Eco-sustainability and energy performance of a straw house

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***Abstract*—Together with Maisonéco, a modular system has been developed to present a solution combining eco-sustainability with versatility, low-costs and very rapid construction times. The first module, built in 2014 in the northern part of Italy, consists in about 30 m^2 of housing module with a wooden structure and a thermal insulating panel made by compact straw with parallel fibers. The monitoring and data collection system was designed and implemented by the Institute of Technical and Professional Education - LyTechPro of Verrès (AO) within the Projet Energie, an educational project funded by CVA S.p.A., a leading production company for electricity from renewable sources owned by the Aosta Valley Autonomous Region. In this work, the experimental measurements are presented for two years, evaluating the energy performance of the straw house during the heating and cooling seasons with the indoor and outdoor thermo-hygrometric conditions. Straw does not have the best performance compared with standard insulating materials but, considering a greater thinness of the block, may reach higher levels of thermal insulation. From an environmental point of view, straw can be used in green building as it is a degradable material, its production derives by agricultural waste with low environmental impact as does not requires industrial process. Moreover, its recycling could also be exploited by agricultural sector to expand the market and thus become suppliers of straw also for the construction sector. Finally, straw characteristics are also combined with low costs, as waste material, with 2.5-3.5 euros per block or 1,000-1,400 euros per 150 m^2 building.**

Keywords — green house; straw envelope; measurement campaign; thermal transmittance; dynamic characteristics.

I. Introduction

Buildings with very low energy consumption or nearly Zero Energy Buildings (nZEB), as we know them today, were hypothesized for the first time after the energy crises in the '70s and '80s. Only recently, concrete actions have been developed and promoted to reduce energy consumption and greenhouse gas emissions and the first nZEBs were built with the technologies available on the market.

The term nZEB (nearly Zero Energy Building) indicates building with very high energy performance considering two concepts together: low energy consumption and the use of renewable sources with low emissions technologies [1]. The nZEB was mentioned in a package of European Directives defined by the acronym EPBD (Energy Performance Building Directions) in 2010 and it was remarked also in future European strategies in terms of sustainable development, inviting state members to introduce regulations to improve the energy buildings' performance. Of particular interest is the article 9 of EPBD 31/2010, which established that all new buildings will be nZEB starting from January 2021, while for public buildings the deadline is January 2019. The same article indicates that state members should give a national definition of nZEBs.

Therefore, referring to the Italian legislation from the Decree 192/2005 (successively integrated and amended by others Decrees and Laws) the requirements on buildings energy performance with energy efficiency measures and renewable energy sources have increased a lot. In particular, in the Italian National Guidelines for the Energy Certification of Buildings (Decree June 26th 2015) the nZEB is defined as a building that meets all the minimum requirements in force and complies with the obligation to use renewable energy sources as prescribed by Decree n. 28 of March 3rd 2011.

A. Buildings requirements in Italy

Referring to Italian buildings requirements, the following prescriptions are reported:

Winter performance. Maximum values of:

- Thermal transmittance for the envelope structures of the building (U_{max} in Table I).
- Thermal exchange coefficient of the heat transmission through the envelope ($H'_{T,max}$ in Table II).

TABLE I. Thermal transmittance limits [W/m^2/K]

Envelope element	U_{max} for the Italian climatic zones				
	A/B	***C***	***D***	***E***	***F***
Window	3.00	2.20	1.80	1.40	1.10
Wall	0.43	0.34	0.29	0.26	0.24
Floor	0.44	0.38	0.29	0.26	0.24
Roof	0.35	0.33	0.26	0.22	0.20

TABLE II. Thermal exchange coefficient H'T [W/m^2/K]

Surface to volume ratio S/V [m^{-1}]	$H'_{T,max}$ for the Italian climatic zones				
	A/B	***C***	***D***	***E***	***F***
$S/V \geq 0.7$	0.58	0.55	0.53	0.50	0.48
$0.7 > S/V \geq 0.4$	0.63	0.60	0.58	0.55	0.53
$0.4 > S/V$	0.80	0.80	0.80	0.75	0.70

Summer performance. For opaque envelope structures:

- Surface mass Ms > 230 Kg/m^2.
- Periodic thermal transmittance Y_{IE} of the opaque structures of the building envelope: <0.10 W/m^2/K for walls; <0.18 W/m^2/K for roofs; <0.14 W/m^2/K for a good summer performance.
- For the transparent envelope: Equivalent summer solar area per unit of floor net surface $A_{sol,c}/A$: < 0.03.

Global energy performance. Maximum values of:

- Energy performance index useful to evaluate the space heating energy demand ($EP_{h,nd}$ in kWh/m^2/y).
- Technological system efficiencies.
- Global energy performance $EP_{gl,tot}$ (kW/m^2/y) in primary energy considering space heating, space

cooling and hot water production (for residential buildings).

B. Buildings requirements in Valle d'Aosta Region

Valle d'Aosta Region is a small mountain territory in North-West part of Italy that has always been very attentive to eco-sustainability and the environment problems.

In the resolution of the Regional Council n. 272 of February 26th 2016, the national laws have been implemented but in Valle d'Aosta Region there are many other initiatives to promote new low emissions technologies. The Regional Law of January 3rd 2006 regulates the procedures aimed to approve environmental energy planning instruments and to promote the implementation of these initiatives. In order to diversify the energy sources and to make the use of conventional sources more efficient and rational, while reducing greenhouse gas (GHG) emissions and climate changes, the region tried to develop:

a) Technologies allowing energy savings, both in stationary and light-mobility applications.
b) Demonstrative facilities and specialized teaching activities.
c) Initiatives aimed at evaluating the energy performance of buildings and planning effective interventions to increase energy efficiency.

The Maisonéco project is part of the demonstration, pilot and experimental equipment activities regulated by Article 6 of the Regional Law. In order to achieve the energy objectives, the region promotes, with the Observation and Activity Center on Energy (COA), the realization of demonstration module with high-energy efficiency, and specific low energy consumptions. The Valle d'Aosta Region grants facilities to local authorities and to private entities for the reimbursement of expenses incurred, up to a maximum of 70 % of the eligible costs documented.

The straw house project, presented in this work, has been realized within the Institute of Technical and Professional Education - LyTechPro of Verrès (AO), ISITP Verres, implementing an automation experimental system for measurement campaigns as a specialized teaching laboratory.

II. STATE OF ART

Human has always tried to use all the materials that are reliable and easy to obtain from the territory for the construction of his home. Straw is one of the oldest building materials used commonly in combination with mud. As evidence of this, there are remains of houses built all over the world: in Germany, there are records of houses with more than 500 years that are still in use, with more than 200 years in England where the technique of combining straw and mud is known as "cob", "cobb" or "clom" [2].

The origin of the house built exclusively with straw blocks is not so ancient; this is due to the fact that the machinery used to pack the straw was invented only in the mid-nineteenth century. The first packer was invented in the United States in 1850 and was totally manual. Later in 1875 a horse-drawn one was created and finally, in 1884, the machine with a steam driven engine [3].

The first documented house built entirely of blocks of straw is located in the plains of Nebraska, built in 1896 by European colonizers [4]. The oldest house still in use today is the home of G. P. Bruñe, built in 1903 [5].

In Europe the first straw houses date back to the early twentieth century and the oldest known house was built in Montargis, France in 1921 [6]. In early 1940s, because of the 2nd World War and the pressures of concrete and steel enterprises, this bio-construction technique fell into disuse.

Only in 1960s, alternative movements in the new Californian architecture gave rise to the first adaptations of the bio-construction with straw. The renaissance of straw buildings began in 1973 with an article written by Roger Welsch for the book "Outside house" [7].

In Québec, Canada, F. Tanguay (inspired by the article by R. Welsch) designed a thatched roof and realized that the same construction system could be used also for the walls of the house. Therefore, in 1981, he built a house of planks and beams filled with blocks of straw in Québec [2].

In 1982, the "Canada Mortgage and Housing Corporation" financed the "Housing technology incentives program" to demonstrate how a system of straw and mortar blocks could be used for the construction of load-bearing walls for residential buildings [8]. In Québec, L, G. de Huli developed a system of walls called a "matrix system" that provided a wall of straw blocks stacked in columns with mortar joints. This wall methodology has been tested and its resistance was verified to: heat dispersions, perforation and moisture condensation.

In 1987 the method of straw construction in the United States was officially resumed. D. Bainbridge published an article on the construction of straw blocks influencing many builders [9]. In 1991, the first book on straw construction was published by S.O. Macdonald [10] and the association "Out on a Bale" was born with the magazine "The Last Straw", both dedicated to straw buildings. In September 1993 took place in Nebraska, the first conference on buildings with straw blocks, "Roots and Rebirth", to which fifty architects, builders and designers attended. In 1993 in Canada, K. Thompson built a straw-building with load-bearing walls that included 7 blocks for the first floor, 3 for the second and a cathedral roof [10]. This structure is of great importance, as the building is built in an area subject to relatively high loads of snow and humidity.

In 1994 in Russia, S. Pittman and B. Mollison, built a straw bale workshop on a collective farm with a wooden structure using straw as thermal insulation [10].

In Europe there is the association "European Straw Bale Network", which was founded in 1998 and which organizes meetings every two years, to share experiences and collectively build with straw bales [11]. Finally, many studies concerning energy, environmental and economic performance of straw buildings are still underway [12, 13].

III. THE CASE STUDY

In 2014, Maisonéco and "Abito Paglia" construction companies (http://abitopaglia.it/), built a residential unit of about 20 m^2, designed with a wood and straw structure. It was presented at the fair "Maison et loisir" in Aosta (Italy) to publicize this type of construction, disseminating principles of environmental sustainability and promoting the use of straw as insulating material (Figs. 1 and 2). To combine eco-sustainability with versatility, a modular system was developed to guarantee very rapid construction times with a resistant and insulated structure; in detail, the supporting part of the construction was made by solid wood, while the insulating part was made by compact straw with fibers parallel to the walls surfaces to ensure a better thermal insulation (Fig. 3).

The structure was assembled on wooden beams that fit perfectly with the straw modules, forming a very compact structure and minimizing the structural thermal bridges. In addition to the basic modules, there were other types of modules that allow to insert windows and doors of various sizes. In the final phase, a wooden external skin was added to create an air gap around the housing module. The roof was realized with a flat structure formed by an impermeable layer covered with gravel.

In detail, the straw walls stratigraphy was composed by (from outside to inside):

- Wooden external skin with 2 cm of wood panels;
- Ventilated air gap with a thickness of 4 cm;
- Oriented Strand Board (OSB) panel of 3 cm;
- Straw compressed by the Maisonéco with filaments parallel to the walls with a total thickness of 0.37 cm;
- Steam barrier;
- OSB panel with a thickness of 3 cm.

Fig. 1. Housing module assembly.

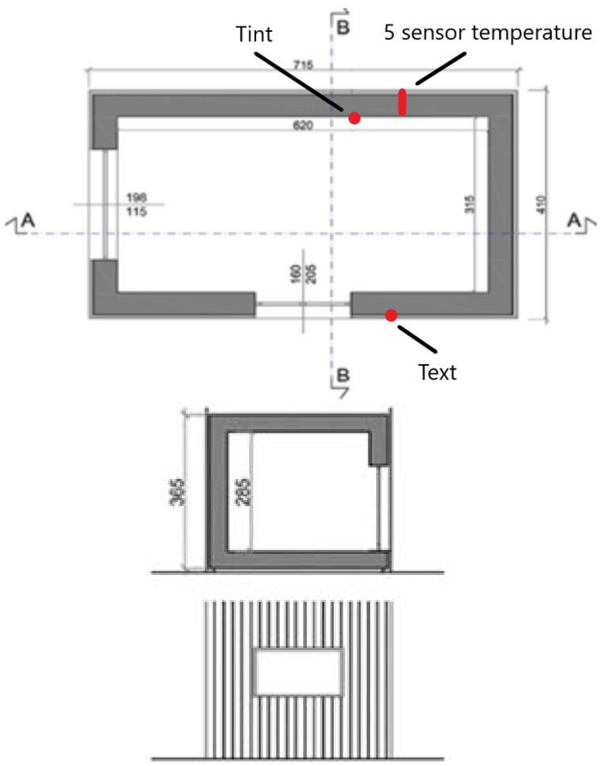

Fig. 2. Planimetry, vertical section B-B and the prospectus with the window of the straw house.

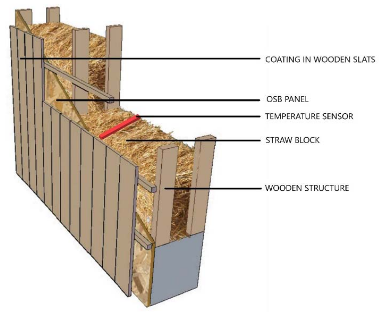

Fig. 3. Wooden straw structure of walls and temperature sensors.

IV. EXPERIMENTAL CAMPAIGN

The ISTP Institute of Verres has developed an automatic measurement system that uses the Arduino platform (https://www.arduino.cc/en/Main/Products). In the experimental campaign, more sensors have been implemented to analyse the thermal behavior and the energy consumption of the house module.

The first version of the system had 2 sensors that monitor air temperature and relative humidity of the indoor and outdoor environments. A thermal imaging camera was used to localize the inside sensor at 1.5 m from the ground and far from thermal bridges.

In a second phase, a heating system, made by an electric heater with a power of 826 W and controlled entirely by an Arduino platform, was added to maintain a constant internal air temperature at 20 °C. This system could record each on/off switch of the heating system. Moreover, 5 temperature sensors were positioned above a rod that crosses the straw-wall to study the distribution of temperatures inside the straw. The characteristics of the sensors used are described in Table III.

TABLE III. SENSORS USED IN THE EXPERIMENTAL CAMPAIGN

Parameter	Sensor	Range	Accuracy
Air temperature	DHT22/AM2302	-40 to 80 °C	0.5 °C
	DS18B20	-55 to 125 °C	0.5 °C from -10 to 85 °C
Air relative humidity	DHT22/AM2302	0 to 100%	2% RH

V. METHODOLOGY

The Italian legislation [D.M. 26/6/15] introduces new criteria for calculating the energy performance and requirements of buildings as required by European Directive EPBD 2010/31/CE. This Italian Decree can be applied in new but also in existing buildings when an energy retrofit is requested, and for high performance buildings as the "nearly zero energy buildings" (nZEB). It must be remembered that in Italy from 2021 new buildings will have to be nZEB and for public buildings this date is anticipated to 2019.

The energy performance considers non only energy consumption for space heating and hot water production but also energy-use for space cooling, lighting systems and energy for the transport of things or people (as the elevators).

In this work an experimental campaign was carried out localizing the straw house near the ISTP Institute of Verres (AO) in Italian climatic zone “E”. The energy performance of the straw house module was evaluated through the measure of the energy consumed for space heating with also measurements of the thermal transmittance of the straw structures. In summertime, space cooling was not necessary above all with a type of structure like the one analyzed.

A. *Thermal transmittances measurements*

The thermal transmittance U was measured according to the Standard ISO 9869-1:2014. To measure the U-value, one heat flow meter with four temperatures probes on both sides of the straw wall are needed. The problem of in-situ measurements is the not steady-state environment condition, then instantaneous measurements are not possible. Standard ISO 9869-1:2014 provides several methods to solve this problem and in this work "the average method" was used. This method allows to measure the thermal resistance, R, and thermal conductance, C, from the inside to the external surface of the straw wall. In steady-state conditions, the thermal resistance R can be defied by the ratio between the surface temperature difference (Tsi - Tso) and the specific heat flux q:

$$R = 1/C = (Tsi - Tso)/q \tag{1}$$

where:

- R is the thermal resistance of wall layers, m^2KW^{-1}
- C is the conductance, $Wm^{-2}K^{-1}$
- Ts is surface temperature (i-inside, o-outside), °C
- Q is the specific heat flux, Wm^{-2}.

The thermal transmittance U of the wall, from the indoor air to the outdoor air, is given by:

$$U = 1/Rtot = q/(Ti - To) \tag{2}$$

with the total thermal resistance of the straw wall:

$$Rtot = Rsi + R + Rso \tag{3}$$

where:

- Rtot is the thermal resistance of the wall m^2KW^{-1}
- T is the air temperature of the environment (i-inside, o-outside), °C
- Rs is the surface resistance of the laminar air layer (i-inside, o-outside) m^2KW^{-1}.

In situ, the conductance of a wall can be calculated by using its average values calculated in all the previous instants of flux and temperatures, instead of the instant values (average method described in ISO 9869-1:2014). The average values of thermal flux and surface temperatures differences consent to evaluate the average conductance. The graph of the average conductance shows that the average value of C converges after a certain period of time.

$$C = \sum q / \sum(T_{si} - T_{so}) = 1/R. \tag{4}$$

In situ, with the average method, the measurement period must be at least 72 hours if the temperatures are stable and with differences of temperatures greater than 10 °C; otherwise it can be also up to 7 days. Time intervals for measurements are of 15-30 minutes and with light elements, measurements should be carried out during nighttime to avoid the effect of solar radiation.

With this method, the thermal transmittance U was obtained from the conductance (C=1/R) by adding the contribution of inside and outside surface resistances (eq. 3).

B. *Winter energy performance*

The winter energy performance of the straw house was evaluated with the comparison of:

- space heating consumption of the electric heater considering the external weather conditions;
- global average heat exchange coefficient for transmission H'_T with its limit value according to the climatic zone of the site and the S/V of the building.

H'_T ($Wm^{-2}K^{-1}$) is an average thermal transmittance:

$$H'_T = H_{tr,\,adj} / \sum_k A_k \tag{5}$$

where $\sum_k A_k$ is the sum of the heat dispersant surfaces (in m^2) of the opaque and transparent envelope, while $H_{tr,adj}$ is the global heat exchange coefficient for transmission of the envelope (in W/K), calculated according to UNI TS 11300-1 considering also the thermal bridges and the heat exchange towards the ground.

C. *Summer energy performance*

According to the new regulations, there are limits also about the energy consumptions for summer space cooling. The summer energy performance of the straw house was evaluated by the estimation of:

- the surface mass of the straw structures
- the periodic thermal transmittance Y_{IE} of the straw structures calculated with UNI EN ISO 13786:2018 and measured with the experimental campaign.

VI. RESULTS AND DISCUSSION

The first experimental campaign was made to evaluate the thermal transmittance of the straw wall. Due to limited availability of experimental equipment and housing module, these measurements were conducted during spring and summer 2017. The average method with a heat flow meter and surface temperature sensors was adopted to measure the conductance of the straw wall with a result of C = 0.45 $W/m^2/K$. In Fig. 4 the data about surface temperatures and heat flux are presented with the resulting conductance. As it is possible to observe, the surface temperatures are stable with differences of about 15.73 °C and the average heat flux is of 6.75 W/m^2.

Then, considering the ventilated air gap, a thermal transmittance of the straw wall was calculated and is equal to 0.43 $W/m^2/K$ and then a conductibility of the straw equal to 0.21 W/m/K. This value was also confirmed by the measurements in springtime. With this result, the thermal transmittance of the straw wall is higher than the standards limits (Table I), then straw bales would be needed with greater thickness (up to 68 cm) or alternatively a straw with less conductivity (0.11 W/m/K).

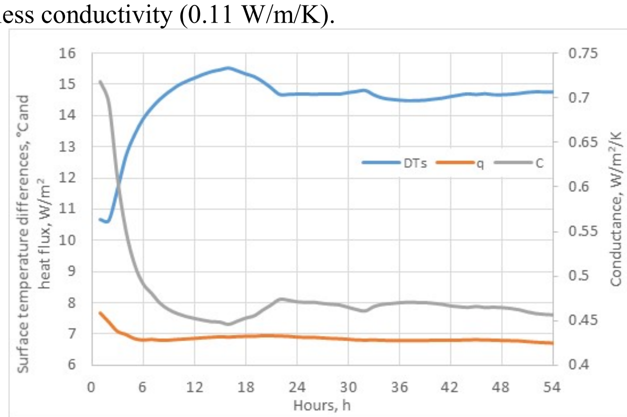

Fig. 4. Average method results of sufaces temperature difference DT (°C), specific heat flux q (W/m^2) and conductance C ($W/m^2/K$).

More measurements, from May 2016 to February 2017, have been made with five more temperature sensors inside the straw wall at different depths to measure the dynamic thermal characteristics of the straw wall. Measurements have been elaborated to calculate sinusoidal variations of straw temperatures T as function of time t with equation [14, 15]:

$$T(t) = T_{avg} + |\Delta T| \cdot \cos(\omega \cdot t + \psi) \tag{6}$$

T_{avg} = average value of temperature, °C

|ΔT| = amplitude of temperature, °C
ω = angular frequency (2π/24, with a time period of 24 h)
t = time, h
ψ = initial phase, h.

In Figs. 5 and 6 the temperature trends inside the straw wall are represented by the dot lines respectively in June and in January with a decrement factor of 0.11-0.12 and a time shift of the periodic thermal transmittance of 19-21 h.

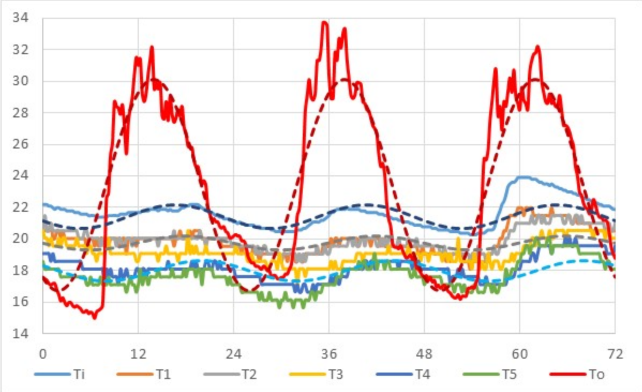

Fig. 5. Experimental campaign in May 2016: measured temperatures inside the straw wall (T1-T5) and calculated sinusoidal variations of temperatures with the dot lines (°C).

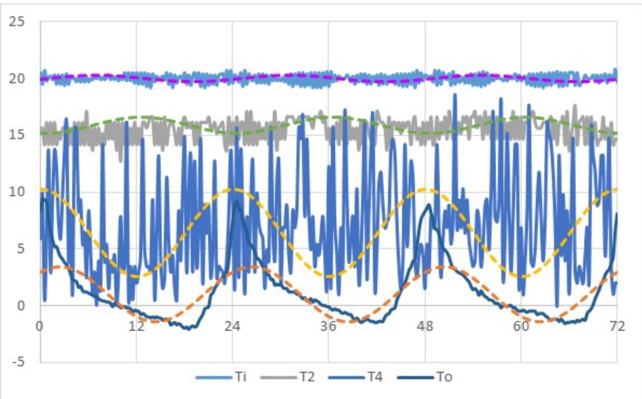

Fig. 6. Experimental campaign in February 2017: measured temperatures inside the straw wall (T1-T5) and calculated sinusoidal variations of temperatures with the dot lines (°C).

Dynamic characteristics of the straw wall were also calculated according to UNI EN ISO 13786:2018 considering a conductivity of the straw of 0.21 W/m/K obtaining a decrement factor of 0.08 and a time shift of the periodic thermal transmittance of 17 h. To obtain a time shift of 21 h, a straw conductivity of 0.13-0.16 W/m/K should be entered, then more measurements should be done especially in wintertime with the heat flux meter to measure with more accuracy the thermal conductivity of the straw. The temperature of the inside environment is quite constant with average air temperature that varies between 20.0 in wintertime and 21.7 °C in summertime but the relative outside temperatures are of about 1.3 and 23.4 °C; this again testifies to the good thermal inertia of the straw wall.

Also the relative humidity has been measured in the indoor and outdoor environments showing a very good attenuation of the humidity in the inside environment (Figs. 7 and 8):

- in wintertime: with values of 0.25-0.26 with external values very variable between 0.10 and 0.48 and
- in summertime: with values of 0.37-0.39 with external values very variable between 0.45 and 0.90.

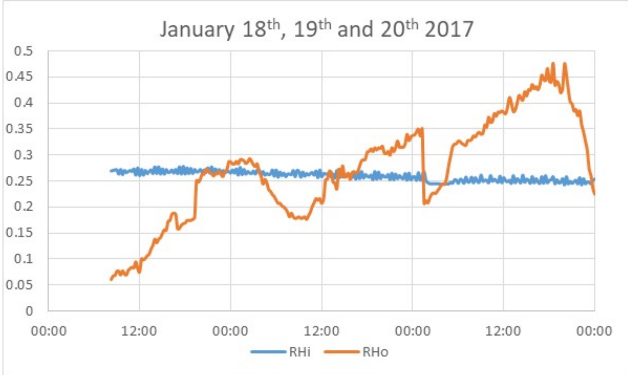

Fig. 7. Experimental campaign in January 2017: measured relative humidity in the inside (i) and outside (o) environments.

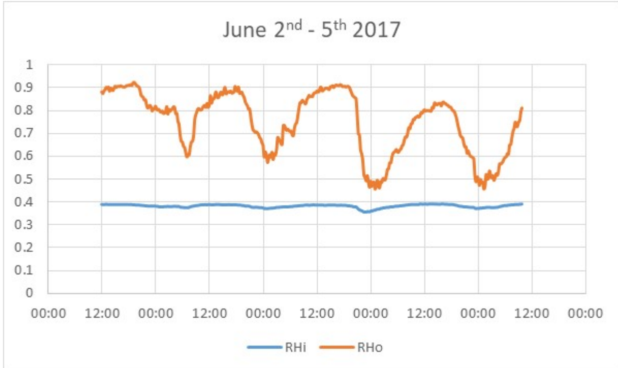

Fig. 8. Experimental campaign in June 2017: measured relative humidity in the inside (i) and outside (o) environments.

Considering the hours of functioning of the electric heater (with a power of 826 W), the energy consumption for space heating was evaluated. As reported in Fig. 9, the daily energy consumption (in December 2016) depends mainly by the air differences between inside and outside environments.

Fig. 9. Daily energy consumption of the electric heater in December 2016 with the temperature differences between inside and outside environments (in orange, °C).

The whole measurement campaign from December 1st 2016 to February 17th 2017 was also used to estimate the heat dispersions by transmission and therefore indirectly the conductivity of the straw. For this evaluation, in order to be able to neglect the solar contributions, only the nocturnal measures were considered; internal gains were absent and a negligible ventilation was considered. Then all the consumption of the electric heater is due to transmission losses and therefore, knowing the average power of the heater W and the dispersing surface (A = 140.76 m^2), it is possible to estimate an average thermal transmittance U of the envelope:

$$W = U \cdot A \cdot DT. \quad (7)$$

In Fig. 10 the evaluation of the average thermal transmittance of the envelope is represented with an average value of 0.17 W/m^2/K. Considering the geometrical characteristics, the thermal transmittance of the different components of the envelope and the linear thermal bridges, the straw conductivity was estimated equal to 0.08 W/m/K. This value, very closed to the values found in literature [12, 13], underlines once again the need for additional thermal transmittance measurements especially in wintertime.

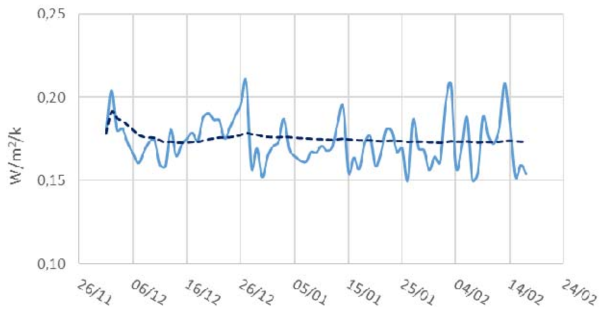

Fig. 10. Simplified method to evaluate the average thermal transmittance of the building envelope by the energy consumption of the electric heater.

TABLE IV. CHARACTERISTICS OF THE VERTICAL STRAW WALL

Wall stratigraphy	Depth. cm	Density. kg/m3	Specific heat. J/Kg/K	Thermal conductivity. W/m/K
OSB Panel	3	650	1700	0.13
Straw	37	340	1900	0.21
OSB Panel	3	650	1700	0.13
Vapor barrier	0.2	110	1800	0.40

Ms = 165 kg/m^2 and Y_{IE} = 0.03 W/m^2/K

TABLE V. CHARACTERISTICS OF THE STRAW ROOF

Roof stratigraphy	Depth. cm	Density. kg/m3	Specific heat. J/Kg/K	Thermal conductivity. W/m/K
Plywood	2	630	1700	0.14
Air gap (n.v.)	5	1	1000	-
OSB Panel	3	650	1700	0.13
Straw	37	340	1900	0.21
OSB Panel	3	650	1700	0.13
Vapour barrier	0.2	110	1800	0.40

Ms = 178 kg/m^2 and Y_{IE} = 0.02 W/m^2/K

TABLE VI. CHARACTERISTICS OF THE STRAW SLAB (WITH A VENTILATED AIR GAP BELOW)

Slab stratigraphy	Depth, cm	Density, kg/m3	Specific heat, J/Kg/K	Thermal conductivity, W/m/K
Wood	2	550	2700	0.14
OSB Panel	3	650	1700	0.13
Straw	37	340	1900	0.21
OSB Panel	3	650	1700	0.13
Vapour barrier	0.2	110	1800	0.40

Ms = 178 kg/m^2 and Y_{IE} = 0.02 W/m^2/K.

Finally, the characteristics of vertical walls and roof with the straw bale were calculated to evaluate also the summer behavior of the structure of the house module with the surface mass Ms and the periodic thermal transmittance Y_{IE}. Tables IV, V and VI show that the surface mass of the structure is lower than the Standard limit of 230 kg/m^2 but the periodic thermal transmittance is much lower than the limits Y_{IE} of 0.10 and 0.18 W/m^2/K.

VII. CONCLUSIONS

The study conducted demonstrate that the straw is a valid thermal insulating material with low environmental impact.

From the point of view of energy consumptions, straw does not have the best performances on the market, but using thicknesses greater than the block size can reach the levels of standard insulation materials. Therefore, straw could be a valid option for building new bio-houses, if it is possible to have the necessary space to make an envelope of this type; it cannot be a valid option for buildings renovations.

From an environmental point of view, straw can be used in green building as it is a degradable material and its production does not require industrial processing. Its recycling could be exploited also by the agricultural sector becoming the main suppliers of this natural technology for the construction of new bio-houses.

From the economic point of view, the bales of straw are a low cost technology because straw is a waste material. More specifically, it has costs that range from 2.5 to 3.5 euros per block and, considering that 400 blocks are needed for a 150 m^2 house, it is possible to obtain a raw material cost of about 1000-1400 euros.

The straw module has shown excellent characteristics not only of thermal insulation but also of thermal inertia and of relative humidity regulator. This module will be used as a demonstration example and further measurement campaigns will still be conducted in the coming winter season to verify its real livability characteristics.

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