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Use of sunspaces to obtain energy savings by preheating the intake air of the ventilation system: Analysis of its main characteristics in the different Spanish climate zones

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A R T I C L E I N F O

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A B S T R A C T

Novel solutions need to be further developed to continue to improve the energy efficiency of buildings achieved over the last few decades. One of these innovative systems is the use of sunspaces to preheat the ventilation intake air and reduce heating consumption. The main goal of this research is to determine the optimal configuration of these sunspaces. For that purpose, a prototype was built to calibrate a simulation model. Once validated, the model was used to calculate the energy savings obtained with 96 sunspace configurations in the different Spanish climate zones. Different key factors were analyzed and the optimal configurations were established in each zone. The results show that, although these systems are based on solar gains, a low thermal transmittance of the glazing has a higher impact on the energy savings than a high solar heat gain coefficient. In addition, introducing inertia tanks is not convenient when the ventilation includes a heat recovery system. While combining sunspaces with heat recovery ventilation is not interesting in warmer climates; in cold climates, heat recovery becomes a determining factor to reduce energy consumption. The use of sunspaces is more efficient as the winter severity increases: while in the warmest Spanish climate zone, only 2.51 kWh·m^{-2}·year^{-1} savings are achieved; in the coldest zone, 39.54 kWh·m^{-2}·year^{-1} savings are obtained, which represents important energy savings of 60%. This research contributes to evaluating and quantifying the impact of key variables on the design, configuration, and operation of sunspaces to improve the energy efficiency of buildings.

1. Introduction

The objective of the European Union (EU) is to achieve a low-carbon economy, for which it is committed to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050 [1]. The reduction of energy consumption and the use of renewable energies in the construction sector constitute important actions to achieve this objective. Thus, all new buildings must be Nearly Zero-Emission Buildings (NZEB) [2]. In this context, new buildings are better insulated and highly airtight, requiring a ventilation system to

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provide optimal indoor air quality. The health and comfort of the occupants are related to indoor air quality [3,4]. However, ventilation produces an increase in energy demand. Orme [5] analyzed the annual energy consumption in the commercial and residential sector of 13 industrialized countries and concluded that air renewal represents approximately 48% of heating consumption. Awbi [6], in turn, estimated that the percentage associated with ventilation was between 30% and 60%. Other researchers gave similar values [7–9]. In addition, this percentage increases as more thermally efficient buildings are built. To improve this aspect, sunspaces can be used to preheat the ventilation intake air. The operation of these systems is simple: the outside air is introduced into the sunspace and it is heated by means of the greenhouse effect before being introduced into the building.

The use of sunspaces attached to the facades to reduce heating demand has been a widely used strategy since the 1970s. Its use in single-family and collective housing, especially as a south-facing glazed gallery, has been extensively analyzed. One of the difficulties in using this type of sunspaces is to adequately distribute the heated air throughout the building. To improve this exchange, it is possible to incorporate a forced ventilation system. However, the combination of sunspaces with mechanical ventilation has not been analyzed in depth. Allesina et al. [10] and Pedrazzi et al. [11] concluded that glazing south-facing balconies and using a simple flow system to introduce the heated air inside the building could be an adequate solution for rehabilitating residential buildings, since energy savings in heating are obtained in a relatively simple way. Both Ma et al. [12] and Ulpiani et al. [13] 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 was 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 introduced only into the adjoining room. Ma et al. [14] 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 could 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 sunspaces to preheat ventilation air in single-family houses, but this can also be applied to multiple dwelling buildings, taking advantage of the collective ventilation system.

Installing sunspaces on the roof of buildings has not been studied in depth, despite having important advantages with respect to those attached to the facade. As the conditioning factors vary when placing them on the roof, it is necessary to complete this study. On flat roof buildings, the shape and volume of the sunspace are not so limited. In addition, the orientation of the building is not so limiting, since it can be installed without following the line of the facade. As many studies show [15–19], the overheating that can occur in the hot season of the year can be a problem in sunspaces attached to facades. However, when installing them on the roof, avoiding overheating is easier, since, in hot seasons, when it is not interesting to heat the air, the sunspaces can be covered or bypassed without affecting the ventilation or natural lighting of the building. One of the most important advantages of roof installation is that mechanical ventilation systems usually take the intake air from the roof; so, when the sunspaces are located there, it is possible to use them to preheat the intake air and introduce it easily and efficiently inside the building. It also allows the sunspace to be combined with a heat recovery ventilation system. An example of this can be seen in the "Home With a Skin" project presented at the Solar Decathlon Europe 2014 [20] by Delft University of Technology. Their proposal included a sunspace attached to the facade and to the south slope of the roof. In winter, the preheated air in the sunspace was passed through a heat recovery unit before being introduced into the house through the mechanical ventilation system. In cold climates, combining sunspaces with a heat recovery ventilation system can provide great energy savings, an aspect that also requires further analysis, especially in collective housing buildings.

In order to fill all these gaps detected in the state of the art, a modular sunspace to preheat ventilation intake air was designed in a

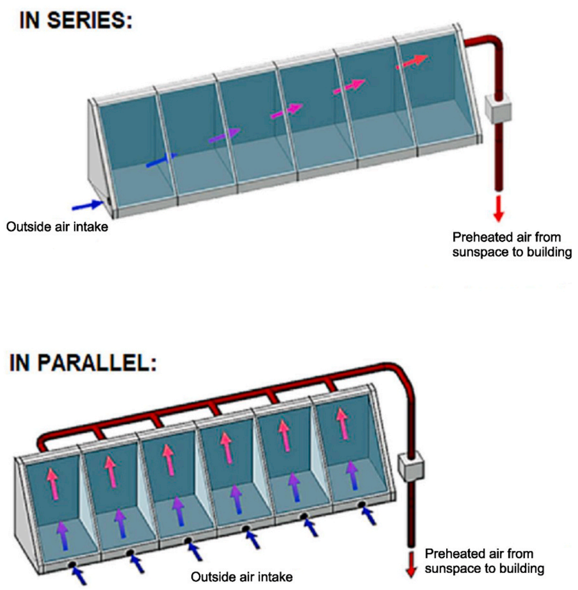

Fig. 1. Scheme of operation of the sunspace in series and in parallel.

previous study [21]. Starting from this first research, the objective of this paper is to complete the previous investigation by analyzing the main characteristics that affect the performance of this type of systems and quantify the savings obtained in different climate zones with the optimal configurations.

2. Methodology

2.1. Sunspace design

The sunspace was designed in the shape of a triangular prism whose south-facing side was fully glazed to capture as much solar radiation as possible. The rest of the surfaces were opaque and insulated to avoid thermal losses. The more perpendicular the solar radiation reaches the glass, the greater the solar gain in the sunspace. However, since the position of the sun varies depending on the latitude throughout the year and day, the optimal glazing angle changes. To determine this convenient glazing angle, the solar gains obtained with different degrees of inclination (from 35° to 70° in steps of 5°) were calculated using the EnergyPlus program in the different Spanish climate zones. It was concluded that the optimum angle was 55° in Spain, so it was designed with this degree of inclination.

A modular design was chosen to improve the adaptability of the sunspace to different locations and energy needs. In addition, being modular allows the modules to be installed in series or in parallel. Fig. 1 compares the operation of the sunspace depending on its installation mode.

When modules are installed in series, outside air is drawn in at one end of the sunspace. After heating up as it flows through the sunspace, it exits at the opposite end and is drawn into the building via the mechanical ventilation system. When the modules are installed in parallel, on the other hand, the air is introduced through the lower part of each one of the modules and, once heated in each compartment, the air is conducted inside the building.

It is possible to combine sunspaces with a heat recovery ventilation system. As shown in Fig. 2, the outside air would be preheated in the heat recovery unit before it is led into the sunspace, to be further heated before entering the building. In this way, greater energy savings will be obtained in the heating of the building; however, the energy consumption in the fans will be higher, so it is necessary to analyze which alternative is more satisfactory.

2.2. Prototype construction and simulation model validation

A prototype of one of these sunspace modules was built on the terrace of the Higher Technical School of Architecture of the University of the Basque Country (UPV/EHU), as can be seen in Fig. 3 [21]. The prototype was monitored during different periods of the year with different meteorological characteristics (see Table 1). In turn, the prototype served to validate the simulation model

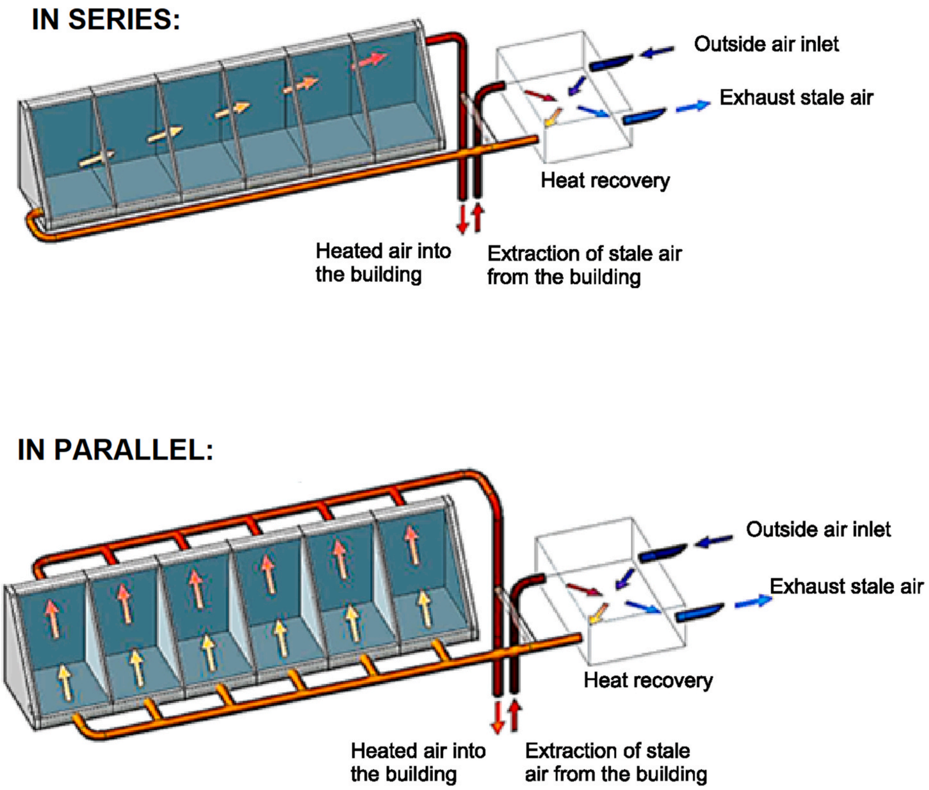

Fig. 2. Operation of sunspace in combination with a heat recovery ventilation system.

created by Design Builder that uses EnergyPlus as a calculation engine. Energy simulation, specifically the EnergyPlus software, has been used and validated in multiple investigations related to sunspaces [13,22–24]. Even so, due to the complexity of the simulation of glazed systems, it is convenient to calibrate and validate the model, for which the data obtained in the prototype have been compared with the results obtained through the simulation. In the simulation model, the same characteristics of the prototype were introduced and the different elements of the terrace that could shade the sunspace were modeled to make the results comparable. At the same time, a new climate file was introduced in the program with the meteorological data of each period obtained from the Spanish State Meteorological Agency (AEMET). Horizontal global, direct normal and horizontal diffuse solar radiation, as well as dry-bulb outdoor temperature, dew temperature, cloud cover, etc., were included.

The three main sources that explain how to determine the degree of confidence and establish validation criteria are Guideline 14 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (hereinafter ASHRAE) [25], the Federal Energy Management Program (hereinafter FEMP) [26] and the International Performance Measurements and Verification Protocol (hereinafter IPMVP) [27]. In these protocols, the main uncertainty indices used are the Normalized Mean Bias Error (NMBE), the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), and the Coefficient of Determination (R^2). Many other authors have used these criteria to validate their simulation models [28–30]. Table 2 summarizes the criteria of the three main documents to validate the simulation models.

To validate the model, the sunspace module experimental and simulation hourly temperatures were compared and it was checked if they were within the limits established by each of the reference protocols in each of the measurement periods (see Table 3).

The results show that, in all the periods, there was great agreement between the simulation results and the experimental measurements. The values of NMBE, CV(RMSE), and R^2 were clearly within the limits established by ASHRAE, FEMP, and IPMVP. It can be concluded that the simulation model is valid and that it is correctly calibrated. Once the model had been validated, computer simulation was used to analyze the energy behavior of the building with the different sunspace configurations. The size of the module used in the simulation was the same as the prototype. Climate files extracted from EnergyPlus Weather Data were used in the simulation.

2.3. Analyzed variants

This paper analyzes how the main characteristics of the sunspace influence the obtained energy savings. Table 4 summarizes the different variants analyzed and their main characteristics. These variants can be combined with each other to form 96 different sunspace configurations. For an easier reading of the results, we have used a numerical and color code. A pair of numbers was assigned to each variant: one for the group to which it belongs (1. type of glass, 2. degree of insulation, 3. use or not of inertia, 4. use or not of heat recovery and 5. Installation in series or parallel) and another for the variant that is within that group. In this way, we have assigned five pairs of numbers to each of the possible sunspace configurations, one pair for each group of variables or factors. In turn, each configuration will also be defined by five colors.

2.4. Case study

To quantify the savings that the use of this type of sunspace could entail, a building located in Pamplona, a city in northern Spain

Fig. 3. Sunspace prototype installed at the Higher Technical School of Architecture of the UPV/EHU.

Table 1
Calibration periods.

Period	Date	Characteristics		
		Thermal Inertia	Season	Heating period
P1	31/07/2019-06/08/2019	No	Summer	No
P2	11/11/2019-17/11/2019	No	Autumn	Yes
P3	27/12/2020-02/01/2021	No	Winter	Yes
P4	28/01/2021-03/02/2021	No	Winter	Yes
P5	05/02/2020-11/02/2020	Yes	Winter	Yes
P6	10/08/2020-16/08/2020	Yes	Summer	No
P7	15/11/2020-21/11/2020	Yes	Autumn	Yes
P8	12/02/2021-18/02/2021	Yes	Winter	Yes

Table 2
Validation criteria for simulation models.

Calibration criteria	Index	FEMP	ASHRAE	IPMVP
Monthly criteria %	NMBE	±5	±5	±20
	CV(RMSE)	15	15	–
Hourly criteria %	NMBE	±10	±10	±5
	CV(RMSE)	30	30	20
Recommendation	R^2	–	>0,75	>0,75

Table 3
Results of the NMBE, CV(RMSE), and R^2 indices for the calibration periods.

Period	Results	FEMP	ASHRAE	IPMVP
NMBE				
P1	1,58	±10	±10	±5
P2	-4,80			
P3	-3,55			
P4	-0,56			
P5	1,81			
P6	1,95			
P7	-3,27			
P8	3,56			
CV(RMSE)				
P1	7,99	30	30	20
P2	8,35			
P3	16,90			
P4	17,30			
P5	12,17			
P6	7,79			
P7	8,20			
P8	15,98			
$\mathbf{R^2}$				
P1	0,95	-	>0,75	>0,75
P2	0,97			
P3	0,89			
P4	0,78			
P5	0,97			
P6	0,91			
P7	0,96			
P8	0,90			

with a Cf2b climate, according to the Köppen-Geiger classification, was chosen. The building has a rectangular floor plan of 47 × 13 m, with a north-south orientation on its longest facades. It has commercial premises on the ground floor and two upper floors for housing (6 dwellings per floor). Fig. 4 shows the south facade of the building.

Table 5 presents the thermal particularities of the building, as well as the characteristics of the HVAC system. The building has a mechanical ventilation system whose total ventilation flow has been defined based on the minimum flows required by the Spanish Technical Building Code [31]. The set point temperatures for heating and the use profiles of the building have also been established according to the Spanish Technical Building Code.

On the roof of the building, it is possible to install a sunspace with 36 modules, which means a 45 m long sunspace with 112.50 m^2 of glass. Fig. 5 shows an infographic of the building when installing this sunspace, made using the SketchUp software.

Table 4
Summary of variants analyzed.

Factor		Variant
1. Type of glass	1.1	**Simple glass 6 mm** SHGC= 0.815 Light transmission = 0.885 U= 5.265 W·m^{-2}·K^{-1}
	1.2	**Double glass. 5+5/10air/6** SHGC=0.722 Light transmission = 0.801 U= 2.738 W·m^{-2}·K^{-1}
	1.3	**Low E double glass. 6/12argon/4** SHGC=0.592 Light transmission = 0.796 U=1.40 W·m^{-2}·K^{-1}
2. Insulation	2.0	**Without insulation**
	2.1	**Cork chipboard 8 cm** U= 0.462 W·m^{-2}·K^{-1}
	2.2	**Cork chipboard 16 cm** U= 0.231 W·m^{-2}·K^{-1}
	2.3	**Cork chipboard 24 cm** U= 0.154 W·m^{-2}·K^{-1}
3. Thermal inertia (heat accumulators)	3.1	**No inertia** No water tanks
	3.2	**With inertia** Water tanks 6 cm high on the ground (117 l per module)
4. Heat recovery	4.1.	**Without heat recovery** Single intake ventilation.
	4.2	**With heat recovery** Ventilation with heat recovery. Efficiency: 85%
5. Installation in series or parallel	5.1	**In series.** Sunspace modules installed in series.
	5.2	**In parallel.** Sunspace modules installed in parallel.

Fig. 4. Photograph of the south elevation of the selected building (source: Google Maps).

This building was tested without the sunspace and with all 96 sunspace configurations installed on the rooftop. For each case, the final and primary energy consumptions for heating the building were calculated. In addition, the primary and final energy consumptions in the fans of each ventilation system were obtained to get the total primary energy consumption and thus be able to compare the efficiency of each sunspace configuration. To determine the electrical power of each ventilation system and establish its

Table 5
Thermal characteristics of the selected building.

Element	Thermal characteristics
Envelope	
Flat roof	U = 0.257 W $m^{-2}K^{-1}$
Facade	U = 0.256 W $m^{-2}K^{-1}$
Gap percentage	17%
Window frame characteristics	Material: Aluminum with thermal break U = 5.014 W $m^{-2}K^{-1}$
Glass characteristics	Double glazing [4–6] SHGC = 0.74 U = 3.146 W $m^{-2}K^{-1}$
HVAC	
Heating	Individual gas boilers and radiators Efficiency 89%
Set point temperature	According to CTE
Usage profiles	According to CTE
Ventilation system	Mechanical ventilation system
Ventilation flowrate	1425 m^3 h^{-1}
Infiltration rate	2 ACH at 50Pa[a]

[a] ACH: Air changes per hour.

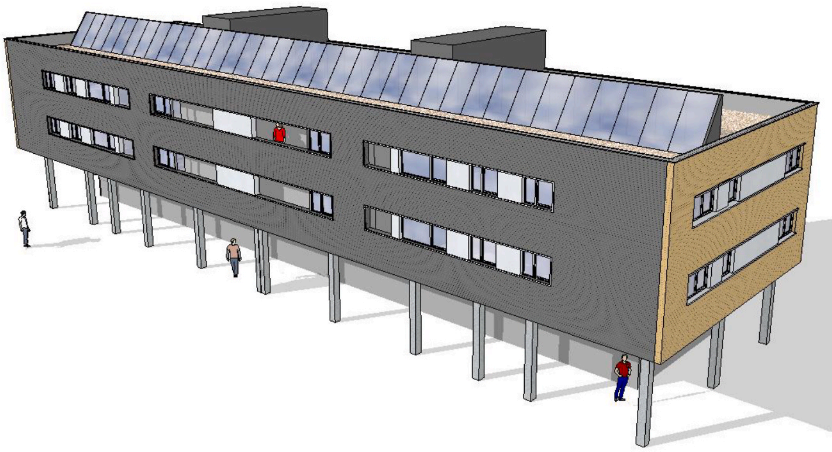

Fig. 5. Infographic of the building with the designed sunspace.

energy consumption, the recommended values of Specific Fan Power of the Air Infiltration and Ventilation Center were used [32]. To convert the final energy of the different sources into primary energy, the coefficients established by the Spanish government were considered [33].

2.5. Climate analysis

To study the influence of the climate on this type of system and on its characteristics, the different Spanish climate zones were analyzed. The Spanish Technical Building Code (CTE) [31] differentiates five climate zones according to their winter severity (A, B, C, D, and E; from the mildest to the coldest). In addition to Pamplona's climate simulation, the energy saving results of the most populous city in each climate zone were compared. The main climatic characteristics are summarized in Table 6.

In each climate zone, the energy consumptions of the building without a sunspace and with the 96 sunspace configurations incorporated into the building were computed. To analyze the influence of the climate on each variable, each group of variants was analyzed separately. Finally, the best configurations and obtained energy savings were established for each climate zone.

3. Results

3.1. Different variable analysis

3.1.1. Type of glass

Fig. 6 shows the average primary energy consumption of the building when installing the different configurations depending on the type of glass used. In the graph, the cities are ordered, from left to right, from least to greatest winter severity.

As the severity of winter increases, the type of glass selected becomes more important. In Malaga (Climate Zone A), as heating consumption is minimal, the obtained savings are also minimal, and the differences between the different types of glass are

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 EnergyPlus Weather Data, with which the simulations have been done.
[c] Heating period of Spanish Technical Building Code [31].

insignificant. In Burgos (Climate Zone E), on the other hand, with the use of double Low-E glazing, consumption is clearly lower on average than with the rest of the glazing. In all the cities, the highest consumption occurs with single glass panes and the lowest with double Low-E glass panes. The difference between installing double and single glazing is significantly greater than the difference between double glazing and double Low-E glazing. Despite the fact that among the 3 glass types analyzed, the Low-E glass has the lowest Solar Heat Gain Coefficient (SHGC), greater energy savings are obtained since its thermal transmittance (U) is the lowest. It can be concluded that, in order to obtain greater energy savings, the insulating capacity of the glass has a greater impact than the solar gains obtained.

3.1.2. Opaque enclosure insulation thickness

Fig. 7 shows the average total primary energy consumption of the building when installing the sunspaces in Pamplona. To see the influence of the thickness of the sunspace insulation, the results have been organized according to the degree of insulation.

The average consumption is undoubtedly higher when the sunspace envelope is not isolated (variant 2.0). Therefore, the need to insulate the sunspace envelope by at least a minimum is clear. For this reason, the uninsulated variant is discarded in the following calculations. Obviously, the greater the thickness of the insulation, the less thermal loss through the envelope of the sunspace, which means greater energy savings in heating the building. In any case, it can be seen that, once the sunspace is suitably insulated, further thickness increases do not lead to significant savings.

Fig. 8 shows the average primary energy consumption of the building when installing the different configurations in each of the cities based on opaque envelope insulation thickness.

In temperate climates, as heating demand is low, the improvement with increasing thickness is negligible. As the climate gets colder, the impact of further insulating the envelope increases. In any case, it can be observed that, once the envelope is suitably insulated, the differences in savings due to further increasing the insulation are insignificant in all cases. The repercussions of increasing the thickness are less and less: between placing 8 and 16 cm, the differences are greater than between 16 and 24 cm.

3.1.3. Thermal inertia

Fig. 9 shows the average primary energy consumption of the building when installing the different sunspace configurations in each of the selected cities, depending on the use or not of inertia water tanks. As can be seen in the graph, the differences in the means between using inertia and not using it are minimal in all the cities, so the interaction between climate and inertia is not considered significant.

Fig. 10 presents the interaction between inertia and the use of heat recovery when the building is located in Pamplona. It can be observed that the suitability of using the water tanks to get inertia depends on the ventilation system: when a heat recovery system is not installed, its placement slightly improves the results; while, with a heat recovery system, the results with inertia are worse. When heat recovery is installed, during the night hours, the sunspace is not capable of further heating the air that is preheated in the heat recovery unit. Thus, to avoid its cooling, the air is not circulated through the sunspace at night. In these cases, storing heat in the tanks is not convenient, since part of this heat would be lost during the night hours.

3.1.4. Heat recovery system

Fig. 11 shows the average primary energy consumption of the building when installing the different configurations in each of the selected cities, depending on the use or not of a heat recovery ventilation system.

Fig. 11 clearly shows how, in temperate climates, the use of a heat recovery ventilation system is not convenient, since the total primary energy consumption is higher. In these climates, heating consumption practically disappears with a heat recovery system. However, installing this system supposes a greater consumption in the fans. As the demand for heating is small, the savings obtained in heating do not compensate for the higher consumption in the fans. As the severity of winter increases, the demand for heating increases and the installation of heat recovery becomes more and more convenient. In Madrid, the average consumption with heat recovery is already lower than without recovery. In Pamplona, the difference in favor of recovery is significant; while in Burgos, it becomes a determining factor in obtaining the greatest possible energy savings.

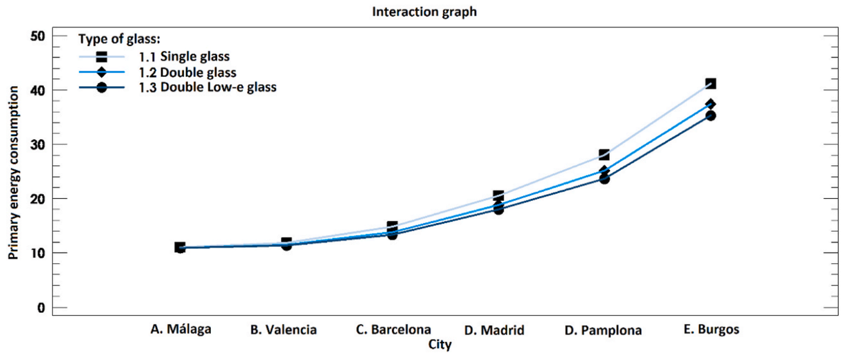

Fig. 6. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in each city depending on the type of glass used.

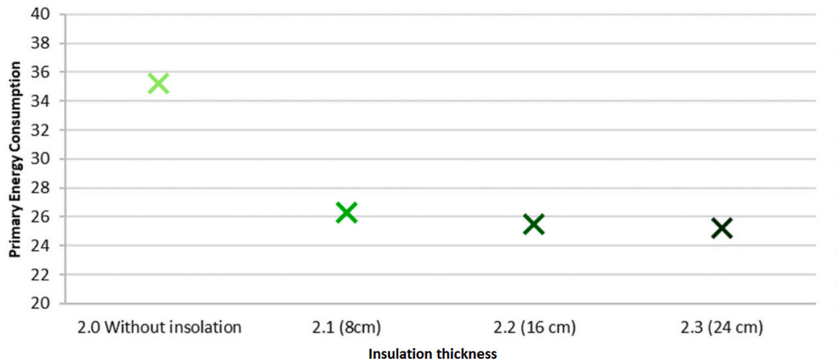

Fig. 7. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in Pamplona depending on the insulation thickness.

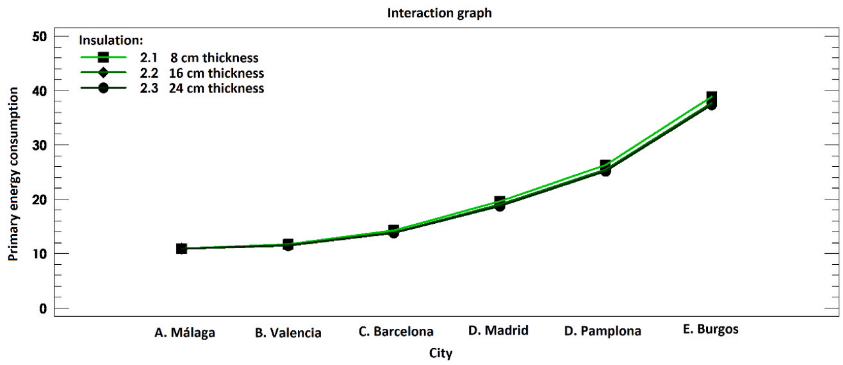

Fig. 8. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in each city depending on the insulation thickness.

3.1.5. Installation mode, in series or parallel

Fig. 12 shows the average primary energy consumption of the building when installing the different configurations in each city, depending on the installation mode of the modules.

In more temperate climates, the difference in average consumption between installing the modules in series and doing so in parallel is minimal. As the severity of winter increases, the differences are greater and the average consumption is lower in parallel, although the differences are not very significant. In Burgos, where the largest difference occurs, it is only 5%.

3.2. Best configurations

Having separately analyzed the influence of the climate on each factor, Table 7 shows the results of the optimal configurations obtained in each Spanish climatic zone. The savings obtained with respect to the building without a sunspace (case 0) are also shown.

The first aspect that can be observed is that, as the severity of winter increases, the energy consumption of the building increases; but at the same time, greater energy savings are obtained when the sunspaces are installed. Therefore, the use of these solar spaces is

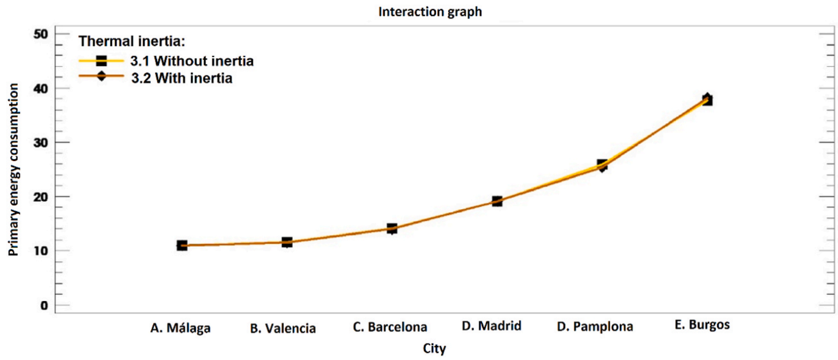

Fig. 9. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in each city depending on the use of inertia.

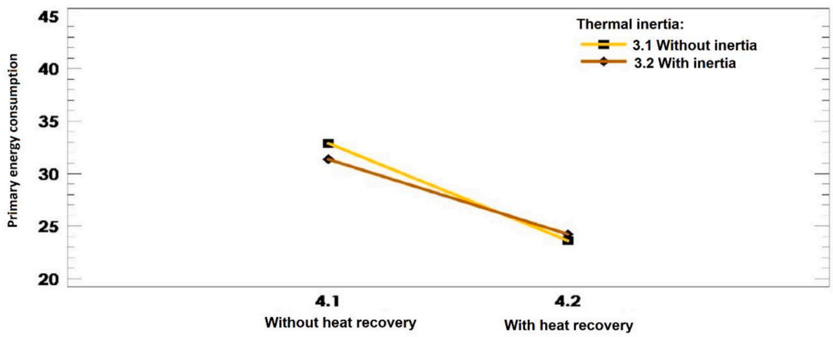

Fig. 10. Interaction graph between inertia and the use of heat recovery when the building is located in Pamplona.

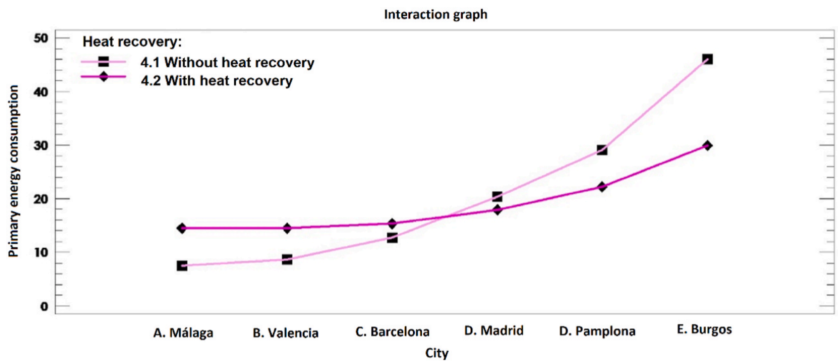

Fig. 11. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in each city depending on the use of a heat recovery ventilation system.

more interesting the more severe the winter climate is. In this way, in Malaga (climate zone A), savings of only 2.51 kWh·m^{-2}·year^{-1} are obtained; while in Burgos (climate zone E), savings of 39.54 kWh·m^{-2}·year^{-1} are achieved.

As can be seen in Table 7, the optimal configuration of the sunspace varies depending on the climate zone. In all the cities, the greatest savings are obtained with double Low-E glazing (variant 1.3). As expected, the configuration with the greatest energy savings in all the cities is achieved with the greatest thickness of insulation (variant 2.3). However, the rest of the variables vary depending on the climatic zone. As seen above, the convenience of using inertia depends on whether or not a heat recovery ventilation system is installed. For this reason, in climate zones A, B and C, where heat recovery is not convenient, inertia (Variant 3.2) improves the results; while in the rest of the climates, where greater savings are obtained with heat recovery, inertia is not recommended. As for heat recovery, in the most temperate climate zones, the use of a heat recovery unit is not convenient. The heating needs in these climates are so small that the savings obtained in heating do not compensate for the higher operation consumption of this ventilation system. For this reason, the greatest savings in Malaga, Valencia and Barcelona are achieved with Variant 4.1. From climate zone D onwards, the use of a heat recovery unit is recommended. In addition, as the weather gets colder, its installation acquires more and more impact. Whether to install the modules in series or in parallel depends on other factors. Depending on the climate zone, it is sometimes

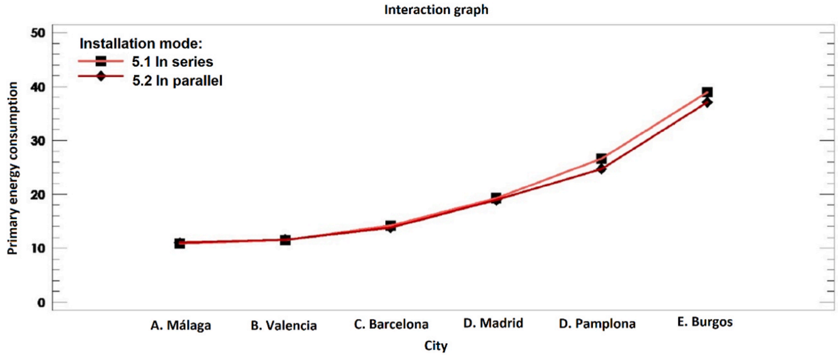

Fig. 12. Means of primary energy consumption (kWh·m^{-2}·year^{-1}) obtained in each city depending on the installation mode.

Table 7
Best configurations of sunspaces depending on Spanish climate zones.

City	Climatic Zone	Optimal configuration					Consumption	Savings	
		1. Type of glass	2. Isolation	3. Thermal Inertia	4. Heat recovery	5. Installation mode	kWh·m^{-2}·year^{-1}	kWh·m^{-2}·year^{-1}	%
Málaga	Zone A	Case 0					9.75	-	-
		1.3	2.3	3.2	4.1	5.1	7.24	2.51	26%
Valencia	Zone B	Case 0					13.66	-	-
		1.3	2.3	3.2	4.1	5.1	7.96	5.70	42%
Barcelona	Zone C	Case 0					21.96	-	-
		1.3	2.3	3.2	4.1	5.2	10.64	11.32	52%
Madrid	Zone D	Case 0					33.32	-	-
		1.3	2.3	3.1	4.2	5.1	16.54	16.78	50%
Pamplona	Zone D	Case 0					45.24	-	-
		1.3	2.3	3.1	4.2	5.1	20.01	25.24	56%
Burgos	Zone E	Case 0					66.09	-	-
		1.3	2.3	3.1	4.2	5.2	26.56	39.54	60%

convenient to install them in parallel and on other occasions, in series, although the differences are small between the two installation modes.

4. Conclusions

This research has shown that the use of sunspaces to preheat the ventilation intake air can significantly improve the energy performance of buildings, but the savings depend on different factors. The main conclusions drawn are summarized below:

- When choosing the glazing for the sunspaces, the low thermal transmittance is more important than a high SHGC. This is obvious when choosing window glazing for a building, but not for sunspaces, as these systems are based on solar gains. Normally, the lower the thermal transmittance of the glass, the lower the solar gains obtained. Even so, the results show that, for all the studied climates, the highest energy savings are obtained with double Low-E glazing, which is the glass among those analyzed with the lowest SHGC, but at the same time, with the lowest thermal transmittance. Therefore, the greater importance of thermal transmittance in obtaining heating savings is demonstrated.
- The more the opaque envelope of the sunspace is insulated, the greater the savings obtained in the building. However, once the sunspace envelope is adequately insulated, the differences between the different thicknesses are small.
- Although other research works have shown that the use of water tanks in sunspaces to increase inertia is desirable [22,35,36], the results obtained demonstrate that this is not always the case. When sunspaces are combined with a heat recovery ventilation system, high inertia involves a higher consumption in the building. In such cases, sunspaces are not able to further heat the air

preheated in the recovery unit during the night hours. Thus, to avoid cooling the air, it does not circulate through the sunspace at night. Therefore, in the cases when sunspaces are combined with heat recovery, it is not convenient to store heat in the tanks, since part of this stored energy would be lost during the night hours.

- While it is not interesting to combine sunspaces with heat recovery ventilation in the warmest climates; in cold climates, much higher total energy savings are achieved in this way. Installing heat recovery means lower consumption in heating the building, but a higher fan operation consumption of the ventilation system. In warm climates, as the heating consumption is very low, the heating savings are minimal and they do not compensate for the higher consumption of the fans due to the operation of the heat recovery ventilation system. As the severity of winter increases, the use of heat recovery is increasingly important, becoming a determining factor in reducing energy consumption in the colder climates.
- As the winter severity increases, more and more energy consumption savings are obtained with the installation of these sunspaces. Thus, while in the warmest climate zone of Spain, only 2.51 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$ are obtained (representing 26%); in the coldest climatic zone, energy savings of 39.54 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$ are obtained (which represents a 60%). Therefore, it can be concluded that, while in warm climate zones the use of this type of sunspace is not of great interest; the primary energy savings are really important in colder zones.

This work contributes to identifying key variables in the design, configuration, and operation of sunspaces; as well as evaluating and quantifying their impact on the energy efficiency of buildings. This research has shown that the use of sunspaces to preheat the intake air of the ventilation system can contribute to meeting the fundamental goal of reducing greenhouse gas emissions, since they significantly reduce the energy consumption of buildings, especially if properly designed and used in cold climates.

CRediT author statement

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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.

Data availability

Data will be made available on request.

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