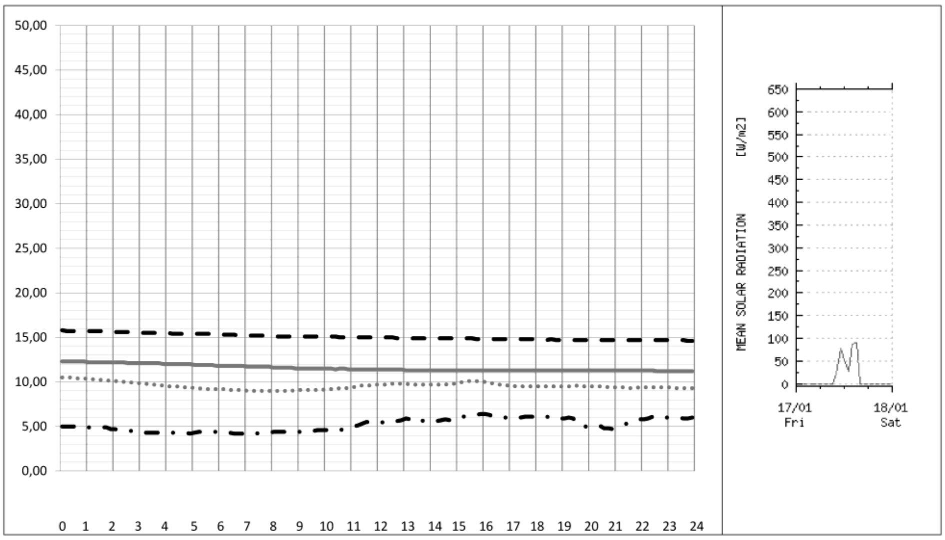
Figure 10. *15 January 2014, Buildings A and B; Same Line Code as Figure 9*



Reading of Data on 17 January 2014

The diagram (see Figure 11) refers to the temperature recordings of mini data loggers 1, 2, 3 and 4 in the A1 lodging and its solar glasshouse. The day of the survey was rather cold and not very sunny. The roles carried out by the insulation and by the presence of the thermal gap of the glasshouse seem to be significant, temperatures inside the lodgings being constantly between 14 and 16 °C, with external temperatures between 4 and 6 °C approximately.

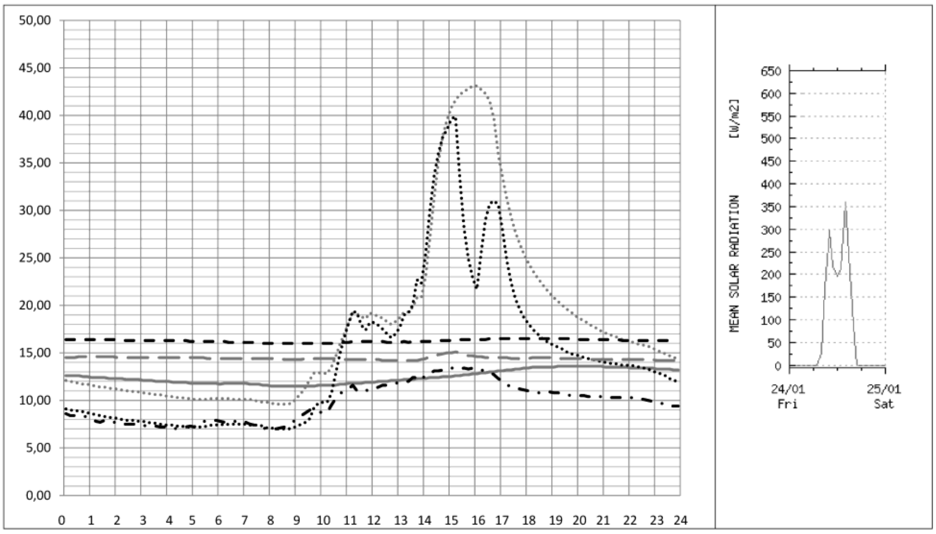
Figure 11. *17 January 2013, Building A; Same Line Code as Figure 8*



Reading of Data on 24 January 2013

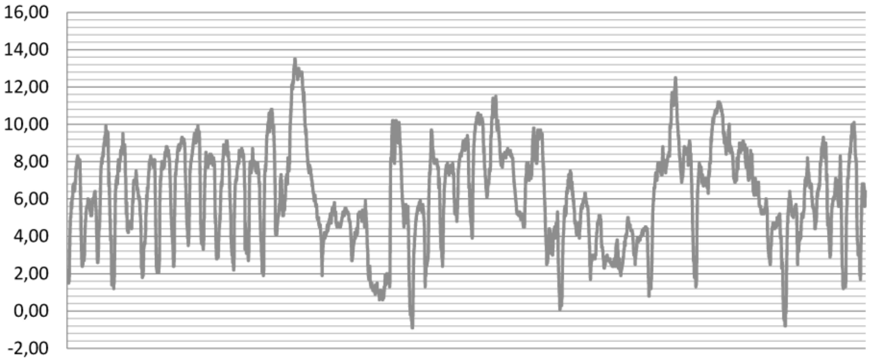
The day was averagely sunny (see Figure 12), with stable interior temperatures, considerably higher than the external ones. However, as in other cases, the ‘bell’ of the temperature graphics of the premises heated by the passive solar systems is not emphasised, meaning that the interior contribution offered by the natural convection is not too high.

Figure 12. *24 January 2014, Buildings A and B; Same Line Code as Figure 9*



From analysis of the temperature graphics from 4 December to 26 January we can observe that the passive solar solutions and the insulation installed during the recent building renovation are both efficient. Comfort range temperatures can be reached inside the rooms of the analysed buildings without using other heating systems, particularly on sunny days; even on cloudy days the indoor temperature is stable and considerably higher than outside temperatures, with a difference that goes beyond 13 °C (Figure 13).

Figure 13. *Trend in Temperature Difference between the Outside and the Inside of the A1 Lodging without the Use of Heating Systems for the Period 4 December to 26 January*



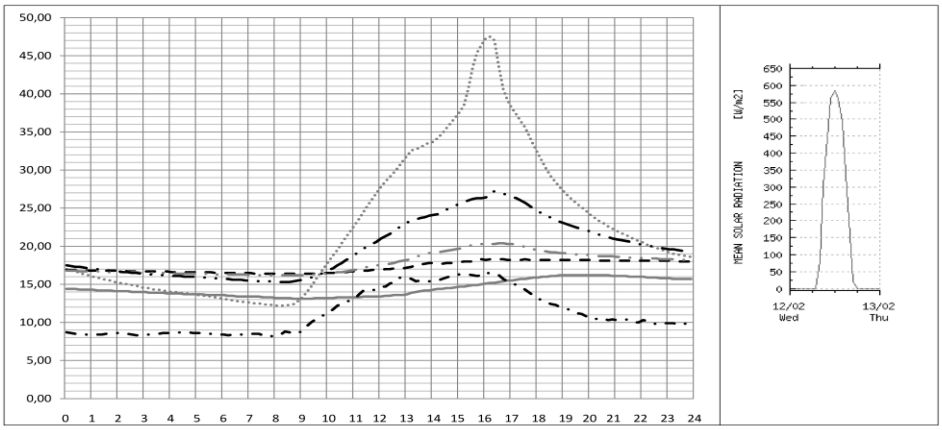
The solar glasshouse seems to guarantee a substantial contribution, more than that of the Trombe-Michel wall.

Two more mini data loggers were inserted in building A. Mini data logger 7 was inserted in lodging A1 next to the hallway connected to the glasshouse through a French window that was kept closed, and an air vent was placed next to the window joint. Mini data logger 8 was inserted in the same spot as the previous one (the hallway), but in lodging A2 (similar to A1), but here the French-window was left open. The results of the new surveys demonstrated that in some circumstances the heat transfer between the glasshouse and inner space could be more efficient and provide an increased air movement. Changes were therefore made to the solar system valves of the glasshouse on 17 February and further data were recorded until 24 March, the day on which measurements with the thermo-anemometer were carried out in relation to these valves.

Reading of Data on 12 February 2014

The diagram (see Figure 14) refers to the temperatures recordings of mini data loggers 1, 2, 3, 4, 7 and 8; the data concern lodgings A1 and A2 and their glasshouses. The day of the survey was very sunny with maximum radiation intensity of almost 600 W/m^2. The reading of the temperature curves is particularly interesting as it shows an appreciable difference between the room heated by convection and the rooms heated in a semi-direct way (mini data logger 7) and direct way (mini data logger 8). In the second case there is a stronger ‘bell’ trend, meaning that the thermal transfer between glasshouse and interior is more efficient. The result obtained has caused us to consider the possibility of making changes to wall valves for convective heat transfers. The closure devices of these valves were taken out on 17 February, inside (with adjustable fins) and outside (with fixed grill).

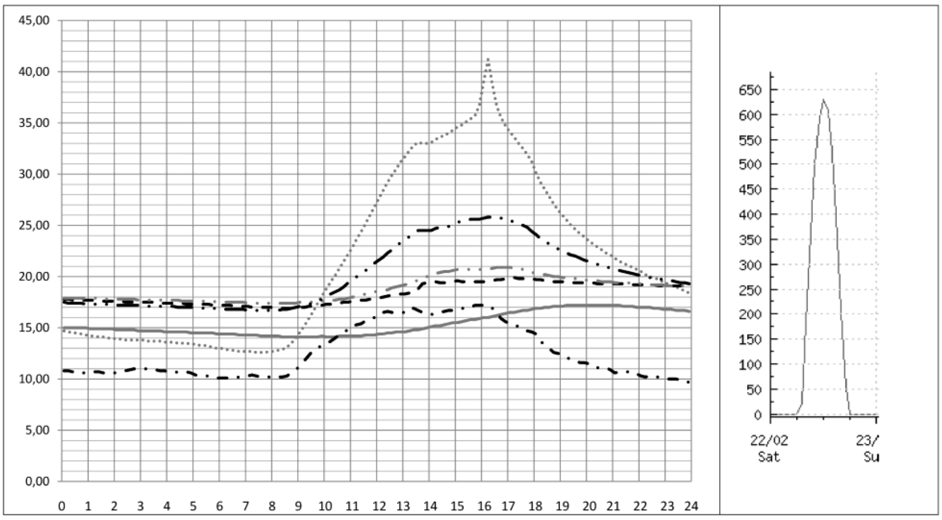
Figure 14. *12 February 2014, Building A; Same Line Code as Figure 8 Except: Dash Dot Dot Grey Line = Temperature Inside the Room Heated by Solar Greenhouse in a Semi-direct Way; Dash Dot Dot Black Line = Temperature Inside the Room Heated by Solar Greenhouse in a Direct Way*



Reading of Data on 22 February 2014

The diagram (see Figure 15) refers to the temperature recordings of mini data loggers 1, 2, 3, 4, 7 and 8. The day considered for the survey was very sunny with maximum radiation intensity over 600 W/m^2. What is significant is the change found in relation to the curve corresponding to the rooms heated by the glasshouse by convection through the wall valves whose inner and exterior grids were removed: there is an obvious ‘bell’ trend that shows how the removal of the grids meant improved convection heat transfer between the glasshouse and the adjacent interior premises.

Figure 15. *22 February 2014, Building A; Same Line Code as Figure 14*

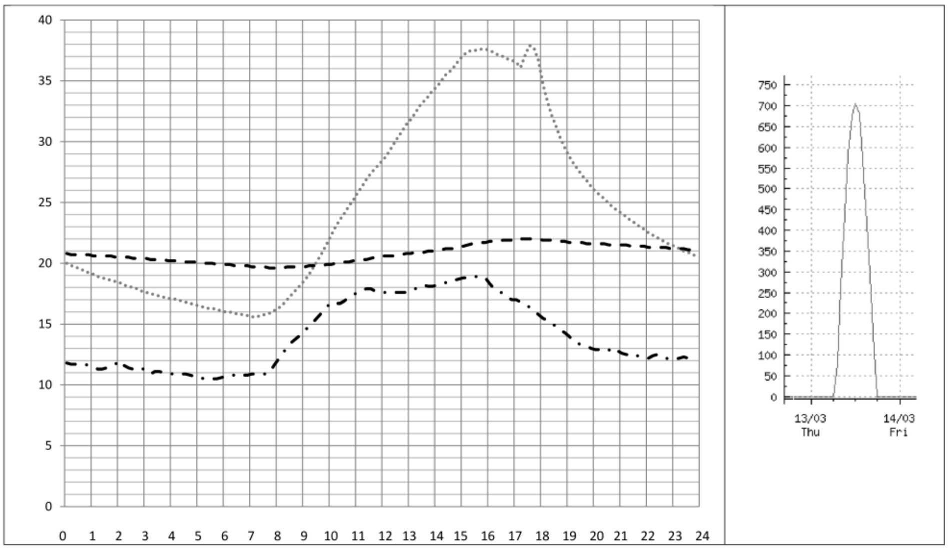


Reading of Data on 13 March 2014

The graphic (see Figure 16) refers to the temperature surveys of mini data loggers 2, 3, 4; the data therefore relate to the external temperatures, the inside of the solar glasshouse and the rooms heated by convection. The day considered for the survey was very sunny with maximum radiation intensity of approximately 700 W/m^2. The performance of the system is significant with an interior temperature between almost 20 °C and 22 °C when the external temperatures are between 10 °C and 18 °C. The wider opening of the wall valves (because of the removal of the interior and exterior grids) does not imply excessive heat loss in the night.

Tests with the thermo-anemometer were performed on 24 March 2014 for better evaluation of the differences in flow through the wall valves. The results are significant and they mainly show that the presence of the external closing grid (not adjustable) hinders the air flow significantly; for example, in correspondence with glasshouse temperatures around 29 °C a three- to four-fold decrease in flow speed is recorded with or without this grid.

Figure 16. *13 March 2014, Same Line Code as Figure 8*



Results and Conclusions

The monitoring campaign allowed us to confirm some of the performances we expected and also to highlight different performances because of changes made during the construction phase.

Passive solar systems offer good efficiency in energy retrofits if the buildings are thermally insulated. With passive solar systems, buildings in the Mediterranean climate, with fairly mild winters, are almost self-sufficient in the heating season. During the test period, corresponding to the coldest season of the year (note that temperatures this year did not fall below 2 °C), the passive solar systems in the case study demonstrated guaranteed indoor temperatures significantly higher than the external ones on cold and cloudy days; inside the buildings, on sunny days, comfort range temperatures were reached. Reasonably balanced internal temperatures were recorded, without peaks during daylight or drops during the night. For the whole considered period, without any heating system, lodging A1 maintained temperatures between 13.30 °C and 22.40 °C. This implies that these solar technology solutions are able to guarantee a great decrease in energy consumption for artificial heating of the lodgings.

For an insulated standard-height room, and a Mediterranean climate, we can assume that there is a good convective flow between the solar glasshouse and the inner space, with a ratio between glasshouse and heated volume of approximately one to two. The net area of the wall valves and the air of the separation wall between glasshouse and interiors need at least a ratio of 5 to 100. A retrofit with passive solar technologies could, however, have difficulties in obtaining sufficiently large ventilation grids. For example, although in this case the renovation work was carried out without moving the tenants and their furniture, in buildings with small dimensions it is difficult to organise air vents. The closure devices of small air vents have to be very well dimensioned: over-tight meshes are to be avoided and valves with adjustable fins preferred.

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