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Advantages of straw-bale in the building sector and a case study

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ABSTRACT

Straw presents several benefits when considering it for the construction sector in substitution of conventional materials. Not only has lower embodied energy and density, but also has valuable thermal properties for passive construction. Using rice-straw bales for construction could reduce the current waste-management problem for the city, saving costs for the material supply in the construction sector while providing better building and air-quality for the city.

This research compiles different studies addressing the issue of using straw-bales for the construction, concluding with the main advantages of this material for professional building. The study also presents a monitored case study constructed in Villareal (Spain) using prefabricated modules of straw-bales. The study also comprises a detailed dynamic energy simulation with Energy Plus, and the detail of the calibration of the model.

KEYWORDS

Straw bale building, Sustainability, Energy efficiency, Sustainable building

1. INTRODUCTION

The building sector in the European Union (EU) is currently responsible of the 40% energy consumption and 36% of the CO2 equivalent emissions as it is indicated in Directive 2012/27/UE [1]. In addition, Directive EPBD 2018/844/UE [2] establishes an emissions reduction of 80-95% by 2050, regarding 1990 levels. Moreover, since around 65% of the EU building stock is below 50 years old, the future of building energy performance enhancement will be mainly focused to retrofitting rather than new construction. However, the current trends show that only 0.4-1.2% of the building stock is renovated each year. Conventional materials used in the construction sector present a high embodied energy. Nevertheless, as the use of natural materials in the construction sector has been common since ancient times, specially the use of straw-bales. Recently, the construction with straw-bales has gained some attention.

Straw is an agricultural by-product that presents a problem in some cities, since it is considered a waste in the current linear production paradigm. It is the case of València, a city surrounded by fields, in where the surplus of rice-straw is every year burned producing the consequent health and contamination problems on the city. However, the incipient change to circular models, may change the consideration of some goods, as it is the case of the rice-straw in València.

The objective of this research work is to demonstrate the benefits of the straw-bale construction through a state of the art study and present a case study of a straw-bale building model calibrated with real measurements. The case study here presented will serve in future studies to demonstrate the benefits of straw-bale construction in front of conventional construction. The final purpose of this study consists of rising concern among the scientific community and professionals of the construction sector about the straw-bale construction as an alternative to conventional materials.

2. STATE OF THE ART

Straw-bale construction dates back to 19th century with the invention of the baling machine [3]. Almost completely abandoned during the 1940s due to the WWII and the spread of Portland cement, this technique came back with the oil crisis of 1973, with the rising of energy and environmental concern [3], [4]. Straw-bale construction is nowadays gaining considerable attention among technicians, scientists and politicians. The rising interests on straw-bale as construction material is only due to its properties that make it an ideal alternative for conventional materials.

First, straw-bales present good thermal properties [5] with a reduced thermal conductivity that make it a good insulation material [6]. Nevertheless, the heat conductivity varies a lot significantly depending on straw features: straw type, percentage of humidity, density, orientation of fibers and type of fiber, as Table 1 shows. In Figure 1, the thermal conductivity results have been plotted over the density of the straw-bales. In Figure 1 it is observed that most of the values are concentrated between the density values of 80 to 150 kg/m^3 with a high concentration of heat conductivity results between 0.05 to 0.10 W/mK; coinciding thus with the results by Adrien Chaussand et al. [1]. The good thermal properties of the straw-bales together with their size result in a better thermal behaviour and energy efficiency than conventional construction thanks to a higher thermal transmittance of the straw walls. This is demonstrated in [2], where an energy savings of 1593 MJ/(m^2·year), which account for more than 35 % difference, are achieved by a straw-bales construction in front of a conventional concrete building.

Apart of the good thermal performance, straw-bales present good acoustic properties as demonstrated in [8] and [9], in where the straw-bales are compared in front of the conventional EPS insulation wall. Also straw-bale construction presents a high fire resistance under the Standard Test Methods for Fire Tests of Building Construction and Materials (ASTM E119-19) [10] and the results show a fire resistance of up to 120 minutes. G. Garas and M. Allam [11] also demonstrated it in their study. This resistance highly increases when the walls are earth plastered and the main risk occurs during construction process since the ground is usually fool of straw with high fire risk. Moreover, straw-bale construction shows good structural properties, with several studies in the literature for stress test such as [12] and [13]. However, the water content of the straw-bales could lead to structural damage problems in the construction. As an organic material the straw biologically degrades depending on the water content. In this manner, in straw-bale construction is critical to maintain low moisture levels [34]. Jim Carfare studied the straw-bale construction performance under a maritime climate and concluded that with the proper attention paid in the construction and detailing, the durability of the construction should not be a problem [14]. Similar conclusions, regarding the durability of straw-bale construction have been found in [15]. In order to avoid moisture problems that affect the durability of the building, the authors recommend to always perform a quality control on the straw-bales before construction, guaranteeing a maximum level of moisture of 18 % that coincides with the studies of The Canada Mortgage and Housing Corporation (CMHC) concluding that straw will deteriorate when exceeding 25 % of moisture content [16].

Finally, straw-bale construction presents a reduced environmental impact compared with conventional construction as demonstrated in studies such as [4][17][7][18][19][20]. It should be noted that straw-bales capture CO2 during its life-time, are reincorporated to the system as a waste and their burnout is avoided (not only greenhouse gases emissions are avoided [21] but also other harmful chemical substances as stated in [22]). This issue, regarding their reduced environmental impact, together with its good thermal properties are the key benefits of straw-bale constructions and its potential to substitute conventional materials.

3. METHOD

3.1.Building description

The subject matter of this paper is a single-family (tiny) small house with a total built area of 25 m2. It is located in the municipality of Vila-Real, province of Castellón (Spain). The building has been constructed with prefabricated straw-bale walls by Okambuva company. The building has been designed in accordance with both bioclimatic architecture and ecological building principles. On one side, the goal was to reduce energy consumption while maximizing the comfort inside the building; on the other side, a clear commitment has been adopted towards the responsible use of existing resources, following a strict sustainability approach in the construction.

Figure 1. Straw-bale building case study picture. Source: Okambuva.

The house has been built on a tyre foundation, that is, used car tyres filled with gravel, and the floor insulation has been executed with wood fibre boards of 80 mm thickness resting on a sawn timber structure and OSB panels. The building vertical enclosure consists of prefabricated rice straw and wood modules of 25 cm wall thickness, the straw being compressed with a density of 130 kg/m3 and presenting a relative humidity of < 15%. The structural sawn timber of the prefabricated modules presents the mechanical grading C24 according to the European Standard UNE-EN14081 and its dimensions are 100x150 mm. The prefabricated modules are externally coated with multitherm wooden panels of 22 mm thickness. Additionally, the south and east walls are protected with a ventilated facade system made of larch wood slats and the north and west facades are plastered with lime. Moreover, the inner walls have been completely plastered with clay. The roof consists of a double-roofing system; the horizontal lower roof, resting on the straw modules, is made of wooden boards (t=22 mm) on the inner side and multitherm panels (t=22 mm) on the outer side. The roof insulation consists of wood fibre boards of 80 mm thickness, identical to the floor insulation. The upper shed roof is ventilated and rests on two horizontal beams and several crossbeams, which in turn support a green roof comprising a geotextile sheet, a waterproofing layer, a draining layer and the vegetable substrate with plants. Finally, the windows are composed of a wooden frame with low transmittance and low emissivity triple glazing (0.9 W/m^2·K), while the main door is made of solid pinewood. The resulting thermal transmittance of the different building enclosures has been included in Table 1.

Table 1 Thermal Transmittance of the different enclosures. Straw-bale and conventional house typologies.

House typology	**Thermal Transmittance (W/m^2/K)**			
	External Wall	*Floor*	*Roof*	*Window*
Straw-bale house	0.21	0.30	0.28	0.90

In Table 2, the different thermal conductivities regarding the properties of straw-bales from different authors on the literature are presented. With Table 2, Figure 2 shows the resulting thermal conductivity regarding the density of the straw-bales. A wide variation is observed regarding the thermal conductivity of the straw-bales with its properties, especially with their density.

Table 2. Straw-bale properties extracted from literature.

Authors	**Origin of Straw**	**Density (kg/m^3)**	**Thermal Conductivity (W/m·K)**		
			Parallel	*Perpendicular*	*Mean Value*
Munch-Andersen and Andersen [23]	-	62	0.082		0.082
	-	75	0.057	0.052	0.0545
	-	81	-	0.057	0.057
	-	90	0.06	0.056	0.058
	-	90	0.05-0.06	0.05-0.06	0.055
	-	100	-	0.038	0.038
	-	150	0.06	0.048	0.054
A. Sabapathy [24]	Rice	50-90	0.12-0.03		0.075
Lebed and Augaitis [25]	-	80-190	$0.00155+0.000357\rho+(3.381/\rho)$		0.0748
Costes et al. [6]	Wheat	68.1-122.7	$0.0444+0.000272\rho$		0.0703
Douzane et al. [26]	-	80	$0.067*(1+0.0078T)$	$0.046*(1+0.009T)$	0.0682
Palumbo et al. [27]	Barley (81%)	107.5	$0.037+0.019*\%HR$		0.0399
Vėjelienė [28]	-	50-120	$0.10312-0.00036\rho+0.0000175\rho^2$	$0.09637-0.001460\rho+0.0000107\rho^2$	0.1243
Ashour [5]	Wheat	82-138	$0.0399-0.00023\rho+0.00269T$		0.0819
	Barley	68-98	$0.0625-0.0005\rho+0.002237T$		0.0769
ITeCons [29]	Rice	78.7-83.3	-	-	0.0409
McCabe [30]	Wheat-Rice	130	0.0605	0.0487	0.0546
Shea et al. [31]	Wheat	90	0.06	0.056	0.058
		63	-	-	0.0594
		76	-	-	0.0621
		85	-	-	0.0619
		107	-	-	0.0642
		114	-	-	0.0642
		123	-	-	0.0636
Saini et al. [32]	-	90-110	-	-	0.045
Douzane et al. [26]	-	80	0.072	0.051	0.0615
Conti [33]	-	75	0.066	-	0.066
Grelat [34]	-	77	0.066	-	0.066
Marques et al. [8]	Rice	80	-	-	0.0393
		100	-	-	0.0392
Cascone et al. [35]	Wheat	78	-	-	0.0573
Cascone et al. [36]	Wheat	200	-	-	0.06
		250	-	-	0.07
		300	-	-	0.075
		350	-	-	0.08
Gallegos-Ortega et al. [37]	Wheat	115	-	-	0.0939
Zhang et al. [38]	Wheat	-	-	-	0.074
D’Alessandro et al. [3]	Wheat	80	-	-	0.052
Wei et al. [39]	Rice	250	0.051-0.053		0.052

Goodhew and Griffiths [40]	Rice	60-90	0.07-0.09		0.08
Buratti et al. [19]	-	105.69	-	-	0.065
Brzyski et al. [41]	Rye	50.9	-	-	0.0473
Evola [9]	Wheat	75	-	-	0.069
Drozd et al. [42]	-	-	-	-	0.08
Seitz et al. [43]	Barley	89.5	-	0.11-0.17	0.14
		90.1	-	0.11-0.16	0.135
		89.6	-	0.08-0.17	0.125
	Spelt	131	-	0.14-0.17	0.155
	Wheat	291	0.15-0.21		0.18
		333	0.14-0.15		0.145
		372	0.20-0.25		0.225

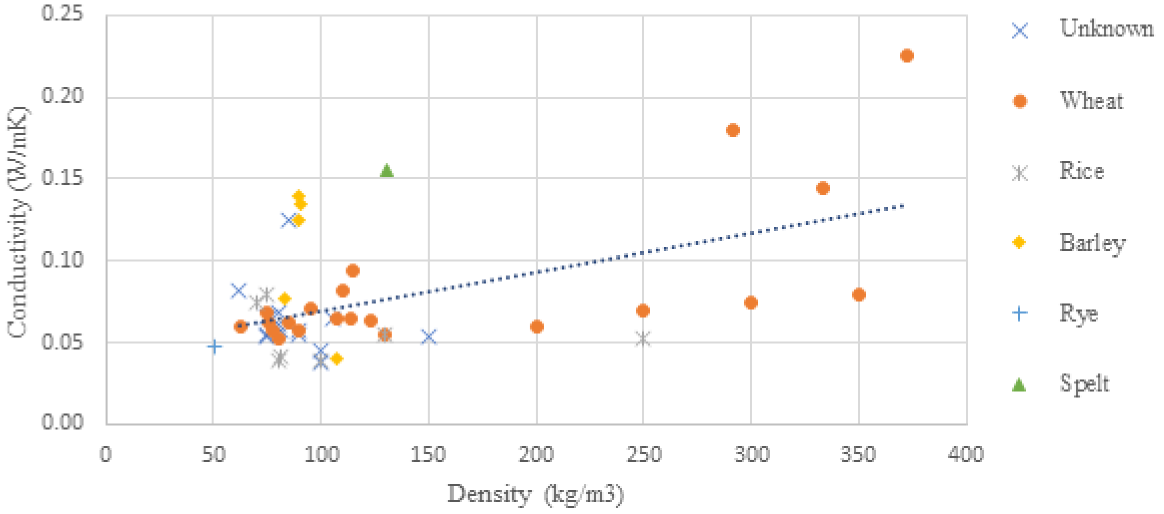

Figure 2:Thermal conductivity of Straw according to its density and origin.

3.2.Energy model and measurement methodology

In order to assess the energy behavior of the cases being compared, energy simulation software has been used. Concretely, *CYPE* software (*Cypetherm HE Plus* and *IFC Builder*), that uses *Energy+* as calculation engine, has been used for modelling the system.

The different enclosures data of the straw-bale house have been included in the software as detailed in section 3.1. Building description. The thermal properties of the materials have been included considering the ones provided by the manufacturers, and the resulting thermal transmittance of each enclosure of the building are included in Table 2. For the thermal properties of the straw-bales, the data from the literature was used knowing the density of the Straw-bales used: 130 kg/m^3 due to the impossibility of measuring them in the laboratory. A thermal conductivity of 0.071 W/mK was used and a sensitivity study was performed considering the results of the calibration for different thermal conductivities of the straw-bales that is presented in section 4. RESULTS AND DISCUSSION. No occupation was considered for the calibration due to the inoccupancy of the house during the monitoring period. Considering the energy assessment, the occupation and temperature set-points (21 ºC in heating mode and 25 ºC in cooling mode) defined by the Spanish Building Code (DB HE CTE [44], DB HS CTE [45], RITE [46]) have been used for the annual simulation (not for the calibration). Finally, considering that the house has no HVAC system it was not implemented in the model.

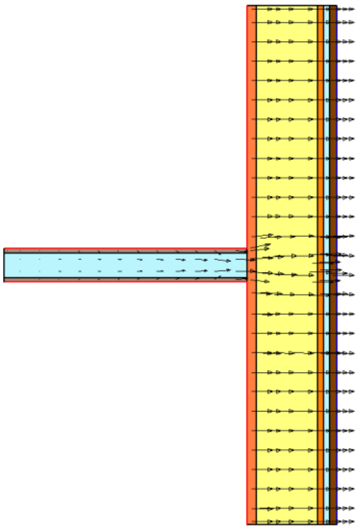

Figure 3. Thermal bridge between partition and External wall.

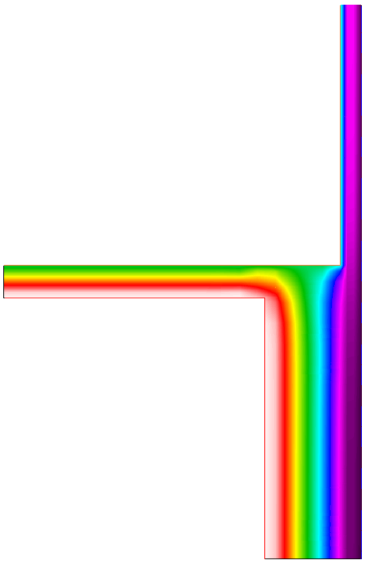

Figure 4. Thermal bridge between external wall and internal floor slab.

Apart from the basic parameters of the model, the thermal bridges of the straw-bale house have been assessed and quantified using *THERM* software. The thermal bridges have been evaluated according to the normative: UNE-EN ISO 10211 [47], UNE-EN ISO 13370 [48] and UNE-EN ISO 6946 [49]. The results, as shown in Table 3, have been included in the energy model. As an exemplification, the results considering the thermal bridges between the partition and the external wall and the internal floor are shown in Figure 3 and Figure 4 respectively. Figure 3 shows the heat flow vectors in the thermal bridge, whereas Figure 4 shows a temperature map representing the temperature in each point for an internal temperature of 20 ºC and an exterior temperature of 0 ºC.

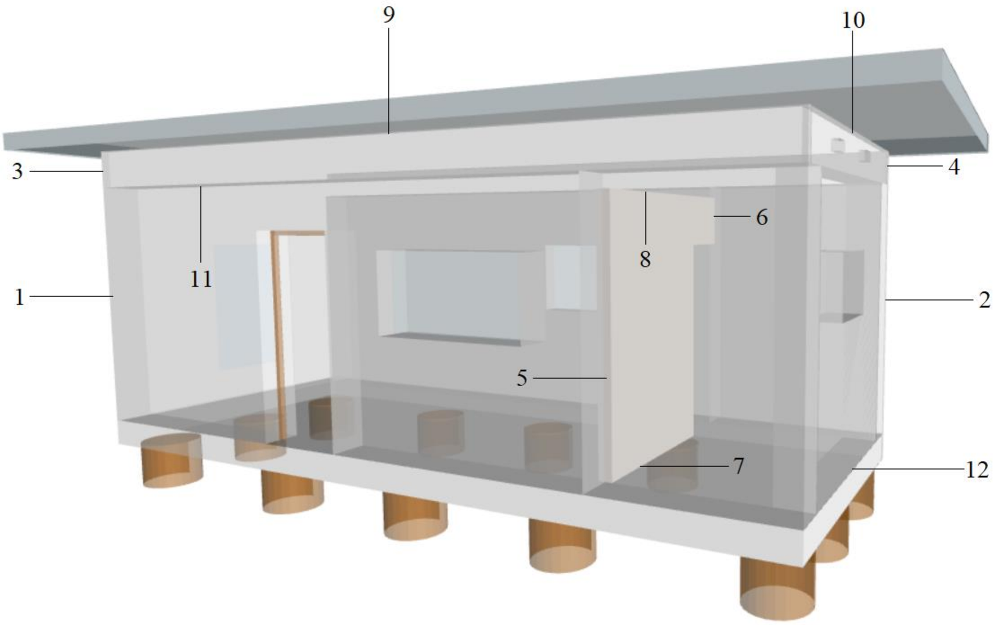

Figure 5. Numbering of thermal bridges at enclosure junctions. 3D view of the house model (IFC Builder).

Table 3. Thermal bridges results of the straw-bale house, calculated by means of THERM.

	Linear Transmittance (W/m)
1. Wall corner (Wood)	0.033
2. Wall corner (Mortar)	0.032
3. Light wall corner (Wood)	0.027
4. Light wall corner (Mortar)	0.007
5. Partition – Wall (Wood)	0.019
6. Partition – Wall (Mortar)	0.02
7. Internal partition – Ground floor	0.04
8. Partition – Internal floor slab	0.036
9. Roof – Light wall (Wood)	0.2
10. Roof – Light wall (Mortar)	0.127
11. Wall – Internal floor slab	0.167
12. External partition – Ground floor	0.195

Considering the calibration process, weather data from a nearby weather station (Villareal EEA) of the Spanish “Ministerio de Agricultura, Pesca y Alimentación” has been used [50]. Once the model was calibrated, SWEC (Spanish Weather for Energy Calculations) data created from the Spanish Building Code regulation has been used for the energy analysis. The Straw-bale house has been monitored with the objective of validating the software model created. The monitoring has been performed following the recommendations of A. de Gracia et al. [51]. Thus, eight temperature digital sensors (DS18B20) have been installed in the building, three of them in the center of the building, four in each interior façade and one monitoring exterior ambient temperature. An *Arduino ONE* has been used as datalogger sorting the data in a 5 minutes time step and with an absolute error of ±0.5ºC . More than two-month data have been gathered, from October 25th to January 4th, in order to validate the model created with *Energy+* software.

3.3. Validation and simulation methodology

Considering the validation of the model with the actual data gathered, ASHRAE criteria has been followed. To this purpose, the guidelines for the validation methodology defined in [52], [53] have been used. Accordingly, the values of Root Mean Square Error (RMSE) and Mean Bias Error (MBE) defined in Equation (1) and Equation (2) have been used for the validation. Additionally, the R-squared defined in Equation (3) has also been used although it is not required but recommended by ASHRAE guideline.

$$RMSE\ (\%) = \left(\frac{100}{T_{m,av}}\right)\cdot\left[\frac{1}{n}\cdot\sum(T_s - T_m)^2\right]^{0.5} \tag{1}$$

$$MBE\ (\%) = \left(\frac{100}{T_{m,av}}\right)\cdot\frac{\sum(T_s - T_m)}{n} \tag{2}$$

$$R^2 = \left(\frac{n\cdot\sum(T_m\cdot T_s) - \sum T_m\cdot\sum T_s}{\sqrt{\left(n\cdot\sum {T_m}^2 - (\sum T_m)^2\right)\cdot\left(n\cdot\sum {T_s}^2 - (\sum T_s)^2\right)}}\right)^2 \tag{3}$$

Where T_s and T_m are respectively the temperature obtained from the model and the temperature from the real data, $T_{m,av}$ corresponds with the average temperature of the real data and n as the total number of data points.

In order to validate the model with the real measurements, the defined values of RMSE and MBE have to be lower than 30 % and 10 % respectively [52], [53]. It is also recommended by ASHRAE a value of R-squared above 0.75 [54]. Considering the thermal transmittance of the straw-bales as the only unknown parameter of the model, no iterative calibration process was needed.

4. RESULTS AND DISCUSSION

ASHRAE guidelines have been used to validate the straw-bale building model. The methodology presented in [55][54][56] has been followed once the model was built up and all the real in-situ measurements have been processed.

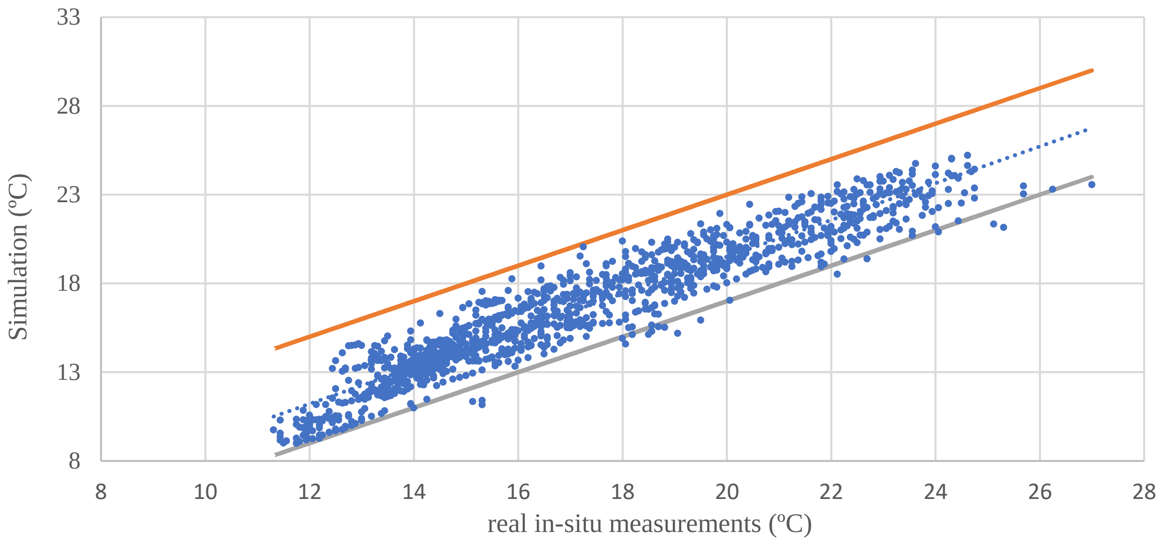

Figure 6. Correlation between simulated temperature and real in-situ measurements.

In *Figure 6* the results of the model have been plotted versus the real in-situ temperature measurements, including ±3 ºC error bands. A value of 0.90 R-squared parameter has been obtained, as specified in Eq. (3). Although this value is not considered as an indicator for the validation of the model, ASHRAE recommends a value above 0.75 [56].

Concerning the validation of the building model, the values of RMSE and MBE have been calculated as specified in Eq. (1) and Eq. (2). The results of the RMSE and MBE, 7.53 % and 3.48 %, are below the specifications of ASHRAE for the validation of 30 % and 10 % respectively [56]. Considering the R-squared, RMSE and MBE results and the specifications from ASHRAE guideline the authors consider the model validated with the building in-situ real measurements.

Table 4. MBE and RMSE results for the model considering the variation of the thermal transmittance of the straw-bale walls.

Conductivity [W/(m·K)]	MBE	RMSE
0.04	1.80%	5.13%
0.05	1.94%	5.16%
0.06	2.06%	5.19%
0.07	2.18%	5.22%
0.08	2.28%	5.25%
0.09	2.38%	5.28%

The results show deviations lower than 0.2 ºC considering the in-situ real measurements and little variations of the indicators of MBE and RMSE, concluding that the thermal transmittance of the straw-bale walls has not significant effect over the building model. Therefore, the value of 0.071 W/(m·K) obtained from the literature for the straw-bales of the project of 130 kg/m^3 is the thermal transmittance value implemented in the building model for the straw-bale walls.

The annual simulations results are included in Table 5. Annual energy demand of the case study. The results show an annual energy demand of 2354 kWh/year for heating and 474 kWh/year for cooling, which accounts for an annual energy demand of 2828 kWh/year. These value corresponds to a demand per conditioned area of:

Table 5. Annual energy demand of the case study.

Cooling demand [kWh/m2]	Heating demand [kWh/m2]	Total demand [kWh/m2]
18.96	94.15	113.11

5. CONCLUSIONS

This research work aims to raise concern among the scientific community and professionals of the construction sector about the straw-bale construction as an alternative to conventional materials. To this purpose, a state of the art with the advantages and disadvantages of this type of construction has been performed. Furthermore, a calibrated straw-bale building model with actual measurements has been presented. The model will serve to compare the straw-bale building with conventional construction energy performance as well as LCA in future studies.

The state of the art study concludes with big advantages of straw-bale construction. It allows to build with the highest energy performance standards and with a very low embodied energy compared with conventional high-efficiency construction. The literature shows evidence of the benefits to include the straw-bale in the construction sector and replace the conventional materials currently used. Little are the disadvantages shown and they can be solved with a good design and proper attention in the construction and detailing. Thus, straw-bale construction shows as an alternative to substitute conventional materials in the way to EU 2050 strategy of decarbonization. Finally, the model has been calibrated according to ASHRAE requirements and is ready for future studies.

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