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Energy savings using sunspaces to preheat ventilation intake air: Experimental and simulation study

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ABSTRACT

This paper investigates the potential benefits of sunspaces to preheat the ventilation intake air to reduce the energy consumption of buildings. When sunspaces are combined with a mechanical ventilation system, it is possible to easily introduce the preheated air into every space of the building, which is of great relevance for energy savings. A modular sunspace prototype was designed and built to analyze its real thermal behavior. After validating the simulation model with experimental results, different sunspace configurations were tested in a residential building for different climates. Our findings indicate that sunspaces can significantly improve the energy behavior of the building, but the savings depend on different factors. First and foremost, the effectiveness of these systems clearly depends on the climate. While in zones with little need for heating the sunspace use is not advisable, in colder zones the energy savings are substantial, even more if they are combined with heat recovery ventilation. In the coldest climatic zone in Spain, annual primary energy savings of 38.48 kWh·m^{-2} were achieved with the best sunspace configuration, which represents a heating saving of 58%. Results also reveal that inertia is not convenient when using heat recovery ventilation. Lastly, when choosing the size of the sunspace, as its efficiency depends on its size, not only total savings should be considered, but also the investment to be made and its return.

1. Introduction

The European Union is committed to developing a sustainable, competitive and secure energy system by 2050 [1]. Considering that almost 50% of the EU's final energy consumption is used for heating and cooling, of which 80% is used in buildings, the achievement of the Union's energy and climate goals is linked to efforts to renovate its building stock by giving priority to energy efficiency.

With the goal of achieving near zero energy buildings (nZEB), constructions are being built better insulated and airtight, which requires a ventilation system to provide optimal indoor air quality. The health and comfort of a building's occupants are related to indoor air quality [2,3]. However, ventilation produces an increase in energy demand. According to Orme [4], who analyzed the annual energy consumption in the commercial and residential sector of 13 industrialized countries, the renewal of air represents approximately 48% of the heating consumption. Awbi [5], in turn, estimates the percentage associated with ventilation at between 30% and 60%. Similar values were given by other researchers [6–8]. Moreover, this percentage increases as more thermally efficient buildings are constructed. The energy-saving potential of ventilation is a major aspect. As such, a heat recovery ventilation system (hereinafter HRV system) is recommended for cold climates to recover both latent and sensible heat, therefore reducing energy consumption [9].

Another important strategy to reduce heating demand is using free solar energy. Although the simplest passive solar system is a window facing the sun (direct gain), indirect systems such as sunspaces take better advantage of these solar gains. Kisilewicz [10] concluded that, although the useful solar gains of both systems are similar, the indirect system considerably reduces the risk of overheating the building. Sánchez-Ostiz et al. [11], in turn, compared a prefabricated sunspace with a window, concluding that the sunspace has a better performance.

The use of attached sunspaces to the facades to reduce winter energy consumption is a strategy that has been widely used since the 70s. It can

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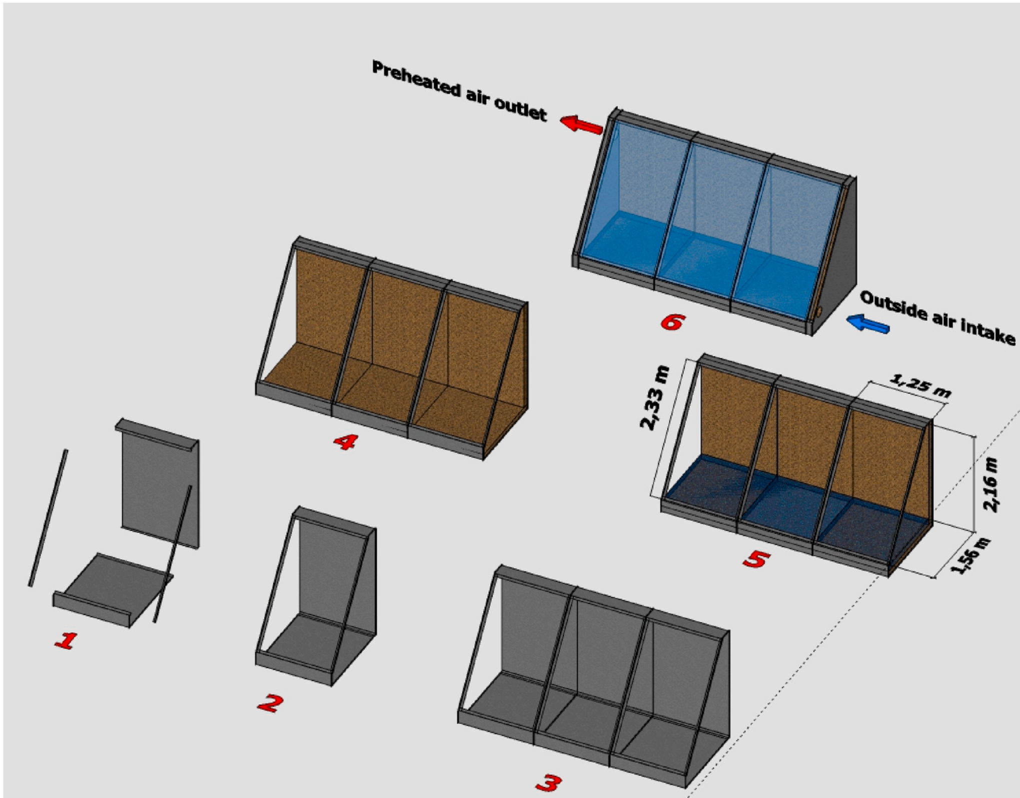

Fig. 1. Sunspace design and construction process.

entail important energy savings, but values vary depending on weather conditions and sunspace characteristics. In their analysis of a glazed gallery located in the north of Spain, Suárez et al. [12] quantified the associated energy savings at between 15% and 32%. Also in Spain, Monge-Barrio and Sánchez-Ostiz [13] analyzed attached sunspaces and found that the overall demand for thermal conditioning can be reduced by 50% on average. Hilliaho et al. [14] studied the impact of different types of glazed spaces, establishing that the energy saving potential of the Finnish building stock from the 1960s to the 1970s varies between 1% and 30%, being typically about 9%. Recent works of research have analyzed sunspaces in different places, climates, and typologies. For example, Chiesa et al. [15] studied the use of attached sunspaces in 50 Southern and Central European locations and concluded that the potential applicability changes with different climatic conditions. Mihalakakou [16] considered the behavior of sunspaces in four European cities (Milan, Dublin, Athens and Florence) to determine that attached sunspaces reduce heating demand in winter, but in summer, especially in southern European countries, overheating problems can appear. However, Bataineh and Fayez [17] stress that overheating during summer can be avoided by night ventilation and interior shading. Aelenei et al. [18] examine different variables in their study of sunspaces in five cities in Portugal, including natural ventilation, shading elements, type of glass and different orientations. Other studies in different locations and climatic conditions include Greece [19], Freiburg [20] and the Mediterranean [21]. According to their results, the energy savings and optimal characteristics of the sunspace depend on the climatic conditions.

For an adequate distribution throughout the building of the heated air in the sunspace, it is possible to incorporate a mechanical ventilation system. Allesina et al. [22] concluded that glazing south-facing balconies and using a simple-flow system to introduce the heated air into the building can be a suitable solution for retrofitting residential buildings, since energy savings can be obtained in a relatively simple way. Both Ma et al. [23] and Ulpiani et al. [24] studied the savings obtained by installing a sunspace with mechanical ventilation that was activated depending on the temperature difference between the adjacent bedroom and the sunspace. In the case of Ma et al., the annual heating load energy consumption can be reduced by nearly 15% with the use of this ventilated sunspace. However, these solutions have several limitations. On the one hand, each dwelling must have its own ventilation system. On the other, preheated air is only introduced into the adjoining room. Ma et al. [25] also experimentally analyzed the thermal performance of a sunspace attached to a single-family house with a central air conditioning system, concluding that about 12% of energy can be saved. In their design, warm air from the sunspace was sent to the central air conditioning room, from where it was distributed throughout the house. The study delved into the use of sunspace to preheat ventilation air in single-family houses, but this use can also be applied in multiple dwelling buildings, taking advantage of the collective ventilation system.

While the use of sunspaces attached to the facade of buildings has been widely analyzed, the energy savings of the rooftop sunspaces remains understudied, in spite of the significant advantages they have over the attached ones. First, when sunspaces are placed on the rooftop, the shape and volume are not so limited. Second, it is possible to position the glazing at an optimal angle, which allows greater solar gains. Third, aesthetic and urban requirements are usually less. Fourth, it is more unlikely that other buildings and elements will shade the sunspace. Last, avoiding overheating is also easier, since the sunspace can be covered or disconnected from the ventilation system.

Previous research has identified further potential benefits of rooftop greenhouses for growing vegetables, since the residual heat of the building, the concentration of CO_2 in the exhausted air and the collected rainwater all improve production conditions [26,27]. The Phileas project also developed a roof greenhouse connected to a central atrium [28]. In addition to vegetable production, these sunspaces can improve the energy performance of the building. Wang et al. [29] proposed a rooftop sunspace on a rural building in China. The conditioned space was

Fig. 2. Image of the built prototype.

separated from the sunspace by a partially glazed slab with vents. This increased the amount of interior daylight throughout the day; improved interior ventilation by allowing control of the opening of the vents; and enhanced the roof insulation owing the layer of air between the ceiling and roof. Nevertheless, these buildings do not take advantage of the heat generated to preheat ventilation intake air. As many buildings with balanced ventilation systems introduce the intake air from the rooftop, it is possible to combine mechanical ventilation with sunspaces to easily introduce the preheated air into every space of the building. This does not usually happen in the attached sunspace, as the preheated air is only introduced into the adjoining room.

In order to fill the gaps in current research, a novel sunspace is proposed to preheat the ventilation intake air flowrate to reduce the energy consumption of the building. Most previous studies focus on single-family dwellings or, when collective residential buildings are analyzed, on solutions consisting of glazing the south-facing balconies. This study, on the other hand, analyzes an innovative modular sunspace capable of adapting to different flat roofs of diverse types of buildings, taking advantage of the benefits of this location. The combination of sunspace with the mechanical ventilation of the building has not been conveniently studied so far, even less in collective housing buildings. The suggested sunspace uses the collective ventilation system to supply preheated air in a simple and economical manner. In addition, the proposal allows combining the sunspace with a heat recovery ventilation system, a solution that is considered to need further study. Thanks to the special characteristics of this design, it is therefore a solution with great energy saving potential compared to other sunspaces.

Our research combined an experimental and a simulation study. A prototype was first designed, built and monitored in order to test the thermal behavior under real conditions. The simulation model was calibrated and validated with experimental results. Finally, a residential building was chosen as a case study to quantify the energy savings that these sunspaces entail. Considering the sunspace behavior in six cities located in the different climatic zones of Spain, our results reveal substantial energy savings in colder climates.

2. Methods

2.1. Design of sunspace

The sunspace was designed to simplify the construction process and increase efficiency. A rectangular triangle section with the hypotenuse fully glazed and facing the sun allows the maximum solar radiation to be captured (facing south in the northern hemisphere). In addition, the remaining surfaces were designed opaque and well insulated to prevent heat losses. Calculating the optimal angle of the glazing is critical, i.e., the more perpendicular the solar radiation reaches the glass, the greater the solar gains in the sunspace. However, since the position and inclination of the sun throughout the year varies according to the latitude, the optimum glazing angle changes. In turn, the climate also influences the solar radiation received. The sunspace with different degrees of inclination (from 35° to 70° in 5° steps) was simulated using the EnergyPlus program. Based on these results, the optimum angle for winter has been established at 55°.

A modular design was proposed to improve the adaptability of sunspaces to different situations. Depending on the available space, the required savings and the cost of the installation, the number of modules could be chosen. Fig. 1 captures the design and construction process. Each module has four pieces of galvanized steel sheet screwed together (step 1 and 2). The modules could be joined together to reach the required size (step 3). After building the steel structure, the insulation panels of expanded cork agglomerate are placed on the opaque surfaces of the envelope (step 4). It is possible to give inertia by introducing heat-storing water tanks over the insulated floor (step 5). Heat storage systems make the temperature inside the sunspaces more stable [12,30,31]. According to the literature, the use of water as heat storage improves the behavior of sunspaces [11,32,33]. Once the steel structure is formed and the insulation and water tanks situated, the glass would be placed to close the south face of the sunspace (step 6). As is often the case in Trombe walls, the interior walls are dark in color to increase absorptivity.

As shown in step 6 of Fig. 1, outside air enters the sunspace from the bottom of one of the lateral sides; it is warmed up as it passes through the

Table 1
Type of sensors and measurements and accuracy.

Sensor	Characteristics
Air temperature sensors	Pt100, 1/3 class, 4 wire Sheath: 316 Stainless Steel 3 mm diameter, 50 mm longitude Working range: -75 °C to 250 °C Crimped direct output Multi-wire cable 4 × 0.5 mm isolated with PFA, T[a].
Surface temperature sensors	Pt100 flexible adhesive Silicone encapsulation Element class 1/3, 4 wires Isolated cable with PFA Dimensions: 30 × 14 × 3,4 mm
Hot-wire thermo-anemometers	Measuring range from 0 to 5 m/s Temperature range −20 … 60 °C/-4 … 140 °F
Electronic flow meter	Model KIMO DMB610C

sunspace until it finally leaves from the top of the opposite lateral side. The preheated air is introduced into the building by a mechanical ventilation system to reduce heating demand.

The installation of the HRV system can entail great energy savings, which could be even higher if combined with sunspaces. If the heat recovery unit preheats the sunspace intake air with the building exhaust air, it will be heated even more in the sunspace before entering the building thanks to the greenhouse effect. Thus, the overall efficiency of the system will improve. As air intakes and outlets are normally located on the roofs in balanced ventilation systems, the configuration of the ducts does not significantly change.

2.2. Experimental study

As shown in Fig. 2, a prototype of one of these modules was built on the terrace of the Higher Technical School of Architecture of the University of the Basque Country, in Donostia-San Sebastian. Located in northern Spain, its climate is Cfb, according to the Köppen-Geiger classification. This prototype is used to analyze the real behavior of these sunspaces, as well as to calibrate the computer model.

The sunspace was located on the rooftop where the most solar radiation is received, with its glazed surface facing south. A double low emissivity glass with argon gas inserted between the panes was used. This glass has a thermal transmittance of 1.4 W m^{-2} K^{-1} and a Solar Heat Gain Coefficient (SHGC) of 0.592. It should be noted that the glazing in sunspaces can become dirty and reduce solar gains. In the case of the constructed prototype, due to the slope of the glazing, it remained reasonably clean. Even so, to compare the measurements with the simulation model, every week during the monitoring periods it was checked and cleaned. Although in this case it was not necessary, it is possible to use self-cleaning glass to improve this situation.

To insulate the opaque envelope of the sunspace, an 8 cm thick cork chipboard with a thermal conductivity coefficient of 0.04 W m^{-1} K^{-1} was chosen. An axial fan was placed to introduce outside air through the lower area of the module. Once the air is preheated, it exits from the top of the opposite side of the enclosure. Thus, it simulates the behavior it would have in normal operation, where the intake air would be preheated in the sunspace before entering the building. The sunspace has been analyzed with and without inertia. To provide inertia, a 75-L tank was incorporated into the floor.

The prototype was equipped with sensors and a Datalogger to record measurements. The sensors were placed at four points to register air temperature: at the air inlet and outlet, and outside and inside the sunspace. Surface temperature sensors were installed on both sides of the enclosure to analyze the thermal resistance. To determine air velocity and estimate the flow rate into the sunspace, two hot-wire thermo-anemometers were installed at the air inlet and outlet. The air velocities and the results obtained by an electronic flow meter were compared, resulting in 135 m^3 h^{-1} average flow. The characteristics of the installed sensors are shown in Table 1.

Table 2
Cases analyzed experimentally and by computer simulation.

Period	Characteristics	Date
P1	Summer. Without inertia	2019-08-02/2019-08-06
P2	Winter. Without inertia	2019-11-16/2019-11-20
P3	Summer. With inertia	2020-08-12/2020-08-16
P4	Winter. With inertia	2020-01-12/2020-01-16

Meteorological data, so important in the behavior of this type of solar systems, was provided by AEMET (State Agency of Meteorology of the Government of Spain) [34]. Air temperature, relative humidity, solar radiation (direct, diffuse and global), atmospheric pressure, cloudiness and wind speed and direction were considered.

The prototype was tested in four periods with different conditions: in summer without inertia; in winter without inertia; in summer with inertia and in winter with inertia (Table 2).

2.2.1. Simulation model validation

The energy simulation was carried out with Design Builder software, which uses the EnergyPlus simulation engine. EnergyPlus has been used and validated in previous research on the use of sunspaces [11,15,35]. Nonetheless, the simulation program was further validated by comparing it to the prototype measurements due to the complexity of these solar systems.

The same characteristics of the prototype were introduced into the computer model to assure result comparability. The different elements of the terrace were also modeled, since they can shade the sunspace. In turn, a climate file with the meteorological data obtained from AEMET [34] was introduced into the program.

As ASHRAE Guidelines 14–2002 [36] and 14–2014 [37] explain, uncertainty analysis is the process of determining the degree of confidence in the true value when using measurement procedures and/or calculations. ASHRAE Guidelines were followed to calibrate the sunspace model. This entails determining two dimensionless indicators of errors, NMBE (Normalized Mean Bias Error) and CV(RMSE) (Coefficient of Variation of the Root Mean Square Error). The simplified NMBE formula and the CV(RMSE) formula [38] are shown in Eq. (1) and Eq. (2):

$$NMBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{n}(M_i)}\ x100(\%) \tag{1}$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i}\left[\frac{(M_i - S_i)^2}{N_i}\right]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} x100(\%) \tag{2}$$

where M_i and S_i are, respectively, the measured and simulated values, and N_i is the number of values used.

According to the ASHRAE guidelines, a building model is calibrated if hourly NMBE values fall within ±10% and hourly CV(RMSE) values fall below 30%. To validate the model, the experimental and simulation temperatures inside the prototype were compared, verifying that they were within the limits. The simulation model was validated in the four periods presented in Table 2.

2.3. Simulation study

2.3.1. Case study

Once the computer model had been validated, a case study was simulated to quantify the savings that the use of this type of sunspaces can entail. The chosen building is located in Pamplona, a city in northern Spain, with a Cf2b climate according to the Köppen-Geiger classification. The building has a rectangular floor plan of 47 × 13 m, with north-south orientation on its longer facades. It has commercial premises on

Fig. 3. South elevation of the selected building.

Table 3
Building thermal characteristics.

Element	Thermal characteristics
Envelope:	
Flat Roof	U = 0,257 W m^{-2} K^{-1}
Facade	U = 0,256 W m^{-2} K^{-1}
Window %	17%
Window frame characteristics	Material: aluminum (with thermal break) U = 5014 W m^{-2} K^{-1}
Glazing characteristics	Double glazing (4-6-4) SHGC = 0,74 U = 3146 W m^{-2} K^{-1}
HVAC	
Heating system	Individual natural gas boilers Efficiency 89%
Ventilation flow per portal	712 m^3 h^{-1}
Total ventilation flow	1425 m^3 h^{-1}

Table 4
Set temperatures for heating.

Period	timetables			
	0:00–6:59	7:00–14:59	15:00–22:59	23:00–23:59
January to May	17 °C	20 °C	20 °C	17 °C
June to September	–	–	–	–
October to December	17 °C	20 °C	20 °C	17 °C

Table 5
Study cases.

Case	Characteristics	Ventilation system
Without heat recovery		
Case 0	Without sunspace	Simple exhaust ventilation
Case 1	Sunspace without inertia	Simple supply ventilation
Case 2	Sunspace with inertia	Simple supply ventilation
With heat recovery		
Case 0-HRV	Without sunspace	Balanced ventilation with heat recovery
Case 1-HRV	Sunspace without inertia	Balanced ventilation with heat recovery
Case 2-HRV	Sunspace with inertia	Balanced ventilation with heat recovery

the ground floor and two upper floors for housing (6 dwellings per floor). Fig. 3 shows the south facade of the building.

The thermal particularities of the building, as well as the HVAC system characteristics are presented in Table 3. The building has a mechanical ventilation system. The total ventilation flow has been defined based on the minimum flow rates required by the Spanish Technical Building Code [39]. The set temperatures for heating and the building's usage profiles have also been established based on the Spanish Technical Building Code. Table 4 illustrates the heating set temperature.

This building was analyzed without sunspace (case 0), incorporating a sunspace without inertia (case 1) and adding the same sunspace, but with water heat storage to give inertia (case 2). Each of these cases in turn was simulated by incorporating an air-to-air heat exchanger to recover energy from the building's exhaust air. According to previously carried out simulations, when an HRV system is installed, it is not convenient to pass the air through the sunspace at night. Instead of heating the air that comes from the heat recovery unit, the sunspace would cool it at night because of the radiative cooling. Therefore, the preheated air in the heat exchanger will only go through the sunspace from 9:00 to 19:00, when it heats the air even more. The cases analyzed are summarized in Table 5.

Due to the building's rooftop characteristics, up to 36 modules could be installed to build a 45 m long sunspace and a total glazed area of 112.50 m^2. Fig. 4 shows how the building would look with the installation of the sunspace.

2.3.2. *Simulation analysis*

Depending on sunspace characteristics, temperatures inside the sunspace vary and hence, building energy savings will also differ. For each case, the air temperature inside the sunspace during the typical winter week was analyzed hour by hour.

Final and primary heating energy consumption was calculated for each case. In addition, final and primary energy consumption in the fans of each ventilation system were obtained to get the total primary energy consumption. To determine the electric power of each ventilation system and to establish its energy consumption, the recommended Specific Fan Power (hereinafter SFP) values of the Air Infiltration and Ventilation Centre were used [40]. The appropriate value of SFP for a specific application depends on the size of the ventilation system, whether it is balanced or has heat recovery, the intermittency of operation, and of course, costs. For case 0, which has a simple exhaust ventilation system, an SFP value of 1 kW m^{-3} s^{-1} was considered. In cases 1 and 2, since installing a simple supply ventilation system to introduce the preheated air into the building has been chosen, a value of 1 kW m^{-3} s^{-1} was also taken into account. The value rises to 2 kW m^{-3} s^{-1} for cases 0-HRV, 1-HRV and 2-HRV, as the heat recovery unit is incorporated. These values are in agreement with the SFP values of the fans installed in actual buildings in Spain. To convert the final energy of the different sources into primary energy, the coefficients established by the Spanish government were considered [41].

To analyze the influence of sunspace size, the primary energy consumption was quantified when 12, 18, 24, 30 and 36 modules were installed. The savings obtained per module for each size were also calculated, dividing the savings obtained by the number of modules.

The Spanish Technical Building Code (CTE) [39] differentiates five

Fig. 4. Image of the building with the sunspace.

Table 6
Locations selected for this Research, according to different winter climate zones in Spain.

City	Latitude	CTE classif.	Köppen– Geiger classif.[a]	HDD_18[b]		Avg. global hor. Rad (Wh/m2)[b]		Avg. Direct Normal Rad (Wh/ m2)[b]		Avg. Diffuse hor. Rad (Wh/m2)[b]		Avg. temp. (◦C)[b]	
				Oct-May[c]	year	Oct-May[c]	year	Oct-May[c]	year	Oct-May[c]	year	Oct-May[c]	year
Málaga	36° 40′	A	Csa	796	796	3934	4828	4637	5436	1389	1531	15,04	17,96
Valencia	39° 30′	B	Csa	1051	1052	3574	4464	3687	4348	1540	1747	13,89	17,26
Barcelona	41° 16	C	Csa	1418	1419	3210	3995	2975	3449	1583	1862	12,26	15,68
Madrid	40° 27′	D	Csa	1936	1965	3452	4420	3467	4217	1537	1779	10,08	14,29
Pamplona	42° 45′	D	Cfb	2243	2279	2831	3844	2877	3939	1369	1551	8,75	12,19
Burgos	42° 21′	E	Cfb	2812	2990	2814	3916	2864	4102	1325	1484	6,38	9,88

[a] Köppen Classification according to Iberian Climate Atlas, by AEMET [34].
[b] These data are extracted from EnergyPus Weather Data, with which the simulations have been done.
[c] Heating period of Spanish Technical Building Code [39].

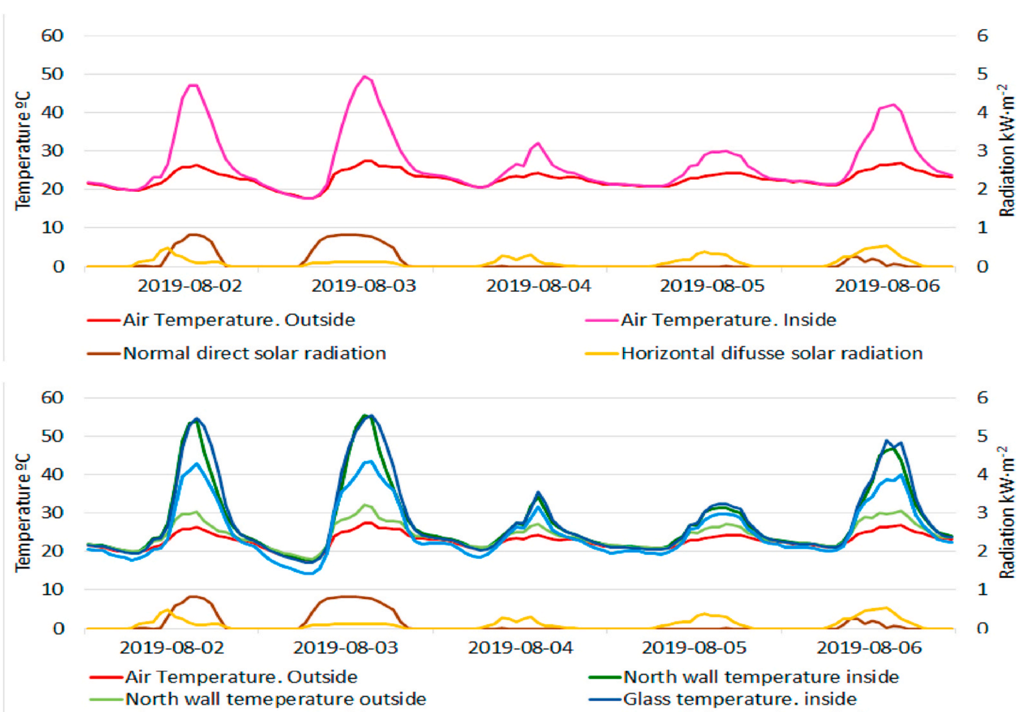

Fig. 5. Comparison of prototype inside and outside temperatures for P1 period.

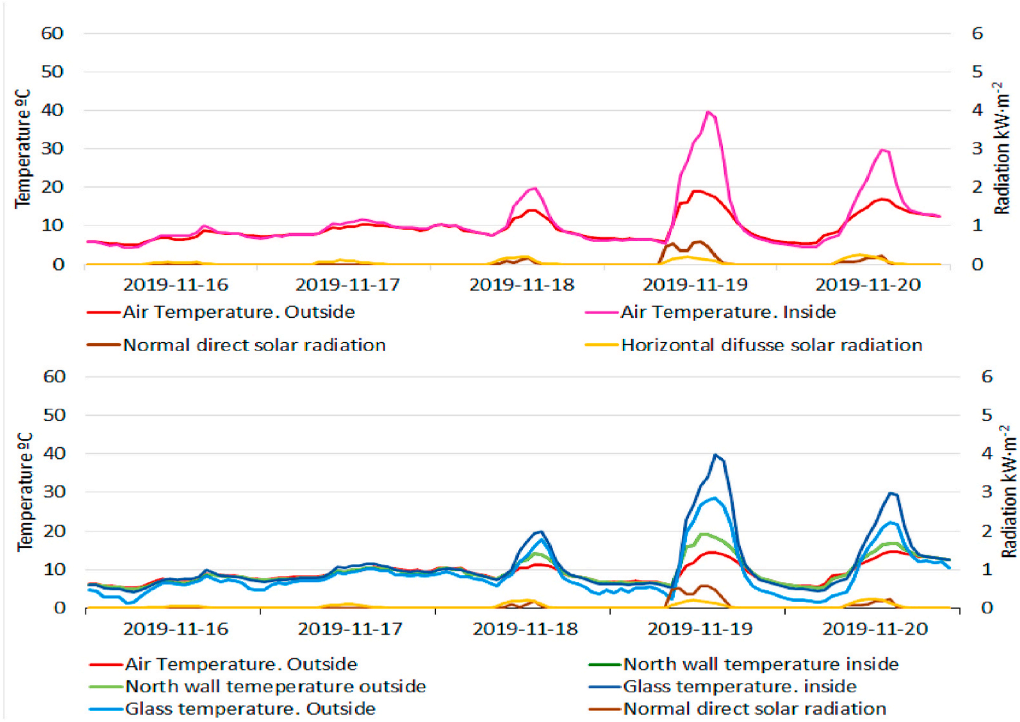

Fig. 6. Comparison of prototype inside and outside temperatures for P2 period.

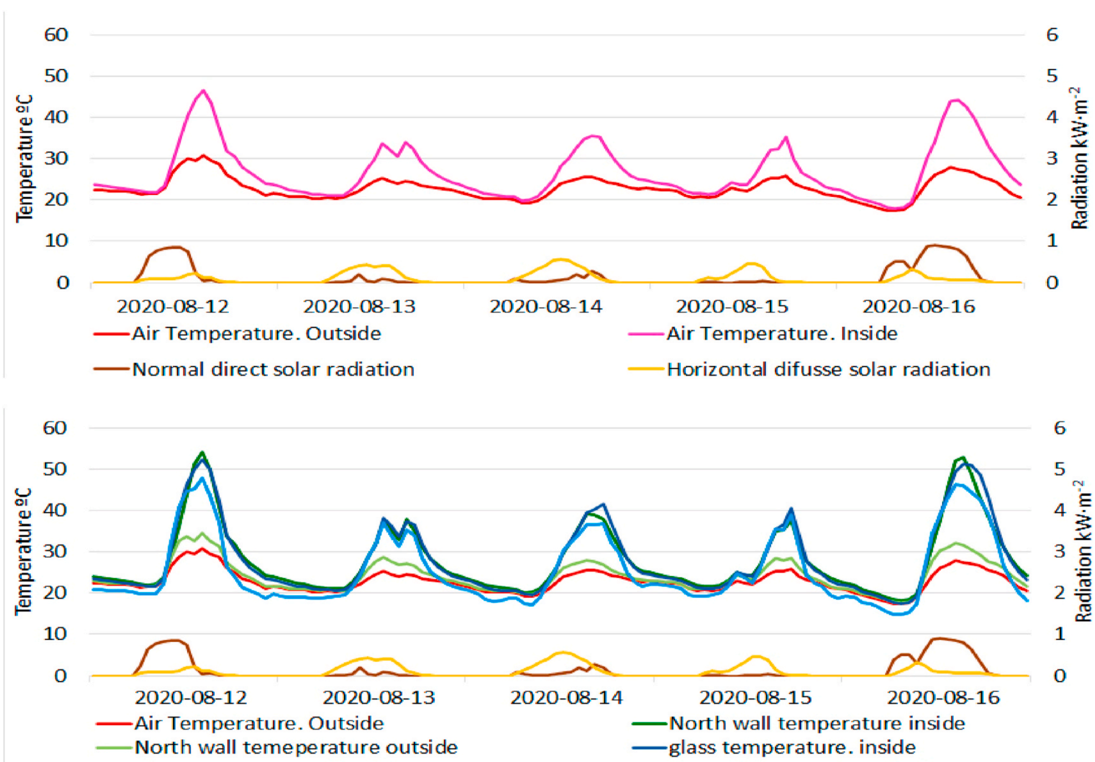

Fig. 7. Comparison of prototype inside and outside temperatures for P3 period.

climatic zones according to their Winter Climate Severity (A, B, C, D, E, from the milder to the coldest winter). In addition to Pamplona, the results of the energy savings of the most populated city in each climatic zone were compared. Their main climatic characteristics are summarized in Table 6.

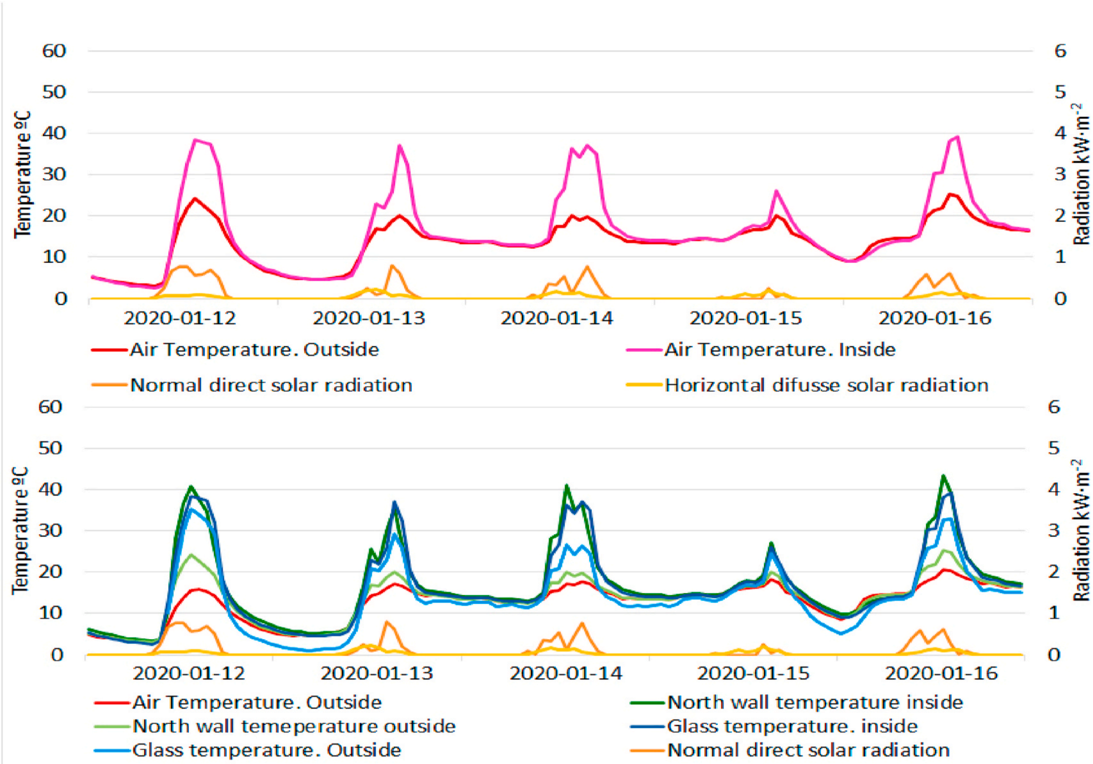

Fig. 8. Comparison of prototype inside and outside temperatures for P4 period.

Table 7
Difference between the outside temperature and the temperature recorded inside the sunspace.

	Day	Solar radiation kWh·m^{-2}		Average temperature difference (°C)			Maximum temperature difference (°C)
		Normal direct	Horizontal diffuse	Total 0h–24h	Day 9h–19h	Night 0h–9h/ 19h–24h	
P1	Day 1	4.97	2.50	5.3	11.6	0.8	21.1
Summer conditions Without inertia	Day 2	8.88	1.41	6.1	13.5	0.8	21.9
	Day 3	0.00	1.80	1.7	3.6	0.4	7.8
	Day 4	0.01	2.60	2.0	4.2	0.5	5.9
	Day 5	1.16	3.90	4.5	9.9	0.7	15,4
P2	Day 1	0.03	0.35	0.1	0.5	−0.1	1.0
Winter conditions Without inertia	Day 2	0.02	0.57	0.3	0.8	0.0	1.3
	Day 3	0.48	1.04	1.0	2.5	0.0	5.9
	Day 4	3.61	1.14	3.1	7.6	−0.1	14.1
	Day 5	0.90	1.35	1.8	4.7	−0.3	9.2
P3	Day 1	5.19	1.25	4.5	9.6	0.9	17.6
Summer conditions With inertia	Day 2	0.44	3.35	3.1	6.0	1.0	10.1
	Day 3	1.20	3.89	3.8	7.0	1.4	14.8
	Day 4	0.09	2.45	2.4	4.3	1.1	12.1
	Day 5	7.66	1.56	6.1	12.2	1.7	20.4
P4	Day 1	4.94	0.55	4.6	9.6	1.0	16.4
Winter conditions With inertia	Day 2	2.26	1.06	2.7	5.6	0.6	15.3
	Day 3	3.17	0.85	3.9	8.2	0.8	16.0
	Day 4	0.46	0.81	1.3	2.1	0.7	6.9
	Day 5	2.83	0.77	2.8	6.7	0.0	14.5

3. Results and discussion

3.1. Experimental results

3.1.1. Analysis of the behavior of the prototype

Figs. 5–8 present the temperatures obtained inside and outside the sunspace in each period. The upper part of the graphs displays air temperatures, while the lower part shows surface temperatures of the enclosure. Normal direct solar radiation and diffuse horizontal solar radiation are also included.

During days with high solar radiation, indoor air temperatures are much higher than outdoor ones. However, when there is little radiation, there is practically no difference between outdoor and indoor temperatures, as illustrated in the first two days of Fig. 6. When comparing surface temperatures, the difference by day between the interior and exterior face of the north facade is large because this enclosure has low

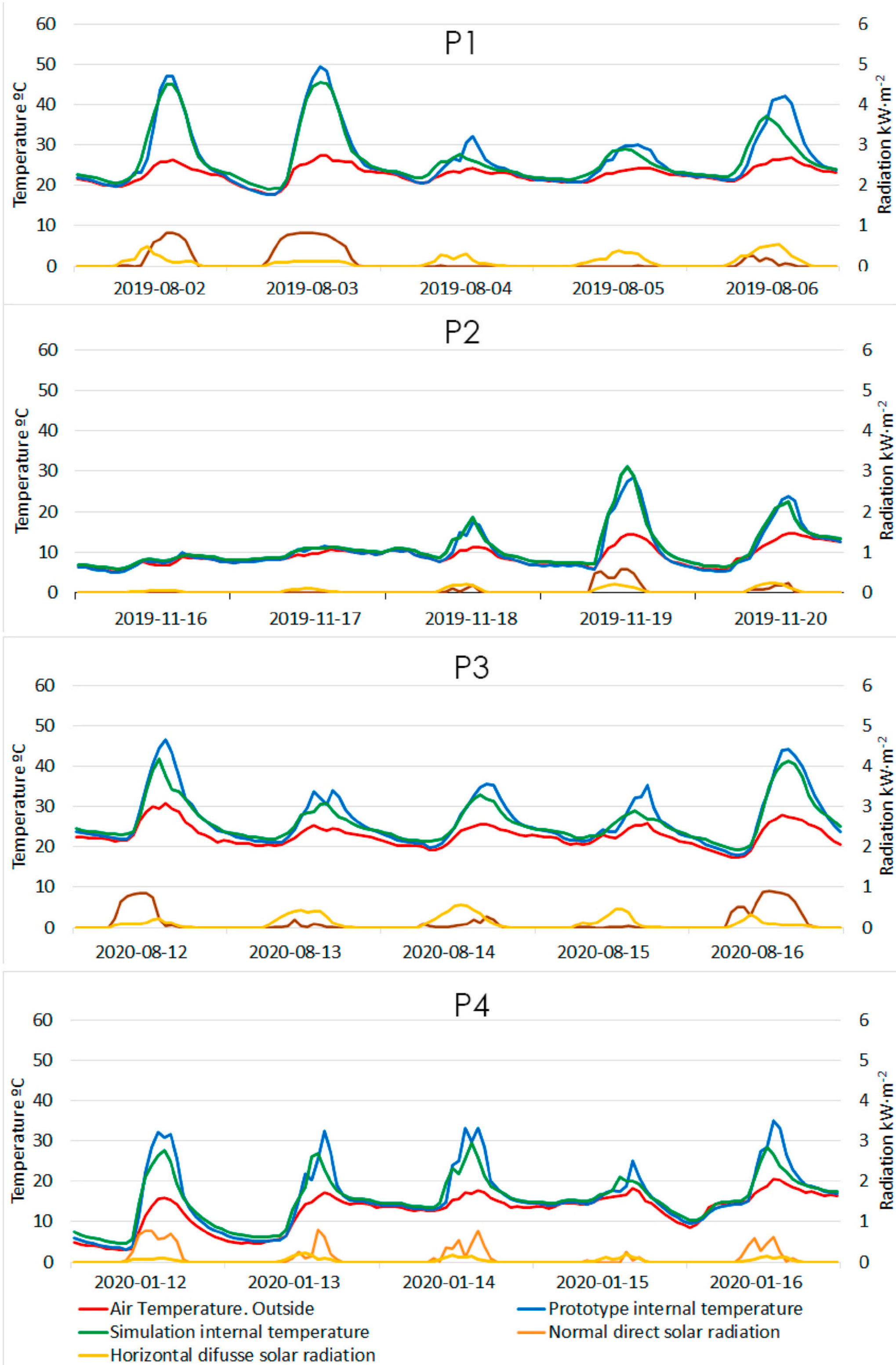

Fig. 9. Comparison of experimental and simulation temperatures in the P1, P2, P3 and P4 periods.

thermal transmittance. At night, surface temperatures drop rapidly to match outside temperatures. In the case of glass, the differences between both faces by day are smaller, since transmittance is higher, which increases thermal losses through the glass. During the night, the temperature of the outer face of the glass clearly drops below the outside temperature.

Table 7 shows the average of the difference between inside and outside air temperatures and the maximum difference achieved each day. The table also includes normal direct and diffuse horizontal solar radiation to check its influence.

On days with the highest solar radiation (day 2 for P1, day 4 for P2, day 5 for P3 and day 1 for P4) the daily average indoor and outdoor

Table 8
NMBE and CV(RMSE) index for prototype 1, 2, 3 and 4.

Prototype	Index	ASHRAE Guideline 14	Results
P1	NMBE	±10	0.48
	CV(RMSE)	30	8.57
P2	NMBE	±10	−6.11
	CV(RMSE)	30	11.89
P3	NMBE	±10	1.87
	CV(RMSE)	30	8.00
P4	NMBE	±10	1,10
	CV(RMSE)	30	17.40

temperature differences are significant, ranging between 3.1 °C and 6.1 °C. In turn, the maximum differences reached at noon are between 14.1 °C and 21.9 °C. On days with less solar radiation (day 3 for the P1, day 1 for the P2, day 4 for the P3 and day 4 for the P4), on the other hand, the daily average differences are only between 0.1 °C and 2.4 °C, and the maximum difference between 1.0 °C and 12.1 °C. Thus, great differences are observed depending on solar radiation. Since sunspace is intended for use in winter, if we compare the periods P2 and P4, both the average and maximum temperature differences are much higher at P4. With the same weather conditions, the maximum temperature reached at noon should be higher at P2 due to its lack of inertia, but as the solar radiation is much lower in this period, this does not occur. Therefore, our experimental results clearly indicate that there are great differences in the temperatures reached inside the sunspace depending on meteorological conditions.

If we now turn to night conditions, average temperature differences are minimal every day. In the P2 period, it even becomes negative, due to radiative cooling. As solar radiation decreases, temperatures drop fast to equal the exterior ones. According to Figs. 7 and 8, when the water heat storage is added to the sunspace (P3 and P4), conditions improve slightly: indoor and outdoor temperatures do not match so quickly. In any case, the effect of the water heat storage is not especially important as the average difference at night only reaches 1.7 °C at best (day 5 of P3).

3.1.2. Simulation model validation

Fig. 9 compares the simulation and experimentally measured temperatures in P1, P2, P3 and P4. During the daytime, experimental temperatures are usually somewhat higher than simulation ones, although this is not always the case, as in period P2. By contrast, at night, simulation temperatures are moderately higher. While at night experimental temperatures equalize outside temperatures, simulation temperatures during the night stay slightly above. Thus, the prototype has marginally less inertia compared to the simulation model. Despite these small differences, there is an acceptable agreement between the simulation and the experimental temperatures in every case. As shown in Table 8, the NMBE and CV (RMSE) values are clearly within the limits set by the ASHRAE to consider that the model is calibrated [37].

3.2. Simulation results

3.2.1. Sunspace temperature results

Fig. 10 provides the temperatures reached at the exit of the 36 module sunspace during the typical winter week. Comparing cases with and without thermal inertia, it is observed that the use of water heat storage clearly varies the behavior of the sunspace temperature, making them more stable. For the configurations without HRV, temperatures reached at noon in case 2 are lower than in case 1. However, at night, the opposite occurs: due to its higher inertia, the temperature in case 2 does not descend as much as in case 1. Regarding configurations with HRV, a similar pattern is observed. In case 1-HRV, the temperatures reached at noon are notably higher than in 2-HRV. In fact, it is in 1-HRV where the highest temperatures of all cases are obtained. At night, on the other hand, the highest temperatures are achieved in 2-HRV.

The use of HRV represents a large increase in sunspace temperatures. Comparing case 1-HRV with case 1 and 2-HRV with 2, the temperatures reached at both day and night are significantly higher when using the HRV system. In the cases with HRV, during the night, air gets into the building from the heat recovery unit without passing through the sunspace, which means that the sunspace air is not renewed and thus, temperatures reached at nighttime are still higher.

The results also reveal that on the sunniest days in case 1, higher temperatures are obtained than in 2-HRV, thanks to its lack of inertia. On the other hand, in days with less solar radiation, temperatures in case 1 are much lower, in fact below the temperatures of 2-HRV. The importance of the weather conditions in this type of sunspaces is again demonstrated.

Table 9 summarizes the maximum and average differences between inside and outside depending on its configuration in the typical winter

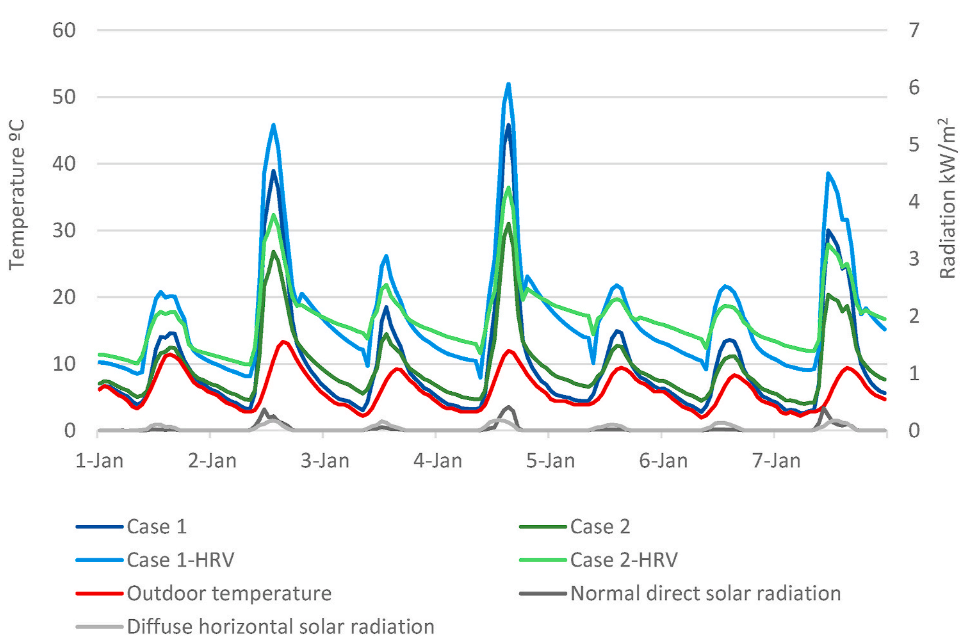

Fig. 10. Temperatures inside the sunspace in the typical winter week depending on the different configurations.

Table 9
Average and maximum differences in the typical winter week.

Day	Solar radiation kWh·m^{-2}		Case	Average temp. difference °C			Maximum temp. difference °C
	Normal direct	Horizontal diffuse		Night 0h–9h/19h–24h	Day 9h–19h	Total 0h–24h	
Day 1	0.10	0.51	1	0.52	2.32	1.27	4.25
			2	1.20	1.21	1.21	2.28
			1-HRV	4.45	8.82	6.27	11.71
			2-HRV	5.44	7.39	6.25	9.21
Day 2	1.49	0.85	1	0.87	14.90	6.72	28.34
			2	2.23	9.04	5.07	16.22
			1-HRV	7.26	21.23	13.08	35.23
			2-HRV	7.92	14.77	10.78	22.19
Day 3	0.28	0.69	1	0.89	5.06	2.63	10.99
			2	2.97	4.04	3.42	7.17
			1-HRV	9.51	12.58	10.79	18.65
			2-HRV	11.18	11.59	11.35	15.01
Day 4	1.47	0.99	1	1.02	14.89	6.80	33.85
			2	2.79	9.02	5.38	19.03
			1-HRV	10.20	21.74	15.01	40.03
			2-HRV	11.58	15.63	13.27	24.45
Day 5	0.15	0.55	1	0.72	3.37	1.83	5.76
			2	2.69	2.84	2.75	3.98
			1-HRV	10.13	11.57	10.32	13.39
			2-HRV	12.46	10.93	11.59	14.32
Day 6	0.13	0.72	1	0.73	3.96	2.08	6.67
			2	1.99	2.91	2.37	4.43
			1-HRV	7.68	11.92	9.45	15.59
			2-HRV	10.39	10.81	10.56	13.20
Day 7	1.33	0.94	1	0.71	13.89	6.20	25.22
			2	2.21	8.84	4.97	15.60
			1-HRV	8.38	21.23	13.73	33.76
			2-HRV	10.48	15.81	12.70	23.12
All the week	4.96	5.26	1	0.78	8.34	3.93	33.85
			2	2.30	5.41	3.60	19.03
			1-HRV	8.23	15.58	11.23	40.03
			2-HRV	9.92	12.42	10.93	24.45

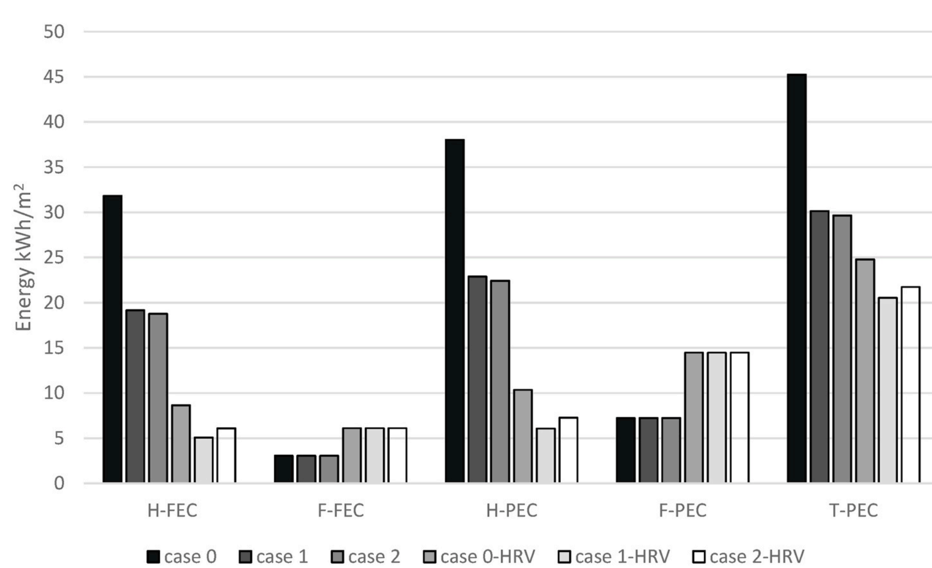

Fig. 11. Annual energy consumption considering the energy used for heating and in fans.

week. At night, the differences in cases 1-HRV and 2-HRV are much greater than in cases 1 and 2, thanks to the incorporation of the HRV system. The results also show how incorporating water heat storage also causes the temperature differences to be bigger: In case 2, differences are greater than in case 1, as happens between 2-HRV and 1-HRV. Thanks to the heat recovery and inertia, it is in 2-HRV where the largest differences are reached during the night. If we now turn to daytime, the largest differences are also due to HRV, but in this case, the highest value corresponds to 1-HRV, because of its lack of inertia. Taking day and night together, there is a large difference between the cases with an HRV system (case 1-HRV and 2-HRV) and those without (case 1 and 2). Nonetheless, the differences between the cases with and without inertia are small. Although the use of water heat storage affects the behavior of the sunspace temperature, the average differences throughout the day

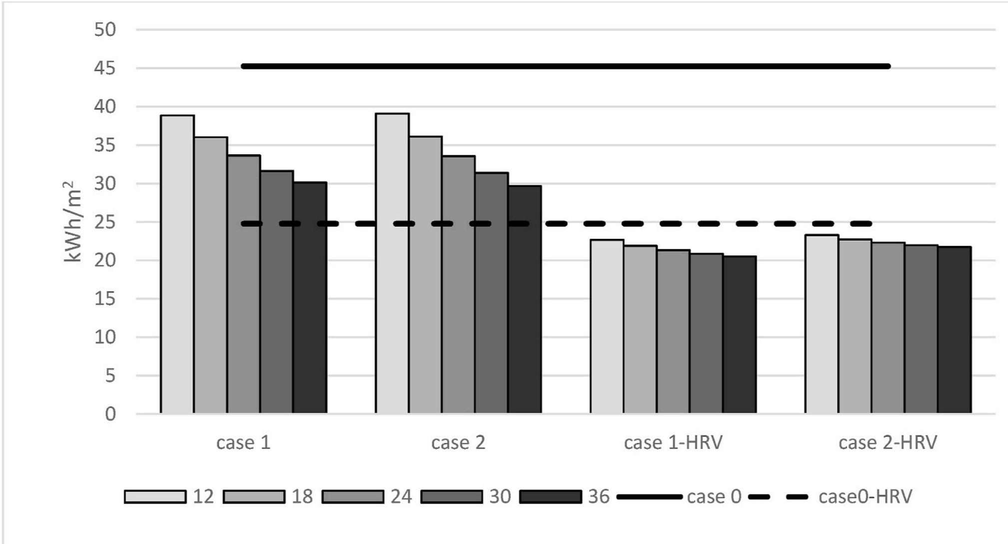

Fig. 12. Annual total primary energy consumption for 12, 18, 24, 30 and 36 module sunspaces.

and night between cases 1 and 2, as well as between cases 1-HRV and 2-HRV are small, since the total solar gains are the same. As expected, the maximum differences are achieved with case 1-HRV, because of the HRV and lack of inertia.

3.2.2. Energy consumption results

Fig. 11 presents the final and primary energy consumption results for the whole year, including both heating and fans consumption. H-FEC represents Heating final energy consumption; F-FEC, Final energy consumption in fans; H-PEC, Heating primary energy consumption; F-PEC, Primary energy consumption in fans; and T-PEC, Total Primary energy consumption.

If the building without sunspace and without an HRV system (case 0) is considered as the reference, the final and primary heating consumption in cases 1 and 2 are around 40% and 41% lower, respectively. Therefore, in cases without HRV, the results improve when water tanks are incorporated, although the difference is not important (only 1%). Regarding the cases with an HRV system, the heating consumptions are much lower: for cases 0-HRV, 1-HRV and 2-HRV, they are, respectively, around 73%, 84% and 81% lower than case 0. Incorporating water heat storage when using an HRV thus implies higher consumption. As mentioned above, to prevent cooling the air that has been preheated in the heat recovery unit, the air will only go through the sunspace from 9:00 to 19:00. At night, the air enters directly into the building after passing through the heat recovery unit. In this case, storing heat in the sunspace has no sense, as some of that heat will be released at night, when it is not used to heat the air.

With regard to fans, the incorporation of a heat exchanger (cases 0-HRV, 1-HRV and 2-HRV) causes consumption to double. As electricity has a higher primary energy conversion factor than natural gas, the fans have a proportionally greater impact on the total primary consumption.

When analyzing the total primary energy consumption, if case 0 is taken as reference, the total primary energy saving in case 1 is 33%, while in case 2 it rises to 35%. Yet in case 0-HRV, consumption is 45% lower. This result indicates that, in this climate, simply incorporating an HRV system to the building is better than installing any sunspace

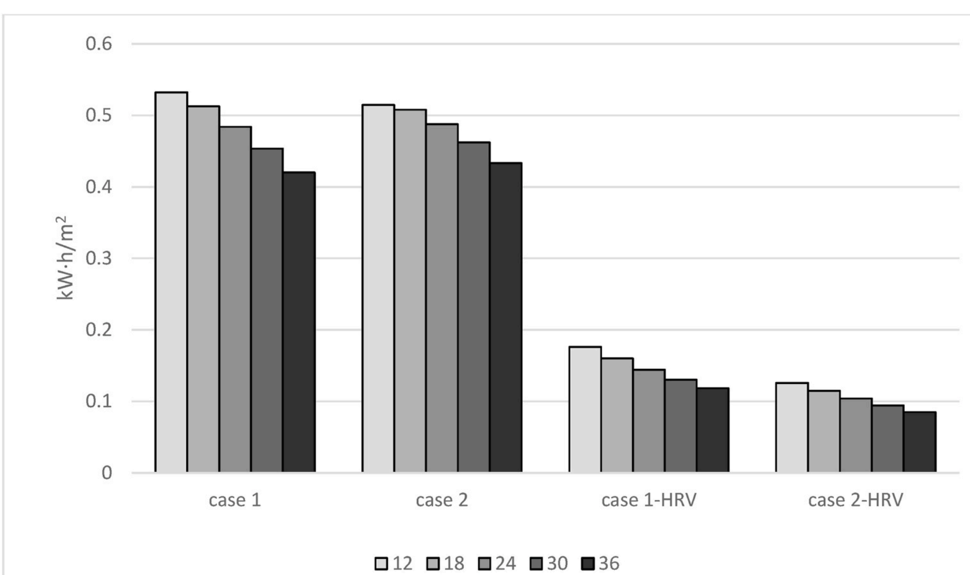

Fig. 13. Annual total primary energy savings per module depending on sunspace size.

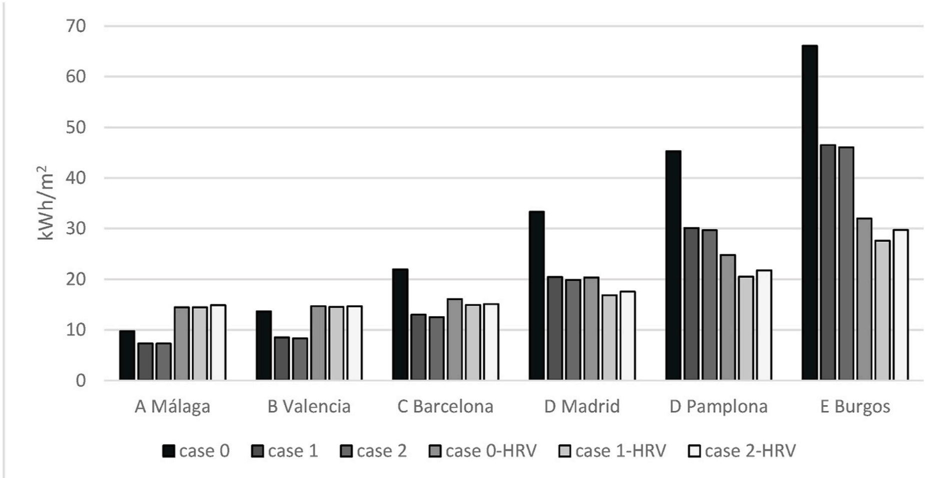

Fig. 14. Annual total primary energy consumption for Malaga, Valencia, Barcelona, Madrid, Pamplona and Burgos.

without HRV (case 1 and 2). Therefore, the installation of a heat recovery unit is a fundamental factor to improve the energy performance of the building. For the case 2-HRV, 52% total primary energy savings are obtained, whereas for the best case (1-HRV), savings rise by 55%, which represents almost 25 kW h$\cdot$m$^{-2}\cdot$y^{-1}.

3.2.3. Number of sunspace modules results

Fig. 12 shows the total primary energy consumption for each case depending on sunspace size. Building consumptions in the cases 0 and 0-HRV are also displayed. Obviously, the more modules installed, the greater the energy savings. However, as the sunspace is larger, the advantages from installing additional modules become less and less. For example, in case 1, when going from 12 to 18 modules, 2.84 kW h m^{-2} savings are obtained; while when going from 30 to 36 modules, savings are only 1.72 kW h m^{-2}. Furthermore, in cases with HRV, the extra savings obtained by increasing the number of modules are much lower than when a heat exchanger is not used.

The above results indicate the convenience of analyzing savings per module to establish how many modules should be installed (Fig. 13). In the cases with HRV, the savings of the 0-HRV case have been subtracted. In this way, only the savings obtained from the sunspaces are considered, without taking into account those from the heat exchanger. In every case, the larger the sunspace, the greater the total savings, although savings per module decrease. As the economic cost of each module is the same, lower savings per module will lead to a higher return on investment. When choosing the size, not only total energy savings, but also the economic cost of the investment and its return must be considered. In cases with HRV the savings per module are significantly lower.

3.2.4. Results according to Spanish climate zones

Primary energy consumption in each Spanish climate zone is presented in Fig. 14. Results illustrate that the advantages of using sunspaces depends on climate conditions. In the area with the least need for heating (zone A Málaga), sunspaces with HRV are not advisable because, instead of obtaining savings, the consumption is even higher than in case 0. The heating energy savings do not compensate for the higher consumption in fans due to heat recovery. In cases without HRV, although energy savings are achieved, they are small. In Valencia (zone B), the situation improves slightly but savings are still small or, when heat recovery is used, consumptions are even still higher than in case 0. In conclusion, in climates with little need for heating, HRV systems and sunspaces are not convenient. In Barcelona (zone C), sunspaces improve the energy behavior of the building in every case. However, the use of HRV is not recommended, as savings are less. In Madrid (Zone D), installing sunspaces without HRV is better than simply installing a heat exchanger. However, combining HRV with sunspaces results in greater savings. In Pamplona (Zone D) and Burgos (Zone E), important savings are achieved. Results indicate that the more severe the winter climate, the greater the savings obtained. Further, the use of the HRV system is increasingly important the colder the climate. Burgos (Zone E) presents the best performance: under the optimal configuration (case 1-HRV), annual savings rise to 38.48 kWh$\cdot$m^{-2} of primary energy, which represents a saving of 58%. In previous research of other mechanically ventilated sunspaces, savings of 15% [23] and 12% [25] were obtained. Although the performance of these systems depends on the particular conditions of each case, the results obtained of 58% demonstrate the great savings potential of the sunspace in this study. At the light of the results, it can be concluded that the use of these sunspaces is really interesting from winter severity conditions corresponding to D climate zone, according to the Spanish technical code, which could be equivalent to a Cfb area from Köppen-Geiger classification. All in all, our research demonstrates that combining HRVs and sunspaces in cold climates substantially improves the energy performance of the building.

4. Conclusions

This paper has addressed the potential benefits of sunspaces to preheat ventilation air and reduce the energy consumption in buildings. In order to analyze the thermal behavior, a sunspace prototype was designed, built and monitored. After validating the simulation model with experimental results, a case study was analyzed to quantify energy savings in residential buildings. Four different sunspace scenarios were considered: with and without heat storage to give inertia, and these two configurations combined with a heat recovery ventilation system. Savings obtained with different sizes of sunspace were analyzed. Finally, in order to consider the influence of climate, the performance of the sunspace was tested for different climatic zones.

Our findings demonstrate that the use of sunspaces improves the energy performance of buildings, but the savings depend on different factors. First, as expected, the meteorological conditions have a great influence on the behavior of these systems. While on sunny days temperatures inside the sunspace are much higher than outside, on cloudy days the differences are significantly small. Second, inertia is not always convenient. In the cases without heat recovery ventilation, using water tanks means a modest improvement in energy savings. Moreover, in cases with HRV, inertia is not useful. In order to avoid cooling the preheated air in the recovery unit at night, the air only goes through the sunspace during the day and, therefore, accumulating the heat is not advisable, since part of the heat will be lost at night. Third, the savings obtained per module vary depending on sunspace size; the larger the sunspace, the lower the savings per module. As the cost of each module is the same, lower savings per module will lead to a higher return on investment. Thus, when choosing the size, not only the total energy savings must be taken into account, but also several economic aspects, such as the investment made and its return. Last, the effectiveness of these systems clearly depends on the climate. When there is little need for heating, the use of sunspaces is not convenient. The savings obtained are small or the energy consumption of the building even increases when a heat recovery system is used, since the savings in heating do not compensate for the higher consumption in the ventilation system. On the other hand, in colder climatic zones the energy savings are especially important. In turn, when these sunspaces are combined with a heat recovery ventilation system, the savings obtained in cold climates are substantial. In the case study, the annual savings vary from 2.47 kWh·m^{-2} in Malaga, located in the warmest climatic zone in Spain, to 38.48 kWh·m^{-2} in Burgos, a city in the coldest zone, which means going from a 25% saving in heating the building to 58%. The more sever the winter climate conditions, the higher the heating demand and therefore, the greater the possibility of savings. As another fundamental factor is the solar radiation, it can be concluded that cold climates with high direct solar radiation are ideal for this type of sunspaces.

We believe this paper presents useful insights into the potential benefits of sunspaces, in particular, when they are combined with a mechanical ventilation system. In these cases, the preheated air is distributed easily throughout the building, which improves the energy saving potentials compare to other type of sunspaces. For us, this is one of the most important contributions of the paper, since the advantages of using sunspaces with mechanical ventilation deserve further research.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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