Towards a sustainable bioclimatic approach for the Peruvian high Andean rural area: Evaluation of the thermal contribution of a greenhouse attached to a dwelling

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Abstract

This study includes the evaluation and validation of two experimental housing modules built in Imata, Arequipa, Peru, at 4500 meters above sea level (masl) and with a very cold climate. The modules are similar, differing only in that one of them has a greenhouse attached to the north wall. The design and materials used in the module envelopes are similar to what is mostly used locally. For the simulation work and the validation of the energetic behavior, both modules were equipped for the acquisition of the temperatures in the interior, and for the simulation, the EnergyPlus software was used. The exchange of air between the module with the greenhouse and its greenhouse was controlled by means of opening and closing the door and window that connected them, using different configurations. When the door and the window are open during daytime, the temperature inside the module can increase 5.7 °C with respect to the module without the greenhouse, and in relation to the external temperature, up to 12.1 °C during the day and up to 16 °C during the night. The data obtained with simulation are in excellent agreement with the data measured inside the two modules for all the proposed configurations. These results strengthen the proposal to use attached greenhouses to obtain sustainable heating for rural high Andean homes which, for the most part, do not have any heating.

Keywords: thermal comfort, solar energy, energy efficiency, attached greenhouse

1. Introduction

In recent years, attention has been prioritized in Peru on the most vulnerable population sectors (due to their social status, age, nutritional status and geographical location) (Presidency of the Council of Ministers, 2019). A particular case is the population settled in the south of the country in the high Andean region located more than 4000 meters above sea level (masl); the health of this population is at risk due to the very cold climate, which has caused the deaths of hundreds of inhabitants. Given this problem, pilot projects of bioclimatic housing construction have been carried out from the government, academia and the private sector to improve the habitability conditions by applying a series of bioclimatic techniques and strategies, prioritizing heat isolation and the use of passive solar systems for heating, such as attached greenhouses (GIZ-MVCS, 2015). Passive solar heating is particularly advantageous when considering that in these areas, the solar resource is abundant (above 6 kWh m^{-2} day^{-1}) (SENAMHI, 2003). These projects focused the studies on determining the temperature inside the house, as a result of the whole envelope, but did not quantify the thermal or energy contribution of each implemented technique. The present study is based on the determination of the thermal energy contribution of a greenhouse attached to an experimental housing module in an Altoandina area.

Although greenhouses are better known in agriculture for the production of vegetables in regions where open field production is not possible because of the climate (Theurl et al., 2017; Li et al., 2017), greenhouses attached to homes are also used in cold climates as a passive heating system with the objective to reduce the demand for active heating. Some studies made in Europe are given here: A comparison of different technological options evaluated in the winter season (Chiesa et al., 2017); a determination of the thermal efficiency of a greenhouse (Schoenau et al., 1990; Bataineh and Fayez, 2011); a determination of solar gain from environments adjacent to an attached greenhouse (Oliveti et al., 2012); contribution to energy efficiency as an efficient strategy for saving

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energy (Ignjatović et al., 2015); a contribution to thermal comfort in the main spaces (Bakos and Tsagas, 2000); use of dynamic simulation software to determine its energy efficiency (Asdrubali et al., 2012; Mihalakakou, 2002); and a validation of results calculated using simulation software with registered experimental data (Mottard and Fissore, 2007).

In the Latin American region, similar studies have also been developed as part of the design and strategies of passive solar homes, similar to the case study in Chile where by comparison, using simulations for complete houses with and without an attached greenhouse, the positive effect of the greenhouse was inferred in the interior environments of the houses (Müller, 2008). In Andean Patagonia, in a cold climate, the temperature was measured over a year in an attached greenhouse during the winter, spring and autumn (González, 2012).

Regarding Peru, some work was done with attached greenhouses in the design of bioclimatic houses to determine their thermal contribution using dynamic simulations (Ramos et al., 2013). These studies were done mostly at the National University of Engineering (UNI), mainly in the framework of undergraduate and graduate thesis, summarized in the thesis of Molina (2016), and focused on solving and looking for alternatives to improve thermal conditions in houses located at more than 3000 masl, with very cold climates (Molina et al., 2019a; Gómez et al., 2016). Likewise, the dynamic simulation program EnergyPlus (U.S. Department of Energy's, n.d.) has been used at UNI for the last ten years as a calculation engine for the analysis of heat transfer in a transient state (Molina, 2018). These works considered the use of solar energy, abundant in the Andean areas, passive heating strategies and the use of local materials, such as adobe (Abanto et al., 2017), complemented with industrial products with good thermal performance. Peru has a technical standard, EM.110: "Thermal and light comfort with energy efficiency", which emphasizes compliance with maximum thermal transmittance in walls, ceilings and floors (MVCS, 2014). However, this standard considers only the insulation property of materials, but not their character as a heat storage material (thermal inertia), a consideration that should be taken into account in climates with high solar radiation and significant daily thermal oscillations.

In the present study, two habitable experimental modules (ME) were built in the village of Imata, in the region of Arequipa, at 4500 masl, at a latitude of 15° 50' South, and a longitude of 71° 5' West, where absolute minimum temperatures of up to -23 °C have been recorded (SENAMHI-FAO, 2010). Prior to the construction of the modules, a diagnosis was made of the housing typology in Imata. There was a predominance of adobe in the construction of walls, a vernacular material of good thermal performance, which little or nothing can help against extremely cold temperatures if the other components of the envelope are not thermally suitable, such as the sheet metal corrugated zinc-iron (known as "calamine" in Peru) to cover the roof (Figure 1a), metal doors and metal frames of single-glass windows (Figure 1b). Due to its high heat conductance, these metal parts of the envelope act as thermal short-circuit, with the result that during the day, the interior of the houses will be overheated and at night they are similar to a refrigerator. If the large infiltrations are added, as a result of badly closing doors and windows, the interior temperature will not be very distant from the outside temperature.

The modules were built with a rectangular base of 3.8 m x 4.8 m each, and only one of them has the greenhouse attached to its north wall that occupies an additional area of 2.4 m x 4.8 m. The construction system used was the traditional method according to the customs of the area, using local materials complemented with other commercial ones. In addition, skylights in the ceiling and false ceilings were implemented, which were constructive elements not typical in the area.

To determine the thermal behavior of the modules, the EnergyPlus software was used, which is a calculation engine based on transient heat transfer models to perform thermal and energy calculations in a house or building (Crawley et al., 2001). The EnergyPlus software is complemented by two other software programs, the SketchUp that provides the structure of the model, i.e., the 3D design; and OpenStudio, which defines spaces, weather and thermal conditions, an interface that uses SketchUp tools for the use of EnergyPlus (Alghoul et al., 2017). Subsequently, the model is validated with real data registered in situ to determine the agreement between real and simulated data.

(a) (b)

Fig. 1: (a) View of a part of the village of Imata, (b) typical dwelling with a corrugated metal sheet roofing and iron window frame and iron door.

2. Description of the experimental modules and attached greenhouse

The habitable experimental modules (ME) are located in the village of Imata, district of San Antonio de Chuca, Caylloma province, in the Arequipa region, at 4500 masl, in the south of Peru. The modules are 18.24 m^2 each and they have the same construction elements and dimensions of their enclosure: floor, walls, ceiling, door, window, false ceiling, and skylights in the ceiling and false ceiling. Experimental module 1 (ME1) does not have a greenhouse and experimental module 2 (ME2) has a greenhouse attached to the north-facing wall. Each module has 2.4 m^2 of skylights in the ceiling and false ceiling, covered with 6 mm thick alveolar polycarbonate sheets, with an UV filter of 3.12. These construction elements do not exist in typical rural houses but are considered to be important passive elements of a bioclimatic house in this region, capable of collecting the solar radiation with the sun at midday near the zenith. The walls are of adobe with a square base of 0.4 m and 0.12 m height (Figure 2a shows the moment of building the walls), with 2 cm thick plaster layers inside and outside. The window has a size of 0.7 m^2 and has a simple glass and an iron frame; the door, with a wooden frame and galvanized sheet of iron, “calamina”, has a size of 1.89 m^2, and 5 cm of expanded polystyrene on the inner side; the false ceilings consist of a 4 mm thick plywood, with 5 cm of expanded polystyrene on top. The floor is made of earth that is levelled and rammed, and the roof is made of corrugated red fiber cement sheets, 4 mm thick. Figure 2b shows the moment of tightening of the fiber cement sheets to the wooden structure of the ceiling.

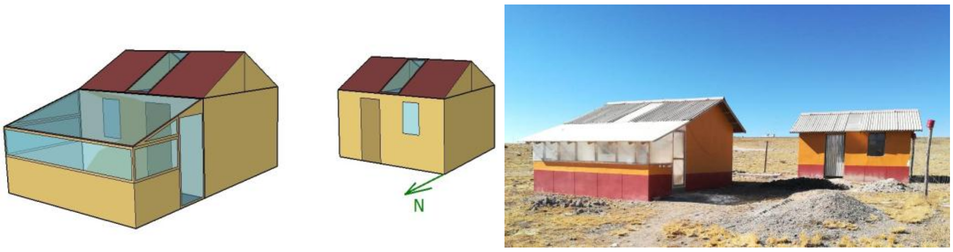
The attached greenhouse in the ME2 occupies an area of 8 m^2, and 18.68 m^2 of surface with alveolar polycarbonate sheets. Figure 2c shows the timber structure. The floor is simple concrete 0.1 m high, and the lower part of the walls is of adobe, 0.85 m high and 0.4 m wide. The 1.63 m^2 door has a wooden frame and alveolar polycarbonate sheet.

(a) (b) (c)

Fig. 2: Views of part of the construction process of the experimental modules, (a) adobe walls, (b) fiber cement roofs, and (c) wooden structure of the attached greenhouse (at ME2).

3. Methodology

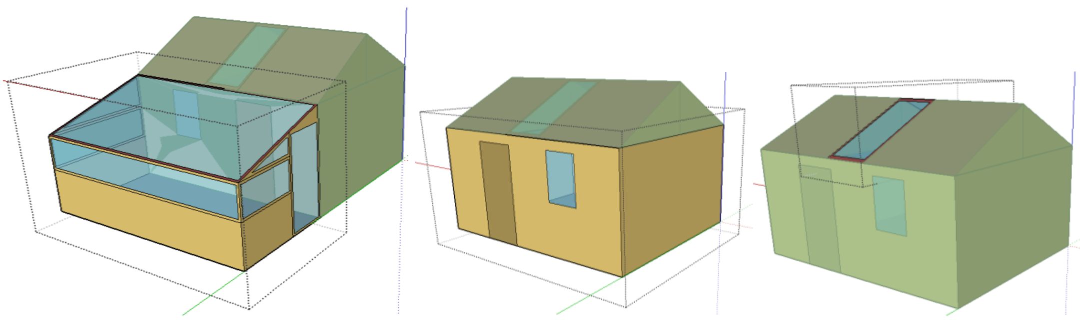
The methodology of evaluation and thermal analysis of the experimental modules, ME1 without a greenhouse and ME2 with an attached greenhouse, begins with separately modeling both modules using the tools of the OpenStudio installed within the SketchUp environment to create the thermal zones and geometry in 3D, as shown at Figure 3a, with respect to the design of the constructed modules (Figure 3b).



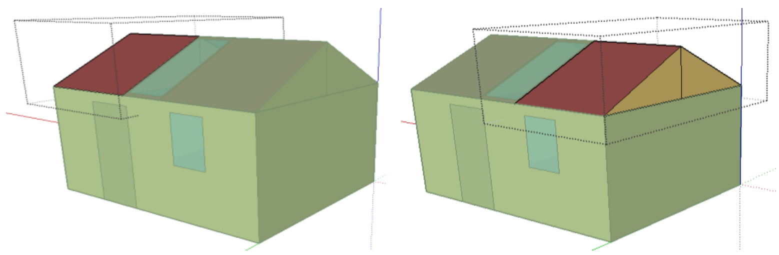
(a) (b)

Fig. 3: (a) The designed modules: with (ME2) and without greenhouse (ME1), (b) The constructed modules

The ME1 has one thermal zone less than the ME2, due to the attached greenhouse at ME2 (Figure 4a). The other four thermal zones, equal for both modules, are the space of the modules below the false ceiling, (Figure 4b), and the three spaces generated in the attic: one is in the center formed by the roof skylights, false ceiling and sidewalls that enclose this space (Figure 4c), and the other two are at each side: at the east (Figure 4d) and west (Figure 4e). The green line in each of the figures represents the north. Subsequently, all surfaces are configured according to the construction element of the envelope and the file with the extension .idf, representing the data input file to EnergyPlus, is saved. Finally, the .idf file is opened, and in the EnergyPlus subprogram EP-Launch, the climate file is entered. In our case, that file was generated with the *Elements program* for the days from December 2 to 12, 2018, as a result of the registration of data with a Davis weather station, *Ventage Pro Plus*, installed on-site at Imata. Variables are entered with the IDF-Editor of the Ep-Launch subprogram.



(a) (b) (c)



(d) (e)

Fig. 4: Thermal zones (in dotted cubes) created in the experimental modules ME1 and ME2.
(a): attached greenhouse at ME2; four common thermal zones: (b): interior, (c): center attic, (d): east attic, and (e): west attic.
The green line indicates north.

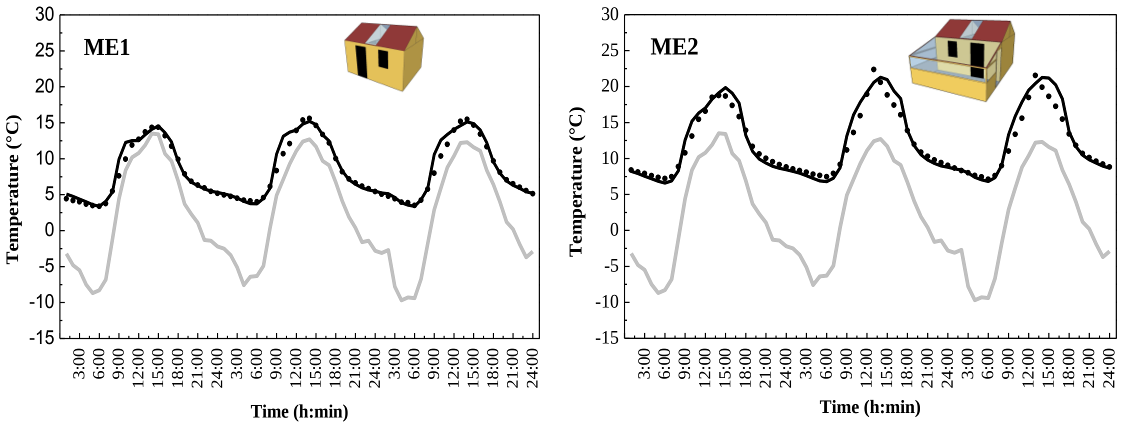
The temperatures inside the experimental modules and the greenhouse were measured every five minutes with Pt100 temperature sensors connected to a four-channel Onset Hobo data logger. To determine, experimentally, the thermal contribution of the greenhouse to the interior temperature of the ME2, the temperature was measured with four different configurations during the days of December 2 to 12, as indicated in Table 1. The entrance door from the outside to the greenhouse remained closed and only opened for the data download, the door and window of ME2 were opened or closed according to the respective configuration, from 8:00 AM to 5:00 PM. ME1 remained closed and only for data download was the door was opened. All these configurations are introduced as input variables to the IDF-Editor of the EnergyPlus, along with the thermophysical properties of the materials, such as density (kg m^{-3}), specific heat (J kg^{-1} K^{-1}) and thermal conductivity (W m^{-1} K^{-1}); data taken from Standard EM.110, in addition to solar absorptivity, air exchanges, and infiltrations. Once the output variables have been defined in the IDF-Editor, the EnergyPlus is executed with the EP-Launch using the trial and error methodology, and the results obtained from the simulation are compared hourly with the experimentally recorded data.

Tab. 1: Measurement configurations in the experimental modules (ME) from December 2 to 12, 2018. From 8:00 AM to 5:00 PM the door or window remained open or closed according to the respective configuration.

Dates	Measurement configuration of the experimental modules (ME)	
	ME1 (without greenhouse)	ME2 (with greenhouse)
Dec 2 to 4	Door and window closed	Door and window closed
Dec 5 to 6		Door and window open
Dec 7 to 9		Door open and window closed
Dec 10 to 12		Door closed and window open

4. Results

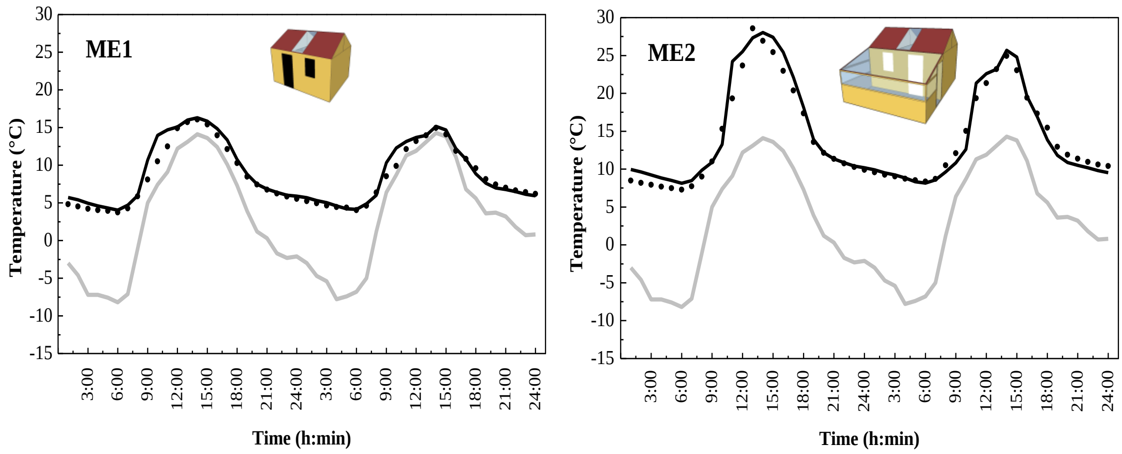
Figure 5 shows the experimental and simulated data of the indoor air temperature of ME1 and ME2 (hereinafter black dotted line for the experimental data and black solid line for the simulated), along with the outside temperature (hereinafter solid gray line) for the closed door and closed window configuration of the ME2 (represented in the image with black color) for the days from December 2 to 4. On the daily average, the indoor air temperature of ME1 was 8.2 °C and of ME2, 12 °C, i.e., the temperature in ME1 was 3.8 °C lower than in ME2. The average outside air temperature was 2.1 °C and the daily average of the difference between the experimental and the simulated temperature was 0.3 °C. Between 9:00 AM and 6:00 PM, on average, the temperature in ME1 is 2.8 °C higher than the outside temperature (Figure 5a), while for ME2 (Figure 5b), there is an average difference of 7 °C between inside and outside. The most notable difference occurs between midnight and 8:00 AM, specifically approximately 5:00 AM, where the average temperature difference between inside and outside was 12.6 °C for ME1, and 16.3 °C for ME2.



(a) (b)

Fig. 5: Hourly temperature in the experimental modules (ME): indoor, simulated (solid black line) and experimental (dotted line), and outdoor (solid gray line); (a) without greenhouse ME1, (b) with greenhouse ME2; from December 2 to 4. The black color on the door and window of the image of ME indicate that they are closed.

Figure 6 shows the experimental and simulated data of the indoor air temperature of ME1 and ME2, along with the outdoor temperature for the open door and window configuration of ME2 from 8:00 AM to 5:00 PM (represented in the image with a white color), for the days from December 5 to 6. On average, the daily indoor air temperature of ME1 was 8.4 °C and of ME2, 14.1 °C, i.e., the temperature in ME1 was 5.7 °C lower than in ME2. The average of the difference between experimental and simulated temperature was 0.4 °C and the average outside temperature was 2.8 °C. For ME1 (Figure 6a), between 9:00 AM and 6:00 PM, the inside temperature was on average 2 °C higher than the outside temperature, while for ME2 (Figure 6b), there was an average difference of 9.8 °C between inside and outside. The most notable difference occurs between 24:00 and 8:00, specifically approximately 5:00 AM, where the average temperature difference between inside and outside was 12.1 °C for ME1, and 16 °C for ME2.

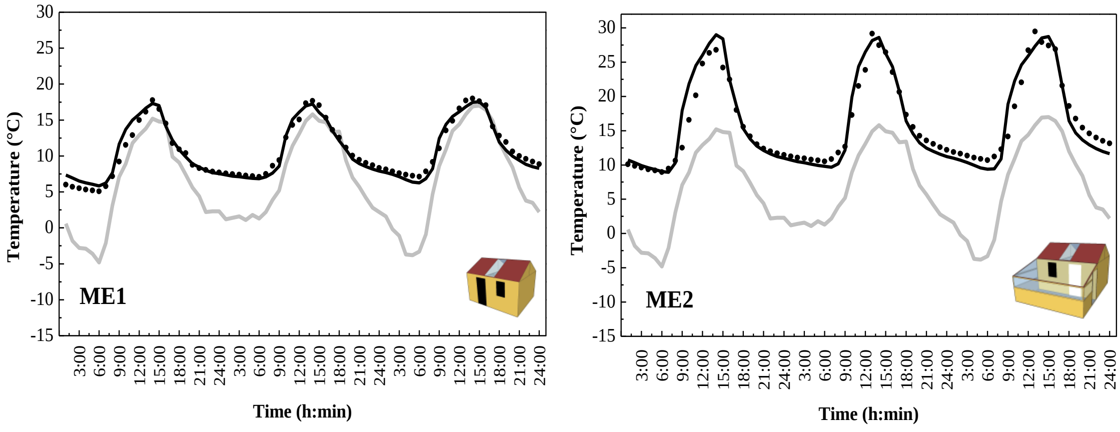


(a) (b)

Fig. 6: Hourly temperature in the experimental modules (ME): inside, simulated (solid black line) and experimental (dotted line), and outside (solid gray line); (a) without greenhouse ME1, (b) with greenhouse ME2; from December 5 to 6. The black color on the door and window of the image of ME indicate closed, and white, open.

Figure 7 shows the experimental and simulated data of the indoor air temperature of ME1 and ME2, as along with the outdoor temperature, for the open door and closed window configuration (from 8:00 AM to 5:00 PM) of ME2 (represented in the image, white if open, and black if closed), for the days from December 7 to 9. On average, the daily indoor air temperature of ME1 was 10.7 °C and of ME2, 16.1 °C, i.e., the temperature in ME1 was 5.4 °C lower than in ME2, with an average daily difference of 0.1 °C between the experimental and simulated temperature. The average outdoor air temperature was 6.5 °C. For ME1 (Figure 7a), between 9:00 AM and 6:00 PM, the indoor temperature was, on average, 1.7 °C higher than the outside temperature, while for

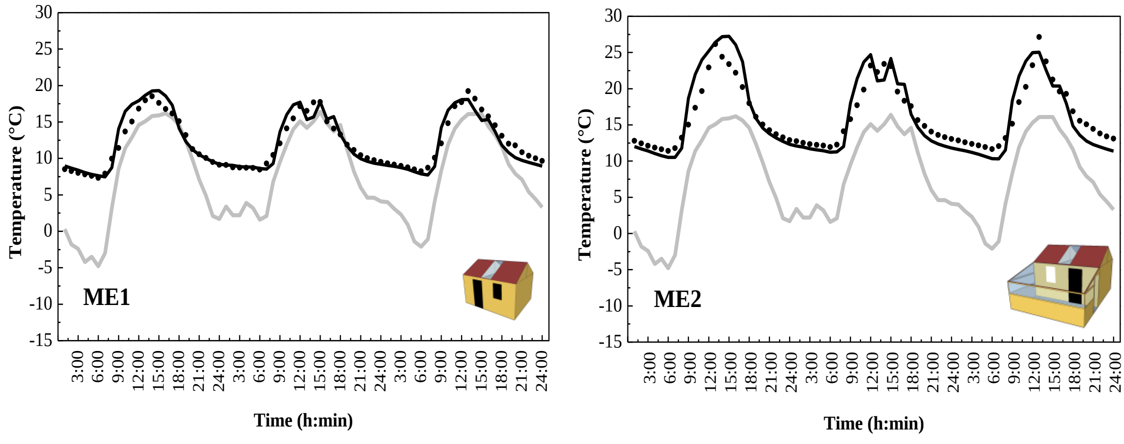
ME2 (Figure 7b), there was an average difference of 9.2 °C between inside and outside. The most notable difference was observed between 24:00 and 8:00, specifically approximately 5:00 AM, where the average temperature difference was 9 °C for ME1, and 12.6 °C for ME2 between inside and outside.



(a) (b)

Fig. 7: Hourly temperature in the experimental modules (ME): indoor, simulated and experimental (solid black dotted lines), and outdoor (solid gray line); (a) without greenhouse ME1, (b) with greenhouse ME2; from December 7 to 9. The black color on the door or window of the image of ME indicate closed, and white, open.

Finally, Figure 8 shows the experimental and simulated data of the indoor air temperature of ME1 and ME2, along with the outdoor temperature for the closed door and open window configuration (from 8:00 AM to 5:00 PM) of ME2 (represented in the image with a white color if open, and black, if closed), for the days from December 10 to 12. On a daily average, the indoor air temperature of ME1 was 12.1 °C and for ME2, 16.2 °C; i.e., the temperature in ME1 was 4.1 °C lower than in ME2, with an average daily difference of 0.1 °C between experimental and simulated temperatures. The average outdoor air temperature was 7.6 °C. In the case of ME1 (Figure 8a), between 9:00 AM and 6:00 PM, the indoor temperature was on average 1.8 °C higher than the outside temperature, while for ME2 (Figure 8b), there was an average difference of 6.6 °C between inside and outside. The most notable difference occurs between 24:00 and 8:00, specifically approximately 5:00 AM, where the average temperature difference between inside and outside was 9.8 °C for ME1, and 13.4 °C for ME2.



(a) (b)

Fig. 8: Hourly temperature in the experimental modules (ME): inside, simulated and experimental (solid black and dotted lines), and outside (solid gray line) (a) without greenhouse ME1, (b) with greenhouse ME2; from December 10 to 12. The black color on the door or window of the image of ME indicates closed, white indicates open.

The EnergyPlus software also allows the determination of the energy required for heating (Er) in the case that a constant interior design temperature is wanted. For the case under study, a design temperature of 15 ° C had been considered, corresponding to an adaptive thermal well-being model for an Altoandina region (Molina et al., 2019b). The results are presented in Table 2.

It is noteworthy that the MEs do not have an active heating facility, so no experimental validation of these simulated data could be done. It is also difficult to compare the results of the different configurations implemented during the evaluation period of December 2 to 12, 2018, in particular because the average outside temperature increased from 2.1 °C to 7.6 °C during that time. In addition, ME1 is a housing module that is improved if compared with the typical houses in Imata, which do not have a suspended ceiling with a skylight. Nevertheless, the data clearly show that the greenhouse results in a significant reduction of the energy needed for heating, of approximately 30 %.

Tab. 2: Required heating energy (Er) in the experimental modules (ME) without and with greenhouse (ME1 and ME2) considering a thermal well-being design temperature of 15 ° C.

Dates	Er ME1 (kWh day^{-1})	Er ME2 (kWh day^{-1})
Dec 2-4	47.67	31.41
Dec 5-6	30.89	20.74
Dec 7-9	33.89	24.50
Dec 10-12	26.35	18.64

5. Conclusions

Taking advantage of the abundant solar radiation in the Andean areas of Peru, a greenhouse attached to a house contributes significantly to the thermal well-being inside the house. Comparing different configurations regarding the opening and closing of the window and the door connecting the greenhouse and the housing module, the best results were obtained with the door and window open during the daytime. An average temperature increase of 5.7 °C was obtained experimentally in the housing model due to an attached greenhouse. The same result was obtained with a simulation, validating the simulation model. Energetically, if a constant design interior temperature of 15 °C would have been required, the simulation indicates that the greenhouse would have produced a daily energy saving for heating of approximately 30 %.

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