Straw Bale Houses in a Moderate Climate
Adaptable to meet future energy performance requirements?

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ABSTRACT: The energy performance regulations for buildings, introduced in many countries during the last decade, will be tightened in the future, even up to zero energy level. Apart from that, ancient building techniques that use renewable materials, such as straw bales, have a revival, inspired by concerns about the environmental impact of building materials. However, straw bale construction related organisations are concerned whether this building technique will survive the upcoming severe energy performance requirements. In this frame, two recently built straw bale houses in Belgium have been analysed through a post-occupancy evaluation to determine their current performance for energy, comfort and indoor air quality. Furthermore, the possibilities to improve these houses to meet future energy performance regulations have been investigated. The different steps in the strengthening of the energy performance regulation towards 2021 set by the Flemish government are used as reference points. Different scenarios for improvement have been proposed to meet the future energy performance regulations, taking into account the lower insulation quality of straw bales and the higher risk for summer overheating in these lightweight houses.
Keywords: energy performance, zero energy, straw bale, post-occupancy evaluation, summer comfort, trias energetica

INTRODUCTION
The challenges of climate change and the exhaustibility of fossil fuels made governments all over the world introduce energy performance regulations. These regulations will be tightened in the future, as is already the case with the recast of the EU Energy Performance of Buildings Directive (EPBD) that aims for near zero energy houses by 2021 [1]. Apart from that, ancient building techniques that use renewable materials as building materials, have a revival, inspired by concerns about the environmental impact of common building materials. Straw bale building construction is such an ancient technique that is now rediscovered and promoted as a sustainable way of building construction, since it is not only a renewable material, but it also grows close to the construction site, thus avoiding large transportation distances. However, due to the differences in insulation quality between straw bales and more common insulation materials [2], organizations that promote straw bale construction are concerned whether this building technique will be able to survive the upcoming severe energy performance requirements.

In this frame, a twofold analysis has been performed on two recently built detached straw bale houses in Flanders, Belgium: (1) calculations and measurements have been executed on energy consumption, thermal comfort and indoor air quality (IAQ) in order to assess the current situation and (2) theoretical simulations have been executed to investigate to which extent future requirements can be met and which additional measures are needed to achieve these requirements. Subsequent energy saving measures are based on the concept of the Trias Energetica [3]. The pathway towards 2021 for insulation level and energy performance level, as set by the Flemish government [4], is used as reference for the future requirements.

To remain within the imposed limits of this paper, the results for only one straw bale house are presented, but the observations and conclusions were similar for both analyzed houses. First the straw bale house is described as well as the monitoring campaign and the calculation method. Then, the current and future requirements of the Flemish energy performance regulation are presented together with the different scenarios for subsequent energy saving steps that have been simulated to meet the future requirements. Subsequently, the main results are presented and discussed. Finally, conclusions are given.

METHODOLOGY
Description of the straw bale house
The straw bale house is located in the province of Limburg, Belgium, near the border with the Netherlands and Germany. Table 1 gives the main characteristics of the current situation of the dwelling.

Table 1: Main characteristics of the straw bale house

Construction year	2007-2009
Typology	detached
Volume	698m³
Usable floor area	213m²
Heat loss area	604m²
Glass area	45.3m² (of which 21m² south)
Solar shading	fixed horizontal canopy
U roof	0.15 W/m²K
U wall	0.13 W/m²K
U floor	0.26 W/m²K
U window / U profile	0.70 W/m²K / 2.0 W/m²K
Overall U mean	0.26 W/m²K
Heating system	condensing boiler on natural gas floor heating
Domestic hot water	storage tank on the condensing boiler
Ventilation system	natural ventilation with ventilation grids in the windows
Renewable energy	none

Monitoring campaign

In the dwelling, the indoor and outdoor climate have been monitored from January 15th 2011 until November 4th 2011: temperature and relative humidity every 15 minutes for the outdoor climate and in the living room and two bedrooms and CO_2 concentration every 10 minutes in the living room and the master bedroom. The energy consumption of natural gas and electricity has been noted by the occupants from January 16th 2011 until January 22nd 2012 on a weekly basis.

Calculations of energy and comfort

The Flemish version of the EPBD consists of a calculation method for the insulation level and for the overall energy performance level and a simplified assessment method for summer comfort.

The insulation level (called K-level) is calculated based on the overall mean U-value of the building envelope (roofs, walls, floors, windows) and the compactness of the building, being the ratio of heated volume and total heat loss area. The lower the K-level, the better insulated is the dwelling. Currently the legal requirement is K40, representing a maximum overall mean U-value of 0.4W/m²K for a building with compactness of 1m.

The energy performance level is based on the primary energy consumption for heating and domestic hot water, calculated according to EN ISO 13790(2004). For heating, a steady state monthly based one-zone model is used that takes into account the insulation quality of the building envelope, useful internal and solar gains, performance of ventilation and heating system, auxiliary electricity consumption for pumps and fans, and presence of renewable energy systems. The average indoor temperature is 18°C for heating and the outdoor climate is the Test Reference Year of Brussels, Belgium. For domestic hot water, the volume of hot water used is based on the building volume and the energy consumption for domestic hot water depends on the heat production system, presence of a storage tank and solar collectors, and length of pipes. The overall primary energy consumption for the dwelling is the sum of the primary energy consumption for heating, cooling, domestic hot water and auxiliary energy minus the in situ renewable energy production. The overall energy performance level (called E-level) is calculated as the ratio of the yearly primary energy consumption, as calculated above, and the yearly primary energy consumption of a reference building with the same heated volume and same heat loss area. Currently the legal requirement is a maximum E-level E70, representing a maximum of 70% of the primary energy consumption of the reference building.

The risk for summer overheating is assessed through the overheating indicator. The indicator is based on the yearly surplus heat gains, depending on the overall monthly heat gains, thermal capacity of the building and the monthly proportion of heat losses to heat gains. For the overheating indicator a threshold value and a maximum value are set. Below the threshold, no summer overheating is expected, whereas above the maximum value, the summer comfort is assessed as unacceptable and the design needs to be revised. Between threshold and maximum, a risk for summer overheating is assumed, linearly depending on the distance to the threshold value. This risk represents the risk that the occupant will install an active cooling system afterwards, thus increasing the energy consumption significantly. Therefore, a fictitious energy consumption for cooling is included in the overall primary energy consumption, depending on this risk for overheating. This can influence the final E-level negatively, even without a real cooling system being installed.

Current and future requirements of the Flemish energy performance regulation

The Flemish EPBD imposes legal requirements for insulation, net heat demand, energy performance, ventilation and summer comfort. Since the introduction of the EPBD in 2006, requirements systematically have been strengthened and this will continue, as the recast of the EU EPBD obliges EU Member States to aim for near zero energy buildings by 2021. Table 2 gives the evolution of the legal requirements until 2021 as set by the Flemish government up to now. Not all details are already available on how exactly 'near zero energy' should be defined and realized, but the main steps are known. Since no specific changes are foreseen up to now for the requirements on ventilation and summer comfort, these are not mentioned in table 2. Also the tightening of the requirements in 2010 and 2011 is not described in table 2, as the focus is on the future requirements. Since January 2012, a new legal requirement has been introduced, being a maximum net heat demand per m² floor area. Up to now no further information on the strengthening of this requirement is available, but as will be discussed further, this parameter will be crucial in the analysis whether straw bale houses will be able to meet the future requirements. Therefore the thresholds of 30kWh/m².a and 15kWh/m².a are used, as a maximum net heat demand of 15kWh/m².a is an official requirement for passive house certification and 30kWh/m².a has been used by the Belgian government as the requirement for low energy houses in the frame of tax deduction.

Table 2: Evolution of the legal requirements of the Flemish EPBD

Characteristics	2006	2012	2014	2021
Maximum U-value				
Roof (W/m²K)	0.40	0.27	0.24	*0.15?*
Façade (W/m²K)	0.60	0.32	0.24	*0.15?*
Floor (W/m²K)	0.40	0.35	0.30	*0.15?*
Window (W/m²K)	2.5	2.2	1.8	*1.0?*
Glazing (W/m²K)	1.6	1.3	1.1	*0.6?*
Insulation level K (-)	K45	K40[1]	K40	*K15-20?*
Energy performance level E (-)	E100	E70	E60	*E0?*
Net heat demand (kWh/m².a)	-	<70	?	*<15 or <30?*

[1] from 2011 on, the impact of thermal bridges is included in the calculation of the K-level

Subsequent steps to meet the future requirements

A first concern for the Flemish straw bale construction related organisations is the thermal conductivity (λ-value W/mK) of straw bales. Common insulation materials, like mineral wool or polyurethane are factory-manufactured and have certified λ-values, whereas straw bales used for building construction in Flanders are often purchased from local farmers. In order to take the uncertainty on product quality into account, the Flemish government only accepts a λ-value for straw bales of 0.08W/mK [5], although other sources mention a λ-value of 0.045-0.80W/mK depending on moisture content, direction of straw blades and production quality [6-8]. Therefore a first series of calculations has been made to investigate the impact of the λ-value for straw bales on K-level, E-level, net heat demand and primary energy demand. For the dwelling, calculations have been made for a λ-value of 0.045W/mK, 0.06W/mK and 0.08W/mK.

In a second series of calculations, different subsequent energy saving measures have been simulated for the dwelling with the Flemish EPBD calculation method to analyze the ease by which future requirements could be met. The choice of order for the subsequent steps has been based on the concept of Trias Energetica, consisting of 3 principles [3]: (1) reduce the net energy demand by minimizing heat losses and optimizing heat gains, (2) use a maximum of renewable energy to cover the net energy demand, and (3) in case fossil fuels are still needed, use them in an efficient and effective way.

The original situation of the dwelling has been used as starting point and the subsequent energy saving measures can be grouped as follows:

- Measures to increase the insulation level and to decrease the risk for summer overheating: passive house windows (Uglazing = 0.7W/m²K, Uframe = 0,8W/m²K), movable solar shading, extra (conventional) insulation.
- Measures on air tightness and ventilation: the default infiltration rate in the Flemish EPBD is 12m³/h per m² heat loss area at 50Pa and two extra levels have been calculated: 3m³/h.m² and 1m³/h;m³. Also use of an exhaust ventilation system and of a balanced ventilation system with heat recovery of 85% efficiency has been simulated.
- Measures on heating system and renewable energy systems: impact of a soil/water heat pump (SPF=4,53), use of 4m² flat plate solar collector for domestic hot water and photovoltaic (PV) panels for electricity production. Peak power of the PV panels has been determined in order to achieve near zero energy level (E ≈ 0).

RESULTS

Current situation

In table 3 the results of the monitoring campaign of the indoor climate are presented for the winter period (15/1 - 31/3 and 1/10 - 4/11) and the summer period (1/4 -30/9):

mean temperature, standard deviation and minimum and maximum temperature for outside, living room and two sleeping rooms. Slp1 is the master bedroom and south oriented, whereas slp2 is a children's bedroom and north oriented. In this table also the percentage of time the temperature is below, within or above the comfort zone of 20-26°C is presented.

Table 3: Monitored outdoor and indoor climate

Dwelling	outdoor	living	slp1	slp2
Winter period: Jan 15th – March 31st / Oct 1st – Nov 4th				
Mean temp	9,6	21,3	19,7	14,7
Stand.dev.	4,9	1,3	2,1	2,7
Min.temp	-2,4	18,3	13,3	8,2
Max.temp.	26,3	26,7	25,2	22,9
% <20°C	99%	15%	65%	95%
% 20 – 26°C	1%	85%	35%	5%
% >26°C	0%	0%	0%	0%
Summer period: April 1st – Sept 30th				
Mean temp	17,9	23,7	22,7	20,5
Stand.dev.	6,1	1,8	2,3	3,8
Min.temp	5,8	20,6	16,4	14,9
Max.temp.	34,9	29,9	27,9	27,5
% <20°C	72%	0%	7%	38%
% 20 – 26°C	25%	95%	91%	61%
% >26°C	3%	5%	1%	0%

Table 4: Monitored indoor air quality

Dwelling	living		slp1	
	RH (%)	CO_2 (ppm)	RH (%)	CO_2 (ppm)
Winter period: Jan 15th – March 31st / Oct 1st – Nov 4th				
Mean	38,0	712	45,4	1129
Stand.dev.	6,7	141	8,3	341
Min.	23,9	444	27,7	493
Max.	56,1	1577	66,6	1929
Summer period: April 1st – Sept 30th				
Mean	43,1	647	48,1	790
Stand.dev.	7,2	152	7,6	152
Min.	24,5	386	25,3	415
Max.	74,3	1685	70,8	1548

Table 4 presents the monitoring results for the indoor air quality (IAQ) in the living room and the master bedroom by means of the relative humidity (RH) and the CO_2 concentration. The comfort zone for RH is 30-70%. For CO_2 concentration, four IAQ levels or IDA-classes are considered: IDA1 (<800ppm), IDA2 (800-1000ppm), IDA3 (1000-1400ppm) and IDA4 (>1400ppm). For a good IAQ at least IDA2 level has to be aimed for. Figure 1 shows the percentage of time the different IDA-classes were reached in the living room and the master bedroom during winter and figure 2 during summer period. For the living room, only the hours between 7am and 10pm are considered as relevant and for the sleeping room only the hours between 10pm and 7am.

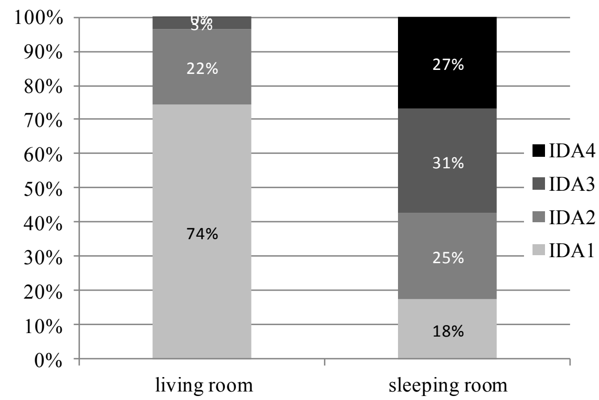

Figure 1: Indoor air quality in IDA-classes during winter

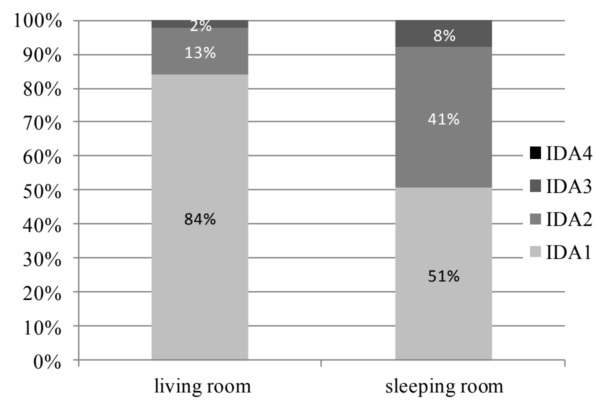

Figure 2: Indoor air quality in IDA-classes during summer

Table 5 presents the monitored and calculated energy consumption (in kWh/m² floor area). Natural gas is used for heating and domestic hot water, whereas electricity is used for lighting, household appliances and as auxiliary energy for pumps, etc. In the Flemish EPBD the gas consumption for heating and domestic hot water as well as the auxiliary electrical energy is calculated, but not the electricity consumption for lighting and appliances. The first column gives the real measured data, whereas in the second column these data are normalized for the climate by means of the degree days: 1522 degree days from 16/1/2011 until 15/1/2012 and 2087 degree days in the Test Reference Year for Brussels.

Table 5: Monitored and calculated energy consumption

In kWh/m².a	16/1/2011 -15/1/2012	normalized monitored	calculated with EPB
Natural gas	57,8	79,2	140,1
Electricity	19,4	19,4	1,6[1]
Total end energy consumption	77,2	98,7	141,7

[1] in the EPB only auxiliary electricity consumption is included

Confrontation with future requirements

First the results for the impact of the λ-value of straw bales are presented. Table 6 gives the U-values of the roof and façade, insulation level, energy performance level, net heat demand and primary energy demand for the dwelling, as built now, for the three different λ-values. The results for λ=0.08W/mK represent the situation according to the Flemish rules, the other results show the impact of a lower λ-value on the different criteria.

Table 6: Impact of λ-value on the current performance of the dwelling

λ-value (W/mK)	0.045	0.06	0.08
Roof (W/m²K)	0.14	0.17	0.20
Façade (W/m²K)	0.12	0.15	0.18
Insulation level K (-)	K29	K31	K33
Energy performance level E(-)	E75	E76	E78
Net heat demand (kWh/m².a)	84.5	88.2	93.0
Primary energy demand (kWh/m².a)	153	156	159

Table 7 presents the evolution of the insulation level K, the energy performance level E, the net heat demand and the risk that active cooling will be installed for the subsequent energy saving measures. For step 1 to 8, each subsequent step is added to the former steps. For step 9, the starting situation is step 4 and balanced ventilation with 85% heat recovery is added, whereas for step 14, step 10 is the starting situation and extra conventional insulation is added.

Table 7: Evolution of insulation level, energy performance level, net heat demand and summer comfort for the subsequent energy saving steps

Subsequent energy saving steps	K-level (-)	E-level (-)	net heat demand (kWh/m².a)	risk for cooling (%)
1.original situation	33	78	93.0	61%
2. =1+PH glazing	26	70	84,9	41%
3. =2+solar shading	26	67	84,9	15%
4. =3+infiltr. 3m³/h.m²	26	54	61,9	15%
5. =4+exhaust ventilation	26	57	61,9	15%
6. =5+solar collector	26	50	61,9	15%
7. =6+heat pump	26	37	61,9	15%
8. =7+PV 8,5kWpeak	26	0	61,9	15%
9. =4+balanced ventilation	25	44	35,7	18%
10. =9+infiltr. 1m³/h.m²	25	41	30,1	18%
11. =10+solar collector	25	35	30,1	18%
12. =11+heat pump	25	27	30,1	18%
13. =12+PV 6kWpeak	25	1	30,1	18%
14. =10+extra insulation	17	33	16,8	29%
15. =14+solar collector	17	28	16,8	29%
16. =15+heat pump	17	20	16,8	29%
17. =16+PV 4kW peak	17	3	16,8	29%

DISCUSSION

Current situation

The monitoring campaign showed that both in winter and in summer the thermal comfort in the living room was mostly within the comfort zone (Table 3). In winter the temperature does not go below 18°C and this occurs mainly during night. In summer the temperature is only 5% of the time above 26°C with a maximum of 29,9°C. In the sleeping rooms the thermal comfort is much less. Especially in the north oriented sleeping room (slp2), the mean temperature in winter is 14,7°C and the temperature is 95% of the time below 20°C. Even in summer the temperature is 38% of the time below 20°C and reaches a minimum value of 14,9°C. The south oriented sleeping room (slp1) performs better with a mean temperature of 19,7°C in winter, although even there a minimum temperature of 13,3°C was reached. The explanation for these low temperatures is the fact that the occupants chose not to heat the sleeping rooms, as they only serve for sleeping.

Also for the indoor air quality (Table 4) there is a clear difference between the living room and the sleeping room (slp1). In the living room both in winter and summer the CO_2 concentration is below 1000ppm (IDA1 and IDA2) for 96% of the time between 7am and 10pm. However in the sleeping room, especially during winter the IAQ is much worse: only 43% of the time between 10pm and 7am at least IDA2 is reached and 27% of the time the CO_2 concentration is above 1400ppm (IDA4). This is probably due to the natural ventilation system with grids in the windows. Due to thermal stack effect, the grids in the sleeping room probably serve more as exhaust system than as supply system. In summer, the IAQ in the sleeping room is much better (92% of the time <1000ppm), probably due to more window opening.

When comparing the monitored and calculated energy consumption (Table 5), it is clear that the real energy consumption is much lower than the theoretically calculated. The normalized monitored natural gas consumption is only 56% of the calculated gas consumption. This might be partly explained by the fact that in the EPB an overall mean indoor temperature of 18°C is assumed, whereas in this dwelling, since the sleeping rooms are not heated, the mean indoor temperature will probably be lower. But even including the electricity consumption for lighting and household appliances, the monitored end energy consumption is lower than the calculated, although the calculated only takes into account the auxiliary electricity consumption for the heating system. It can therefore be concluded that this straw bale house performs better than expected for energy consumption, but that the indoor comfort, both thermal and IAQ, still can be improved.

Confrontation with future requirements

When analyzing the impact of the λ-value on the (calculated) performance (Table 6), it is clear that a lower λ-value has a positive impact on the (calculated) insulation performance of the roof and the façade. However, when considering the overall indicators K- and E-level and net heat demand, this impact is rather small: K-level minus 4 points, E-level minus 3 points and the neat heat demand for a λ-value of 0,045W/mK is 91% of the net heat demand for a λ-value of 0,08W/mK. It is clear that by only changing the λ-value, none of the future requirements, presented in Table 2, will be met.

As can be seen in Table 7, a number of extra measures are needed to achieve a zero energy level (≈ E0) with the straw bale house. By applying passive house glazing, solar shading and an improved air tightness, an E-level of E54, a net heat demand of 61,9kWh/m² and a reduced risk for cooling of 15% can be reached, thus meeting the requirements of 2014. In combination with a solar collector, a heat pump and 8,5kW photovoltaic panels, even E0 can be reached, but the net heat demand remains 61,9 kWh/m², thus not meeting the future requirements of 15 or 30kWh/m². If the future requirement for the net heat demand will be set at 30kWh/m², this can be achieved by applying an air tightness of 1m³/h.m² and a balanced ventilation system with 85% heat recovery. However, if the future requirement for net heat demand will be set at passive house level (15kWh/m²), then extra insulation, apart from the straw bales, will be indispensable. Positively, this will also lead to smaller areas for photovoltaic panels. A disadvantage of this higher insulation performance however is the higher risk for overheating during summer (29%), as the extra insulation will impede the heat transfer towards the outside in summer.

CONCLUSION

This paper analyzed the feasibility of adapting a straw bale house to meet future requirements on energy performance, by analysing the current performance of a straw bale house and investigating the impact of subsequent energy saving steps. It appeared that the concern on which λ-value to use for straw bales is unnecessary, as the impact is small and by only using a lower λ-value, future requirements will never be met. The most important impact parameter for the future will be the requirement for the net heat demand. The current requirement of 70kWh/m² can easily be met by improving the glazing, the solar shading and the air tightness. In case the requirement will be set in the future at 30kWh/m², straw bales can still be used as the only insulation material, but a balanced ventilation system with improved air tightness and heat recovery will be necessary. However, in case the Flemish government will tighten the requirements up to passive house standard, extra insulation will be indispensable. This is not infeasible, as very recently the first straw bale house with passive house certificate is built in Belgium.

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