Title: Hygrothermal Performance, Energy Use and Embodied Emissions in Straw Bale Buildings

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Abstract: Straw bale is a low embodied energy and technically acceptable thermal insulation material. As per today, there is a lack of standardized technical data on utilizing straw bale in building construction, while the existing research studies rather focus on limited specific experimental or computational scenarios without summarizing in an organized way the behaviour of straw bale construction under different climate conditions and assembly configurations. This comparative study presents systematically the hygrothermal and energy performance of straw bale buildings with different exterior cladding and finishing mortar or sheathing board, exposed in various representative climates. The findings provide an insight into the optimal selection of materials and furthermore highlight the importance of climate adaptation of straw bale wall constructions. Overall, straw bale buildings show robust hygrothermal performance, when properly designed, and achieve very low energy use at a minimum of embodied emissions.

Keywords:
Straw bale, thermal insulation, hygrothermal performance, mould growth, energy use, embodied emissions, sustainability

1. Introduction

Straw bale as building material is considered as a viable solution towards the goal of decarbonisation of building sector and climate change mitigation. In building construction, straw bale has been utilized as load bearing wall structure or as infilled insulation material in a post and beam structure, where in both cases it is functioning as thermal insulation material. The main appeal in using straw bale as building material is that it has low environmental impact compared to other insulation materials commonly used in the market, e.g. mineral wool, polystyrene, etc. as found in the study by Milutienė et al. [1]. Even if global warming potential (GWP) of a typical external wall compared to other building elements are relatively low, e.g. 3% of the total greenhouse gas emissions of the building calculated by Sodagar et al. [2], it is nevertheless important to reduce embodied environmental impacts in all building components to achieve nearly zero emission buildings.

On the other hand, in a market survey done on the EU's insulation materials industry for energy efficient buildings [3], it has been found that the use of organic plant-derived materials, such as straw bale, as thermal insulation is not widely practiced, whereas the majority of the building insulation material are either mineral fibrous materials or fossil fuel foams. Another survey by Erbil et al. [4] revealed that performances of building incorporating straw bale are not well appreciated compared to other conventional building materials, despite the fact that the low environmental impacts of straw bale buildings are recognized. This notion of insufficient standardized database and methods regarding straw bale construction by non-practitioners are substantiated in a survey to different stakeholders of construction industry, conducted by White et al. [5].

In general, thermal conductivity of straw bale increases with bulk density ρ, which has been measured and reviewed in more than 40 peer review technical papers. Not unlike other thermal insulation material, thermal conductivity of straw bale is highly dependent on hygrothermal conditions in building components. If subjected to excessive moisture level, there is high possibility of mould growth and straw degradation and its thermal insulation performance will be reduced, as reported in more than 20 different straw bale buildings [6]. Moisture content measured in straw bale walls in different locations, e.g. lime plastered straw bale wall by Douzane et al. [7] in Voyennes France, Thomson and Walker [8] in Cornwall

UK, Robinson et al. [9] in Lincolnshire UK, and Goodhew et al. [10] in Dartmoor UK, clay plastered straw bale wall by Ashour et al. [11] in Bavaria Germany, and Gallegos-Ortega et al. [12] in Tecate Mexico. Other studies have reported findings based on numerical simulations instead. Overall, the findings indicate a risk of mould growth and degradation of straw bale if the respective assemblies are not properly constructed with respect to moisture transport. Despite the central role of exterior layers in straw bale wall constructions, i.e. wall finishing and exterior cladding, and the drastic impact of climate loads on their hygrothermal performance, yet comparative investigation of the effect of different type of wall finishing as well as exterior climate is scarce in existing literature.

Acting as thermal insulation material, straw bale thickness in a wall is the main factor that will influence the energy performance of a straw bale building. The heating demand of straw bale building, which consists of exterior walls with approximately 500mm thickness of straw bale, is lower than the average household heating demand in respective country [6]. Most of the tested straw bale buildings cannot achieve the stringent passive house PHPP requirement for cool and cool-temperate climate zones, but are still within the recommended PHPP U-value for warm-temperate climate zone. Heating demand as low as 7% and 8% of average household consumption were measured by D'Alessandro et al. [13] in Umbria Italy and Chaussinand et al. [14] in Lausanne Switzerland respectively, and up to 55% of average household consumption was measured in other straw bale buildings [7] [15] [16]. Given a relatively thin layer of wall finishing compared to straw bale cross section, there is no clear indication on their impact to overall building energy performance. Indeed, thermographic building performance survey of straw bale wall by Wall et al. [15] and D'Alessandro et al. [13] found no significant thermal bridge between straws and other components in a wall which will undermine the building energy performance.

This comparative study presents systematically hygrothermal and energy performance of straw bale buildings with different exterior finishing and construction details, exposed in various climates. The findings highlight the necessity for variation in straw bale wall constructions according to the local climate conditions and provide an understanding of the optimal selection of materials in different cases. Straw bale buildings show robust hygrothermal performance, when properly designed, and achieve very low energy use at a minimum of embodied emissions.

2. Material and methods

The performance of the case study straw bale building is simulated and evaluated using the methodology shown in Figure 1. Two main elements will be examined on their impact on hygrothermal and energy performance: (i) exterior cladding and weather-resistive layer in straw bale wall assemblies and (ii) exterior climate representing various climate zones. The material properties of straw bale are based on published technical papers [6], while the design of straw bale wall assemblies is based on prescribed guidelines in the 2018 International Residential Code (IRC2018) [17]. Validated software listed in Appendix A, Table A1 are used to model and simulate the performance of straw bale assemblies and buildings under different settings, i.e. (1) designs of wall assembly, (2) exterior climates, and (3) indoor climates.

Heat, air, and moisture transport (HAM) simulations will be performed for twenty different wall assemblies exposed in five exterior climates, while the indoor climate remains the same. The time moisture content w in straw bale receives its highest values will be identified based on the profiles of transient w across the wall cross section. The cross section in straw bale which shows the highest moisture content will then be further researched for mould growth risk. Two additional indoor climates with differentiated moisture loads, i.e. different humidity classes according to ISO 13788, will be included in the mould growth study in order to give a more complete picture of the performance of straw bale.

A 3D building geometry model is employed for building energy simulation (BES). The inputs for BES have stemmed from standard EN 16798-1 [18]. The same set of wall assemblies and exterior climates will be researched in BES analysis as well. A life cycle assessment will be carried out to examine the environmental impacts due to different types of wall finishing and exterior climates on a straw bale building. In particular, the following phases will be included in the assessment: A1-A3 for the embodied and B6 for the operational impacts.

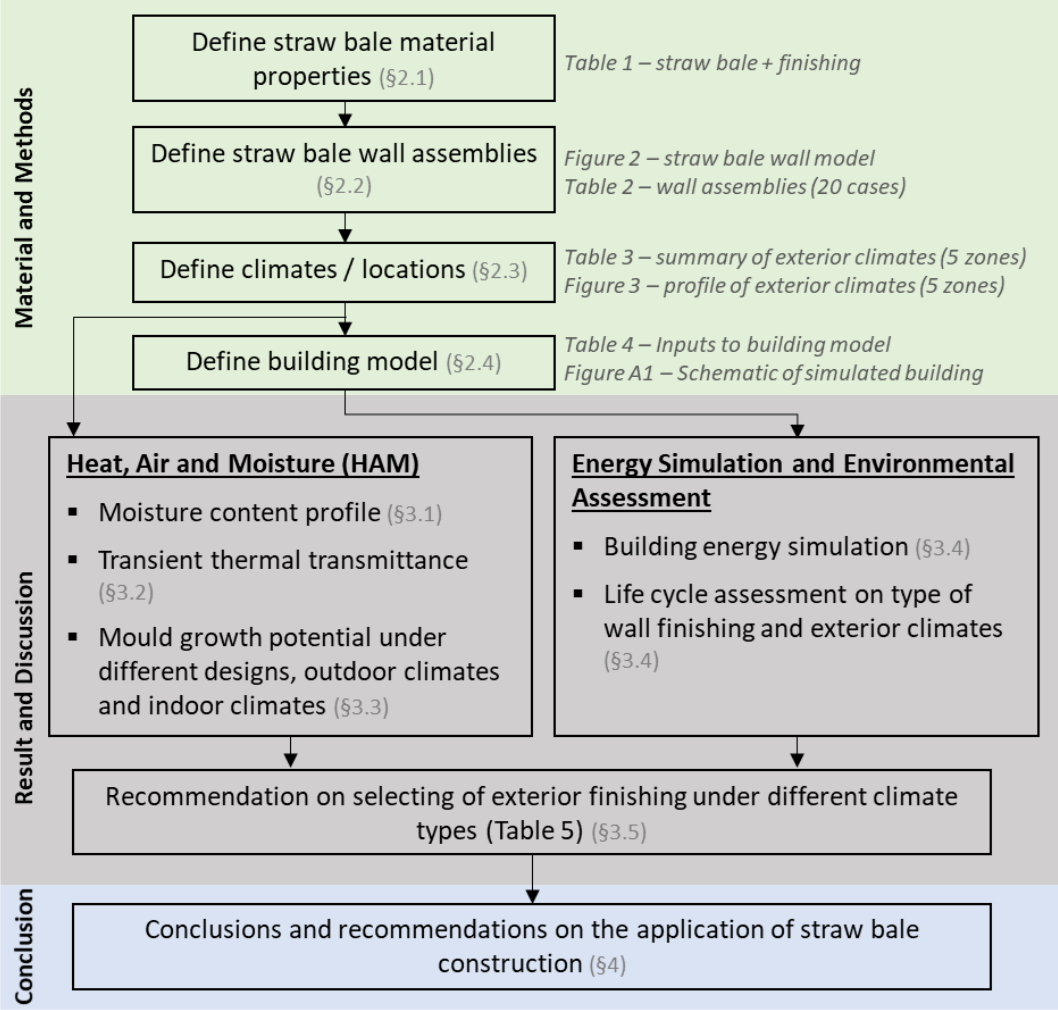


Figure 1 Flowchart of methodology used in this study

2.1. Material properties

Thermal conductivity λ of straw bale with bulk density ρ in the range of 60 to 130kg·m^{-3} has been measured and reviewed in more than 40 technical papers [6]. Under IRC2018 guidelines, the plastered straw bale wall shall have a minimum bale density of 104kg·m^{-3}, however in order to achieve the required fire-resistance rating, a minimum bale density of 120kg·m^{-3} is recommended [17]. Other published studies on straw bale building performance show straw bale density of 80kg·m^{-3} in Douzane et al. [7] and D'Alessandro et al. [13], and 115 kg·m^{-3} in Shea et al. [19]. For straw bale modelling in this study, IRC2018 guideline will be followed and the density of straw bale is set at 120kg·m^{-3}, which will also be used to establish other density dependant properties such as porosity and thermal conductivity.

The measurements reported in existing studies refer mostly to straw bale within the density range between 70 and 110kg·m^{-3} [6]. Among them, thermal conductivity with density around 120kg·m^{-3} can be found, i.e. 0.0490 W·m^{-1}·K^{-1} at 120kg·m^{-3} by Reif et al. [20], 0.0670 W·m^{-1}·K^{-1} at 115kg·m^{-3} and 0.0790 W·m^{-1}·K^{-1} at 123kg·m^{-3} by Costes et al. [21], 0.0642 W·m^{-1}·K^{-1} at 114kg·m^{-3} and 0.0636 W·m^{-1}·K^{-1} at 124kg·m^{-3} by Shea et al. [19]. In this study, the thermal conductivity λ is computed at 0.0678 W·m^{-1}·K^{-1} from the linear fit equation (Eq. 1) derived based on existing measurements as shown in review paper [6]:

$$\lambda = 0.00019.\rho + 0.045 \qquad (Eq.\ 1)$$

The water vapour resistance factor μ of straw bale can be estimated at μ=5 based on dry cup test measurements performed by Marques et al. [22] and Reif et al. [20]. The dry specific heat capacity c_p is set at 2426 $J \cdot kg^{-1} \cdot K^{-1}$ based on study by Samuel et al. [23]. The porosity is interpolated at a value of 0.80 based on studies from Marques et al. [22] and Lebed and Augaitis [24].

Moisture storage function is derived from the proposed moisture storage isotherms by Yin et al. [25] and Lawrence et al. [26], where moisture content C [%] is correlated against relative humidity ϕ with parameter c_s=400%, K_m=0.9773, n=44 and i=1.6,

$$C = \frac{c_s}{1+n(\frac{Km}{\varphi}-1)^{i/3}} \qquad (Eq.\ 2)$$

Additional modification on parameter n=54 in sorption cycle and n=44 in desorption cycle is proposed by Yin et al. [25] for better prediction on transient conditions in straw bale building. For material modelling in this study, n=44 for both sorption/desorption cycles is applied, as the numerical model does not differentiate between the two process and uses the same curve for both of them. Initial built-in moisture is estimated at w = 3.4 $kg \cdot m^{-3}$ under ϕ = 10%, assuming the straw bales have been stored and dried prior construction. The thermal conductivity under moist condition λ_w is approximated using following expression [27], with thermal conductivity supplement b is set at b=1, similar to proposed parameter used for cellulose fibres [28],

$$\lambda_w = \lambda(1 + b.w/\rho) \qquad (Eq.\ 3)$$

Thermal conductivity is assumed independent of temperature.

Table 1 shows the summary of basic material properties of straw bale and different weather resistive layers used in the wall assembly modelling. Material properties of the finishing layers are based on existing material database available in the simulation tool.

Table 1 Summary of basic material properties for straw bale and different wall finishing

Basic material properties	**Bulk density [$kg \cdot m^{-3}$]**	**Porosity [$m^3 \cdot m^{-3}$]**	**Specific Heat Capacity, Dry [$J \cdot kg^{-1} \cdot K^{-1}$]**	**Thermal Conductivity, Dry, 10°C [$W \cdot m^{-1} \cdot K^{-1}$]**	**Water Vapor Diffusion Resistance Factor [-]**
Straw bale	120	0.80	2426	0.0678	5
Lime mortar	1785	0.28	850	0.7000	15
Cement-Lime mortar	1900	0.24	850	0.8000	19
Clay mortar	1568	0.41	488	0.4837	11
Gypsum board (interior)	850	0.65	850	0.2000	8
Wood fibreboard, windbarrier	800	0.80	1700	0.1800	9
Wood fibreboard, porous	270	0.83	1700	0.0600	6
Wood fibreboard, hard	959	0.41	1700	0.1300	227
OSB	595	0.90	1500	0.1300	165
Gypsum board (exterior)	675	0.71	850	0.2000	8
Fibre-cement board	1610	0.15	850	0.1300	83

2.2. Straw bale wall constructions

A pilot building with exterior wall consisting of straw bale used as either main load bearing structure or principal infilled insulation material is used for the assessment of hygrothermal and energy performance . The design of straw bale wall in this study is based on recommended prescriptive requirements for straw bale construction as per Appendix S in the IRC2018 [17]as well as existing case studies on straw bale buildings. In total, twenty type of wall assemblies in total are modelled, as shown in Figure 2 and Table 2.

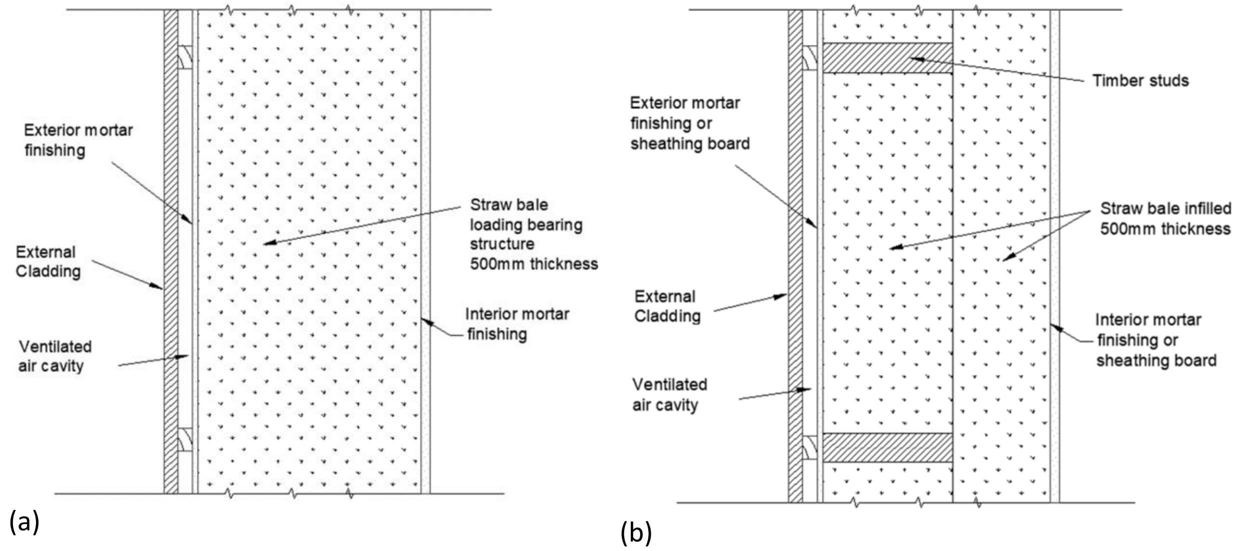


Figure 2 Simplified sketch of straw bale wall assemblies with exterior cladding (a) as load bearing structure (applicable to case 1-3) (b) as infilled insulation only (applicable to all cases)

Table 2 Straw bale (SB) wall assemblies

Cases	**Wall Assemblies (from outside to inside)** $^{\text{note 1}}$
1 & 1’	30mm lime mortar + 500mm SB + 30mm lime mortar
2 & 2’	30mm cement-lime mortar + 500mm SB + 30mm cement-lime mortar
3 & 3’	40mm clay mortar + 500mm SB + 40mm clay mortar
4 & 4’	25mm wood fibreboard (wind barrier) + 500mm SB (infilled only) + 13mm gypsum board
a & a’	13mm wood fibreboard (wind barrier) + 500mm SB (infilled only) + 13mm gypsum board
b & b’	13mm wood fibreboard (porous) + 500mm SB (infilled only) + 13mm gypsum board
c & c’	13mm wood fibreboard (hard) + 500mm SB (infilled only) + 13mm gypsum board
d & d’	15mm OSB + 500mm SB (infilled only) + 13mm gypsum board
e & e’	13mm gypsum board + 500mm SB (infilled only) + 13mm gypsum board
f & f’	13mm fibre-cement board + 500mm SB (infilled only) + 13mm gypsum board

Note 1: SB wall assemblies shown are for wall without exterior cladding (case 1,2,3,4,a,b,c,d,e,f). For SB wall with exterior cladding (case 1’,2’,3’,4’,a’,b’,c’,d’,e’,f’), additional 13mm exterior cladding + 20mm ventilated cavity are added for each corresponding wall assembly.

Performance of exterior wall with straw bale thickness ranging from 490mm to 800mm have been examined in various studies, i.e. 490mm in Shea et al. [19], 520mm in Douzane et al. [7] and Cornato et al. [16], 520mm in D’Alessandro et al. [13], and up to 800mm in Chaussinand et al. [14]. As per IRC2018 recommendation, the thickness of straw bale wall without its plaster shall not be less than 381mm [17]. Based on these references, a 500mm thickness layer of straw bale, either as load bearing structure or infilled insulation material, is applied in all the employed designs in this study.

Four types of straw bale wall finishing mortar are included, i.e. lime mortar for case 1, cement-lime mortar for case 2, clay mortar for case 3, and sheathing board for case 4 which are only applicable where straw bale is used as infilled insulation material. IRC2018 [17] has recommended a maximum finishing mortar’s thickness of 51mm on each side regardless the types of mortar, while a minimum thickness of 38mm for clay mortar and 22mm for lime and cement-lime mortar. Similar finishing mortar's thickness are found in other case studies, i.e. 30mm lime mortar [19], 35mm lime mortar [7], and 40mm clay mortar [13]. Using these as guideline, finishing mortar's thickness of 30mm for lime and cement-lime mortar, and 40mm for clay mortar on each side are incorporated into the designs. In addition, a 25mm wind-barrier grade wood fibre board on exterior and 13mm gypsum board on interior side of straw bale layer are used as sheathing boards in case 4. Case 1', 2', 3' and 4' includes additional exterior cladding with ventilated cavity for extra weather protection, by modelling an air change of 10h^{-1} in a 20mm air layer inside 13mm timber cladding. As per IRC2018 recommendation, the plastered straw bale walls shall be constructed without any vapour barrier/retardant membranes between the straw and interior finishing layer [17]. This recommendation will be also applied in the wall configurations included in this study.

Straw bale wall assemblies with different exterior sheathing boards (Table 2, cases a-f and a'-f') than wind-barrier grade wood fibre board (Table 2, case 4 and 4') are under further investigation with regards to their hygrothermal performance. The interior sheathing board remain the same in all cases, i.e. gypsum board. In total, six different types and thickness of exterior sheathing boards have been tested, along with the respective cases a' to f' that include additional exterior cladding with ventilated cavity.

2.3. Ambient climatic conditions

Five locations in Europe that represent different climate zones have been selected for both the hygrothermal analysis and building energy performance assessment. Table 3 shows the annual weather summary in all five locations, while *Figure 3* shows the exterior air temperature and ϕ profile. Climate A stands for Oslo with warm-summer humid continental climate, Climate B for Tromsø with subarctic climate, Climate C for Lisbon with hot-summer Mediterranean climate, Climate D for Milan with humid subtropical climate and Climate E for Brussels with temperate oceanic climate.

Table 3 Summary of weather profile for simulated exterior climates

Weather profile (annual)	Unit	Climate A	Climate B	Climate C	Climate D	Climate E
Location	-	Oslo, Norway	Tromsø, Norway	Lisbon, Portugal	Milan, Italy	Brussels, Belgium
Köppen climate classification	-	Dfb	Dfc	Csa	Cfa	Cfb
Temperature, mean	°C	6.8	2.1	15.6	14.7	10.3
ϕ, mean	%	73	82	75	68	81
Mean wind speed	m·s^{-1}	2.71	3.25	3.94	1.68	4.36
Normal rain sum	mm·a^{-1}	605	1276	675	747	1024
Global solar radiation, mean	W·m^{-2}	73	78	196	153	105
Global solar radiation, max	W·m^{-2}	751	637	1010	972	878

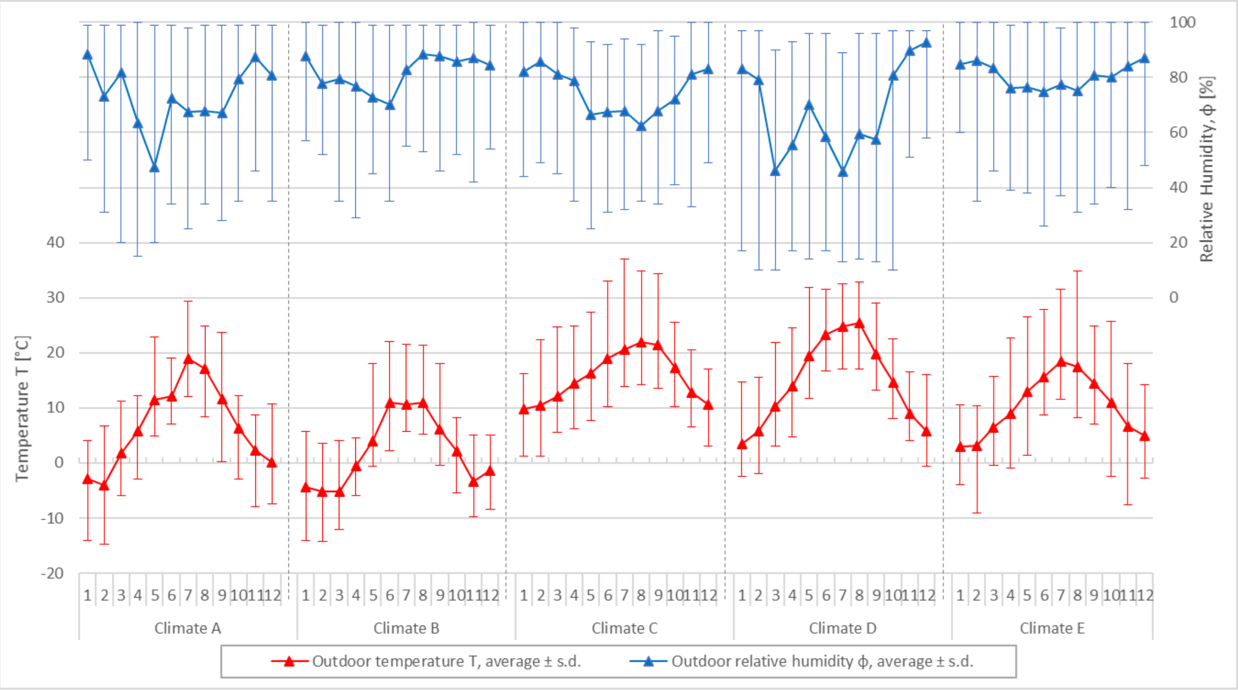


Figure 3 Simulated exterior climates with temperature profile and ϕ profiles

In addition, four main orientations, i.e. south, east, north, and west, of exterior wall will be employed for the hygrothermal simulations in all cases. The interior climate will be set as per EN 13788 with humidity Class 3, which represents buildings with unknown occupancy, while constant air temperature indoors at 20°C will beassumed. Furthermore, humidity class 2, which represents lower moisture loads indoors and humidity class 4, which represents higher moisture loads indoors will be used for getting deeper analysis in the mould growth study.

2.4. Building geometry and input to Building Energy Simulation (BES)

A four-person-household straw bale building has been employed and modelled for the building energy simulation (BES). The building has dimensions of 14m x 10m x 2.8m(W x D x H), with heated floor area of 140m^2, a well-insulated and airtight building envelop and an unheated attic. The schematic representation of the simulated building is shown in Appendix A, Figure A1. The Standard EN16798-1 [18] has been used to set the indoor environment parameters accordingly in order to achieve a medium level of indoor environmental quality category II (IEQ$_{II}$), which is related to normal level of expectations for occupants as per Table 4 in the respective Standard. A heating and cooling system has been included in the model, along with a constant air volume (CAV) mechanical ventilation system with predefined steady air flow. The internal heat and moisture loads are based on software's predefined family household occupancy. Table 4 summarizes the overall inputs to the building energy simulation (BES).

Table 4 Inputs to Building Energy Simulation (BES)

BES Parameters	**Settings**
Major building components	1. Exterior wall: straw bale wall as per Figure 2 and Table 2 2. Ceiling (excluding roof): Wind barrier board + 400mm cellulose insulation + vapour retarder + gypsum board (U-value: 0.09W·m^{-2}·K^{-1}) 3. Floor (excluding foundation): 400mm EPS + radon membrane + 40mm concrete screed + vapour retarder + timber flooring (U-value: 0.10W·m^{-2}·K^{-1})

	4. Windows: three layers energy glazing in wooden frame (U-value: 0.80W$\cdot$m$^{-2}\cdot$K^{-1})
Thermal bridge	Assume no significant thermal bridge. Normalized thermal bridge set at 0.03 W$\cdot$m$^{-2}\cdot$K^{-1} as per NS3700 Table 5 passive house upper limit requirement[29]
Internal loads	Based on four-family household occupancy
Indoor temperature	Minimum 20°C for heating, maximum 26°C for cooling. As per EN16798-1 Table B.2, residential buildings with sedentary activity, category IEQ$_{II}$ [18]
Indoor ϕ	No limit set
Natural ventilation	Not included
Infiltration	N_{50}=0.6h^{-1} assuming good airtightness as per NS3700 Table 5 passive house upper limit requirement [29], equivalent to ACH 0.03 h^{-1}
Mechanical ventilation	7 l$\cdot$s$^{-1}\cdot$person^{-1} as per EN16798-1 Table B.6, expected 20% dissatisfied, category IEQ$_{II}$ [18], equivalent to 100.8 m$^3\cdot$h^{-1}
HVAC	1. Ventilation system with 80% heat recovery efficiency 2. Space heating 3. Space cooling
Exterior climates	Refer to Table 3 for five different settings.

3. Result and Discussion

3.1. Profiles of moisture content

The equilibrium moisture content w in straw bale layer in exterior wall constructions with different assembly configurations and orientations, under the employed climates, is plot on *Figure 4*. The wall orientation with highest w profile is chosen for further investigation. Based on the w profiles simulated for a typical year under different climates, the time where it has the highest w has been identified. The profiles of moisture content across the straw bale cross section (500mm thickness) at that specific point of time have been further studied. in particular, three aspects have been examined: (i) the risk of condensation, which happens when the temperature is reaching thedew point; (ii) the risk of mould growth, which will be substantially higher when the ϕ in the layer is above 80%; (iii) the moisture content w level above 20% as the threshold for further degradation [15]. The results are shown in *Figure 5* and summarized in *Figure 7*. Hereafter, straw bale is referred as 'SB', the whole 500mm thickness of straw bale cross section is referred as 'SB section' and the width of straw bale cross section from exterior finish is referred as 'SB side section'. For reference, w time series profile of north and south oriented walls under different cases and climates are shown in Appendix B, Figure B1 and B2.

In general, the exterior cladding in SB walls ith mortar finishing contributes to more regulated and lower w profile throughout a year, whereas SB walls without cladding show a fluctuated w pattern. Wall assemblies with sheathing board instead of mortar finishing show a regulated and lower w pattern, regardless the additional exterior cladding. Due to the fact that climate zones in northern hemisphere are selected in this case study, north-oriented walls with less daylight exposure show relatively high w profile compared to other orientations. Exception to this are the SB walls with mortar finishing without cladding, i.e. case 1-3, where driving rain have taken the major role in affecting the profile of moisture content in SB: high w are found in south-oriented walls under climate A and C, west-oriented walls under climate B and E, and north oriented walls under climate D.

Among mortar finishing, SB wall with clay mortar shows lower w compared to lime or cement mortar finishing under colder climates, i.e. A, B and E, while SB wall with cement mortar shows lower w under warmer climates, i.e. C and D. High w in SB are shown under climate B and E with high exterior ϕ profile. Average w of 19% for case 1-3 and 15% for case 1'-3' are found in the SB section under climate B. For case 1-3, substantial higher than 20% moisture content has been identified in the SB side section up to 200mm, and reach up to 99% in layer closest to exterior finish. By including cladding in case 1'-3', the SB side section up to 100mm contains moisture content higher than 20%, and reach up to 26% in layer closest to exterior finish. Similar moisture content profile has been also found in the SB cross section, under climate E. In contrast, under climate D with low exterior ϕ profile, the average moisture content in the SB section has been computed at 13% for case 1-3 and 12% for case 1'-3'. For case 1-3, moisture content higher than 20% has been found in SB side section up to 100mm. However only case 1 show high w at SB layer closest to exterior finish, at 96%, followed by 71% for case 3 and 47% for case 2. Case 1'-3' with cladding has shown w less than 20% in its SB section.

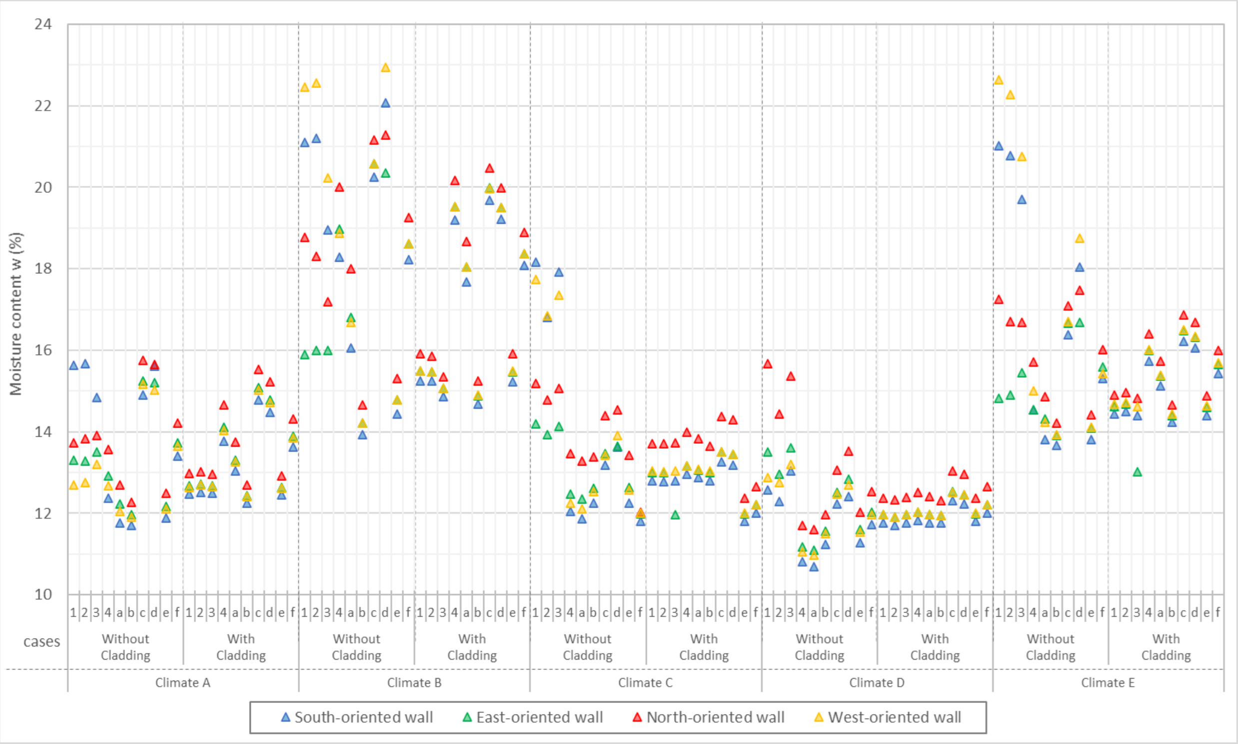
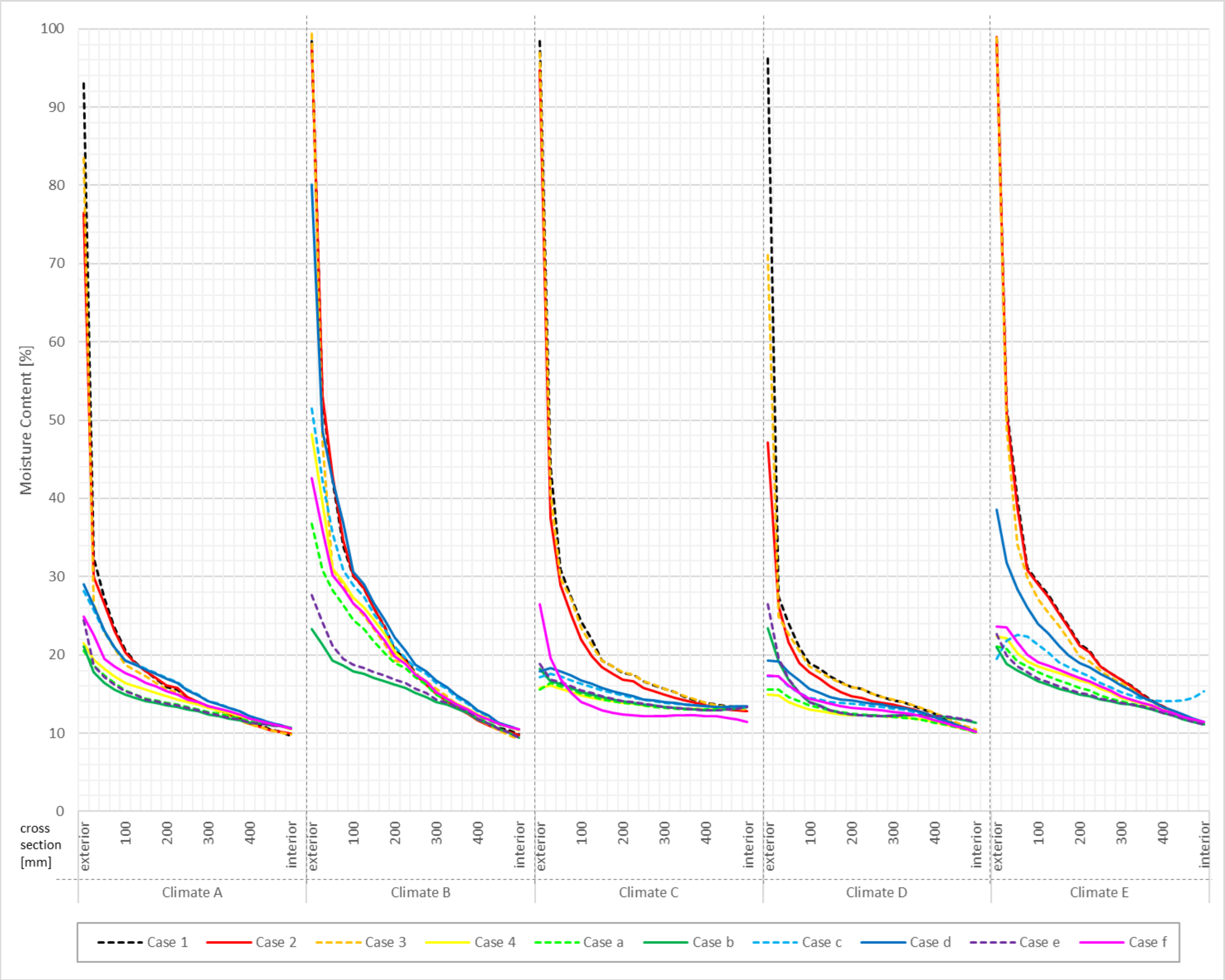
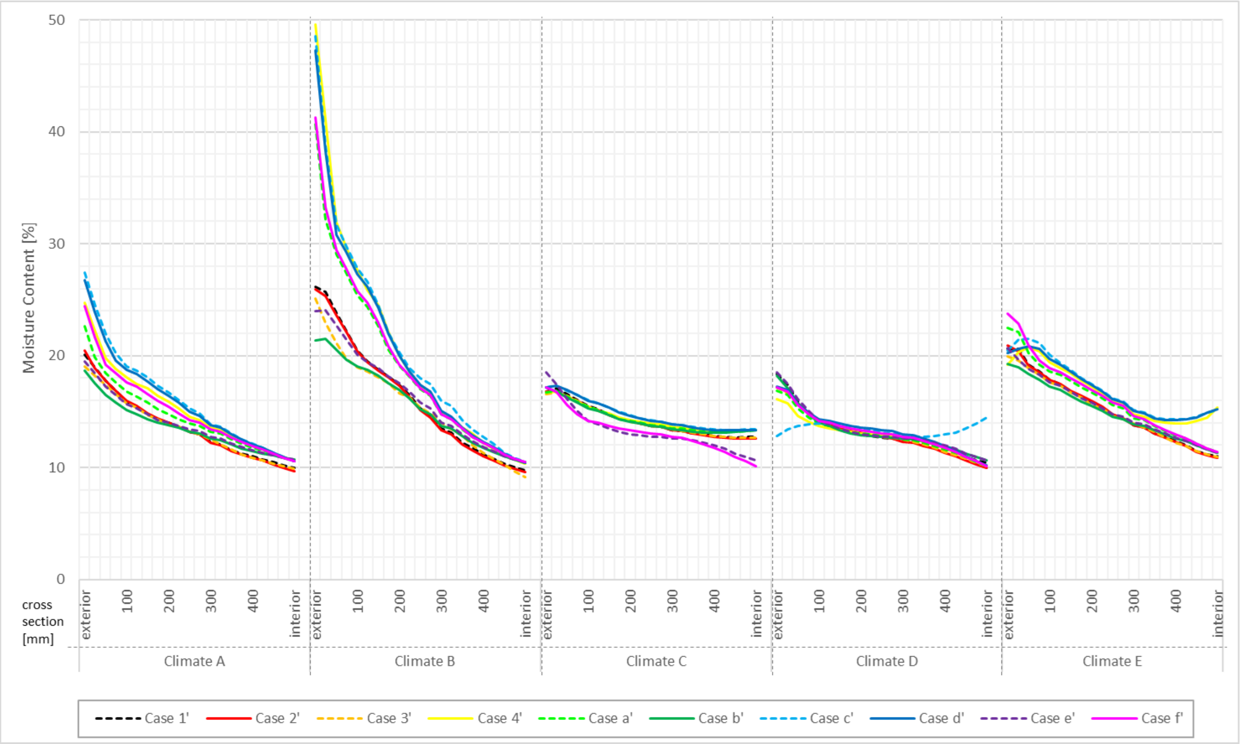


Figure 4 Equilibrium moisture content w [%] of overall SB cross section of each wall orientation in a year, under different case and climate. For reference, w time series of north and south oriented walls under different cases and climates can be found in Appendix B, Figure B1 and B2.


Moisture Content [%]
100
90
80
70
60
50
40
30
20
10
0
cross section [mm]
exterior
100
200
300
400
interior
Climate A
Climate B
Climate C
Climate D
Climate E
Case 1
Case 2
Case 3
Case 4
Case a
Case b
Case c
Case d
Case e
Case f

(a)



(b)

Figure 5 Moisture content of SB cross section under different case and climate for (a) cases without cladding, (b)cases with cladding. Note: y-axis scale of (b) is capped at 50% for clarity.

Based on the moisture content profiles under different climates, SB with exterior sheathing board performed the worst under climate B. The low performance is explained due the fact that climate B has high exterior ϕ and cold climate profile. Under climate B, SB with 15mm OSB as sheathing board without exterior cladding (case d') has the highest moisture content at its layer closest to the sheathing; average moisture content at 22% in the overall SB section, w higher than 20% in SB side section up to 250mm, while it reaches up to 80% in the part closest to exterior finish. High average w also noted in the SB section for wall assemblies with 13mm hard wood fibreboard (case c/c'),i.e. w = 20%, with 25mm wind barrier graded wood fibreboard (original case 4/4'), i.e. w = 19%, followed by 13mm fibre-cement board (case f/f'), i.e.w = 19%, where all of them exhibit moisture content higher than 20% in SB side section up to 250mm. Both SB walls with porous wood fibreboard (case b/b') and gypsum board (case e/e') as exterior finishing layer have the best hygrothermal performance, showing low w profile and ϕ in the SB.

Overall, SB with sheathing board as exterior finish have shown low moisture content under climate C and D, i.e. with average w at 12% and without exceeding 20% throughout its whole cross section, regardless the additional application of exterior cladding. Moisture content higher than 20% are found in SB side section up to 100mm under climate E and up to 50mm under climate A.

It is noted that by reducing the thickness of wind barrier graded wood fibreboard from 25mm (case 4/4') to 13mm (case a/a'), which results into more diffusion open layer, the average moisture content in SB layer is significantly reduced under all five climates.

It is also observed that SB layer in case c, d and f show higher moisture content in the assemblies without exterior cladding, while in case 4, a, b and e show higher w with exterior cladding. This discrepancy can be correlated to water vapour diffusion resistance factor μ of the sheathing board material; hard wood fibreboard (case c), OSB (case d) and cement fibreboard (case f) have higher μ, in comparison to porous wood fibreboard (case 4, a, b) and gypsum board (case e) with lower μ.

The water vapour partial pressure at SB layer (close to exterior sheathing board) and sheathing board (close to exterior air or cavity air) are investigated, using case d/d' to represent sheathing boards of higher µ as well as case a/a' to represent sheathing boards of lower µ under climate B, as shown in Figure 6. It is noted that both higher µ and lower µ sheathing board with exterior cladding (case a' and d') show similar vapour pressure profile, which indicate exterior cladding has regulated hygrothermal performance of the overall wall assemblies and choice of exterior sheathing board become less critical. However, the choice of exterior sheathing board becomes important when no exterior cladding is included in the design. For low µ sheathing board without exterior cladding (case a), there is low resistance for vapour to diffuse in between SB and sheathing board, therefore it is more difficult for the moisture to accumulate at the interface between both layers. For opposite case, with higher µ sheathing board without cladding (case d), the different in µ value between both layers create higher resistance at the interface for vapour diffusion, i.e. easier for moisture accumulation, and hence it is beneficial to include exterior cladding (case d') to avoid vapour flow from exterior environment. However, by including exterior cladding for low µ sheathing board (case a'), the benefit of easy diffusion will be trumped by higher vapour pressure and moisture level in air cavity layer which create higher resistance for vapour to diffuse out to exterior environment.

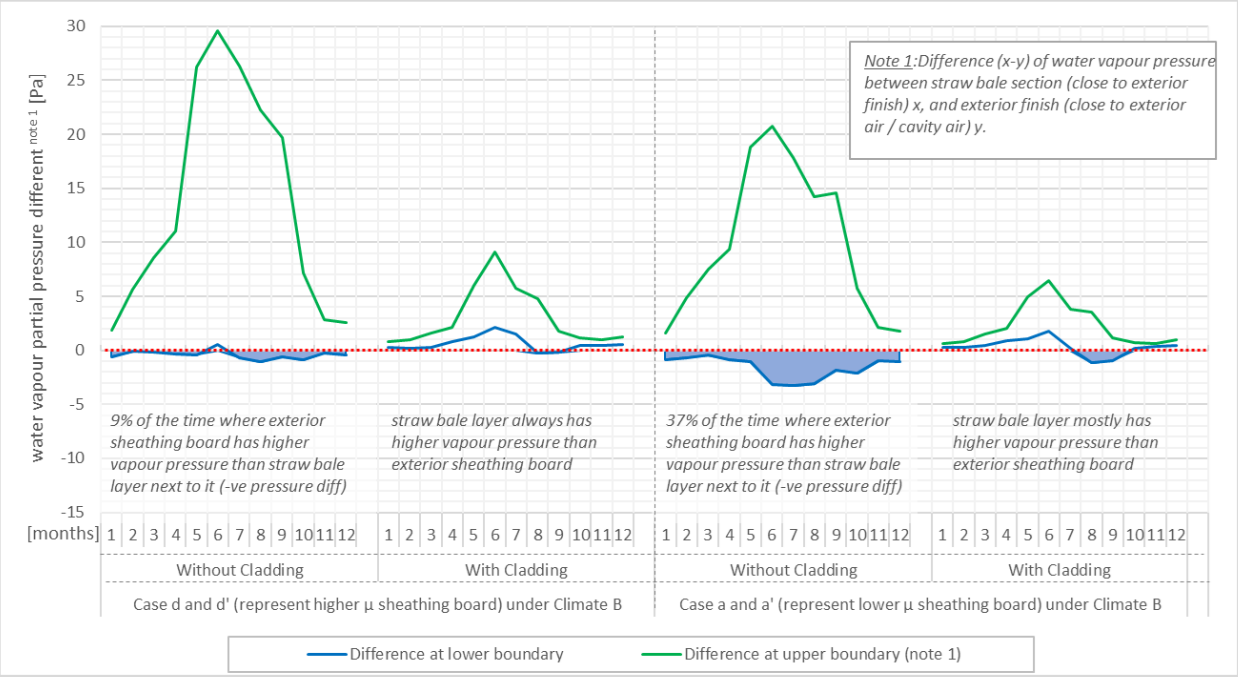


Figure 6 Lower and upper boundary of water vapour partial pressure differences at SB layer (close to exterior sheathing board) and sheathing board (close to exterior air or cavity air) for Case a, a', d and d' under climate B in a year. For reference, time series are shown in Appendix B, Figure B3.

It can be concluded that the SB layer closest to the exterior side has the highest level of w and the highest ϕ, with temperature closest to its dew point. Under all five climates, including warmer climate C, SB layer closest to the interior side has shown low w across its cross section and low ϕ. Low w has been also shown at the middle part of the SB cross section. Therefore, it can be construed that SB layer closest to its exterior side will be most likely subjected to mould growth and degradation compared to other part of SB under different climate conditions.

The results of this study are summarized and compared with other findings from literature, as shown in *Figure 7*. In particular, the average moisture content in the SB section and the first 100mm of SB side section are shown. The plot shows measurements of moisture content w, at their respective highest values. According to the results, the latter are within the range 11% to 28%, under different wall assemblies and climates. To highlight a few: (i) A lime plastered SB wall with interior plasterboard was monitored for 14 months by Douzane et al. [7] in Voyennes France, where the measured moisture content was below 19.5% and neither condensation nor mould growth was observed during the experimental period; (ii) A lime plastered SB wall was monitored for two years by Goodhew et al. [10] in Dartmoor UK, where one out of eight monitored point showed moisture content exceeding 25% and the straw in that section was found degraded once the plaster was removed; (iii) A lime plastered SB wall was monitored for 45 days by Robinson et al. [9] in Lincolnshire UK, and found that the moisture content in some positions reached 25% to 29%, however no degradation was observed; (iv) A lime plastered straw wall was monitored for three years by Thomson and Walker [8] in Cornwall UK, where moisture content up to 28.4% on straw close to the render was measured, and no mould growth was observed.

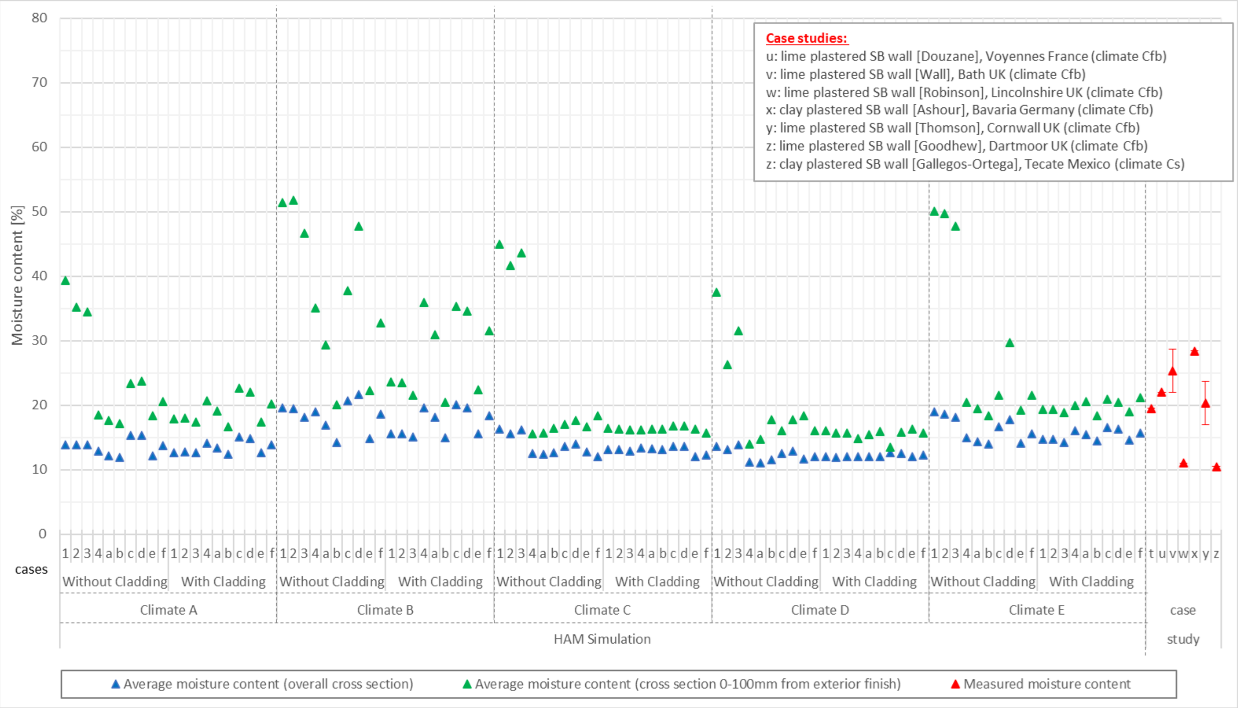


Figure 7 Summary and comparison of moisture content w with case studies from Goodhew et al. [10],*Thomson and Walker* [8], *Ashour et al.* [11], *Robinson et al.* [9], *Wall et al.* [15], *Douzane et al.* [7], *Gallegos-Ortega et al.* [12]. *Blue markers show average w of all four wall orientations in a year, and green markers show average w in the first 100mm of SB cross section from exterior finish.*

3.2. Transient thermal transmittance (U-Value)

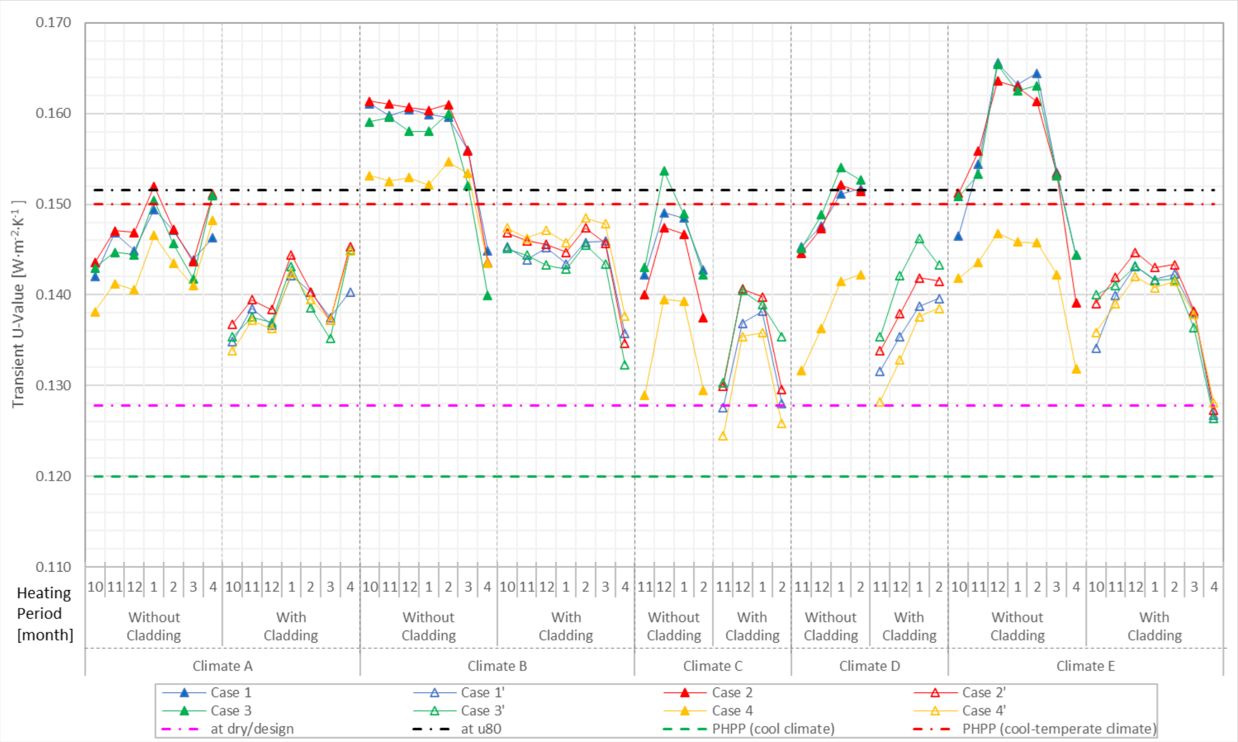
The designed U-value of SB wall assemblies in this study is 0.13 $W.m^{-2}.K^{-1}$, or 0.15 $W.m^{-2}.K^{-1}$ at 80% ϕ (u80), which is close to other existing case studies in the range of 0.12 to 0.20 $W.m^{-2}.K^{-1}$ [6]. For reference, the U-value of these SB wall assemblies is at the borderline of recommended U-value by passive house PHPP standard for cool and cool-temperate climate zones, however well within the recommended PHPP U-value for warm-temperate climate zone [30].

The transient U-value of SB walls during heating period have been investigated and summarized in *Figure 8*. As the direction of the interior heat flux usually may change twice a day during the summer and yield negative effective U-value, calculation of transient U-value from May to September are excluded for the colder climates A, B and E, while for the warmer climates C and D the excluded period has been prolonged from March to October.

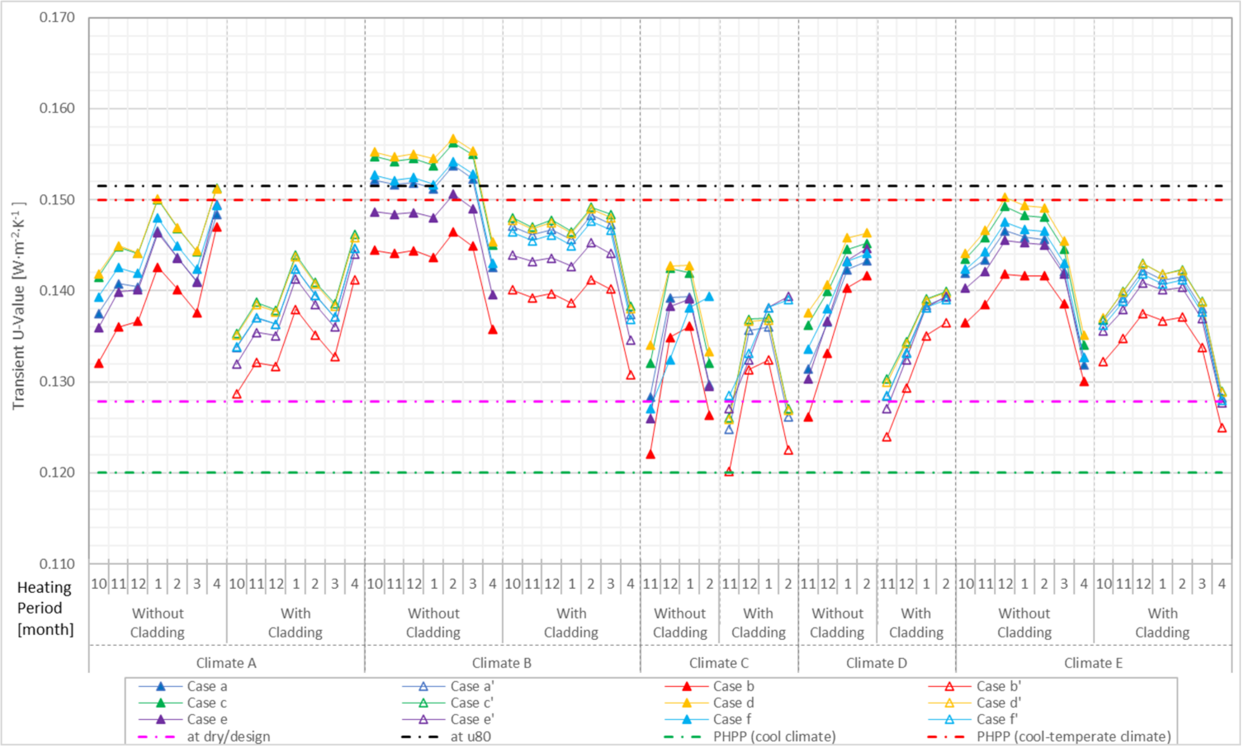
In general, SB walls with exterior cladding have shown lower transient U-value in comparison to walls without cladding during heating period under different exterior finish and exterior climates, with 0.13 W.m^{-2}.K^{-1} and 0.14 W.m^{-2}.K^{-1} in average respectively. For SB walls with mortar finish, cases 1’-3’ show lower transient U-value compared to cases 1-3, about 5% lower in climate A, 7% in climates C and D, 8% in climate B, and 11% in climate E. For SB walls with sheathing boards and exterior cladding, cases 4’ and a’-f’ show approximately 3% lower transient U-value under climate A, C and D, and 4% lower under climate B and E, in comparison to the respective cases 4 and a-f without exterior cladding. The application of exterior cladding in SB wall design has in particular improved their transient U-value under climates with higher annual rain fall, i.e. climate B and E.

SB walls with mortar finish and without cladding (case 1-3) under climate B and E exhibits high transient U-value during heating period; up to 0.165 W.m^{-2}.K^{-1} under climate E and 0.16 W.m^{-2}.K^{-1} under climate B. By using sheathing boards as finishing or including exterior cladding in the design, their highest transient U-value can be reduced to 0.15 W.m^{-2}.K^{-1} or even lower. For climate A, C and D, the highest transient U-values are around or below the u80 (U-value at ϕ = 0.8), i.e. 0.15 W.m^{-2}.K^{-1}. In overall, the transient U-value among different mortar finishing are not deviating significantly under the same climate.

For SB walls with sheathing board as finishing, hard wood fibreboard (case c/c’) and OSB (case d/d’), which have with higher μ compared to other types of sheathing boards, have shown the highest transient U-value. In contrast, sheathing boards with lower μ, i.e. porous wood fibreboard (case b/b’) and gypsum board (case e/e’), have shown a comparable low transient U-value under all climates.



(a)



(b)

Figure 8 Transient U-value of the designed SB walls under different climate profiles for (a) case 1 to 4, (b) case a to f. The markers show highest transient U-value among four different wall orientation for each case and climate type.

3.3. Mould growth risk

The various SB wall assemblies have been further investigated by terms of mould growth risk under various climates, using mould index definition developed by Hukka and Viitanen [31]. Three factors will be investigated on its impact to the mould growth in SB assemblies, i.e. SB designs (Table 2), exterior climates (Table 3), and indoor climates (EN 13788 humidity Class 2 to 4). Based on *Figure 5*, it can be further inferred that SB layer closest to its exterior side has the highest level of moisture content w, and thus will have the highest possibilities of mould growth compared to other part of SB. In this context, SB layer closest to its exterior side will be first analysed for mould growth risk under three indoor humidity classes, as shown in *Figure 9*. Mould index of different depth of SB layer from exterior finish under indoor humidity class 3 have been further investigated and presented in Figure 10.

Finishing layers using clay, lime, or lime-cement mortar without exterior cladding (case 1-3) show high mould growth index under all climates. The index is especially high at its maximum under climate C and E, correspond to combination of high exterior ϕ and air temperature. Mould growth are predicted at SB side section up to 200mm under climate E, followed by 150mm for climate B and C and 50mm for climate A and D. The exterior cladding with ventilated cavity, which provide additional weather protection, has significantly reduced the mould growth potential to none (case 1’, 2’ and 3’).

SB walls with porous wood fibreboard and gypsum board as exterior sheathing board, either with or without exterior cladding, show no mould growth under all climate conditions employed. Other exterior sheathings, i.e. wind barrier graded fibreboard, hard wood fibreboard, fibrecement board and OSB have shown risk for mould growth at SB side section up to 150mm under climate B and 100mm under climate E. No mould growth is predicted on SB wall with all types of simulated sheathings under climate C and D.

Both exterior climate and additional wall protection, e.g. exterior cladding, are the main factor in affecting mould growth risk in the SB layer. In general, SB assemblies under climate B and E, which are characterized by high ϕ, show higher mould index when there is exterior cladding applied, while assemblies with exterior cladding and air cavity show lower mould index. Exception to the latter is the cases where the sheathing board has a relatively high μ value. However, further investigation on the impacts of water vapour diffusion equivalent air layer thickness S_d of a SB's exterior finishing on mould growth potential does not indicate a strong correlation between two.

Figure 11 shows other existing case studies from the literature on mould growth in SB walls. Mould growth risks predicted in this study are higher compared to available case studies, however this might be due to the limited sample size in the existing case studies.

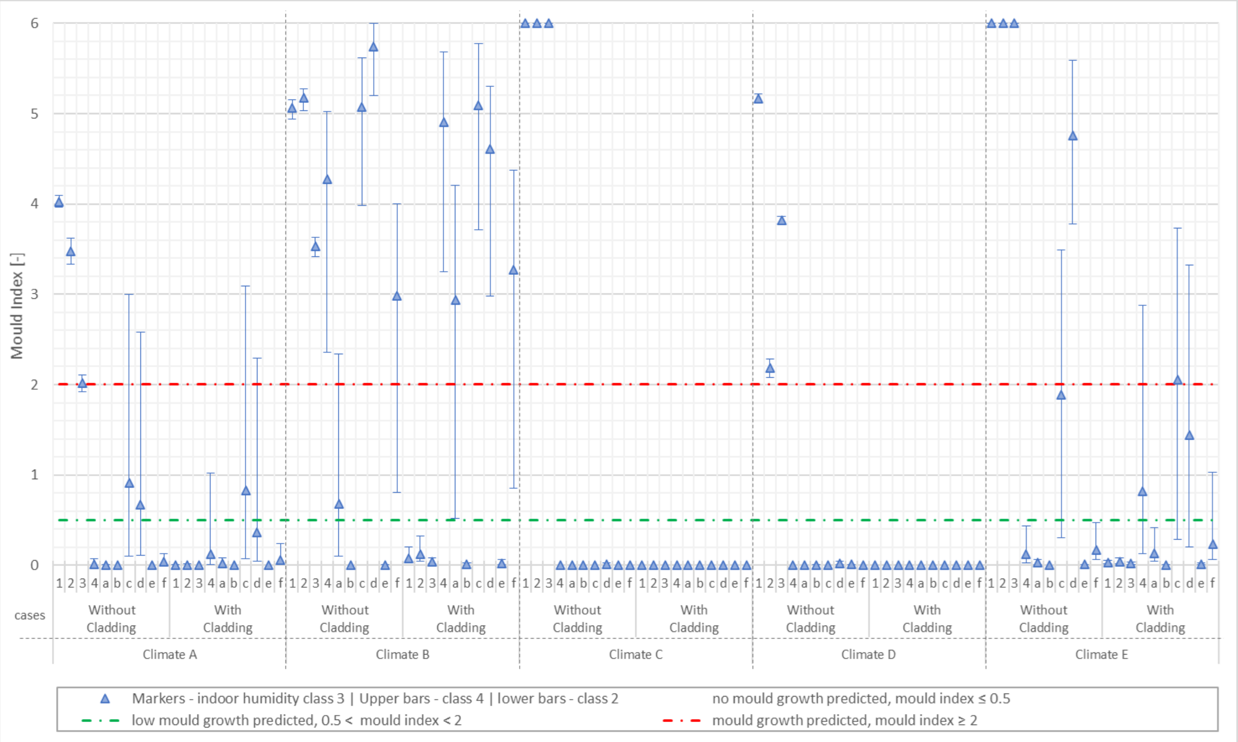
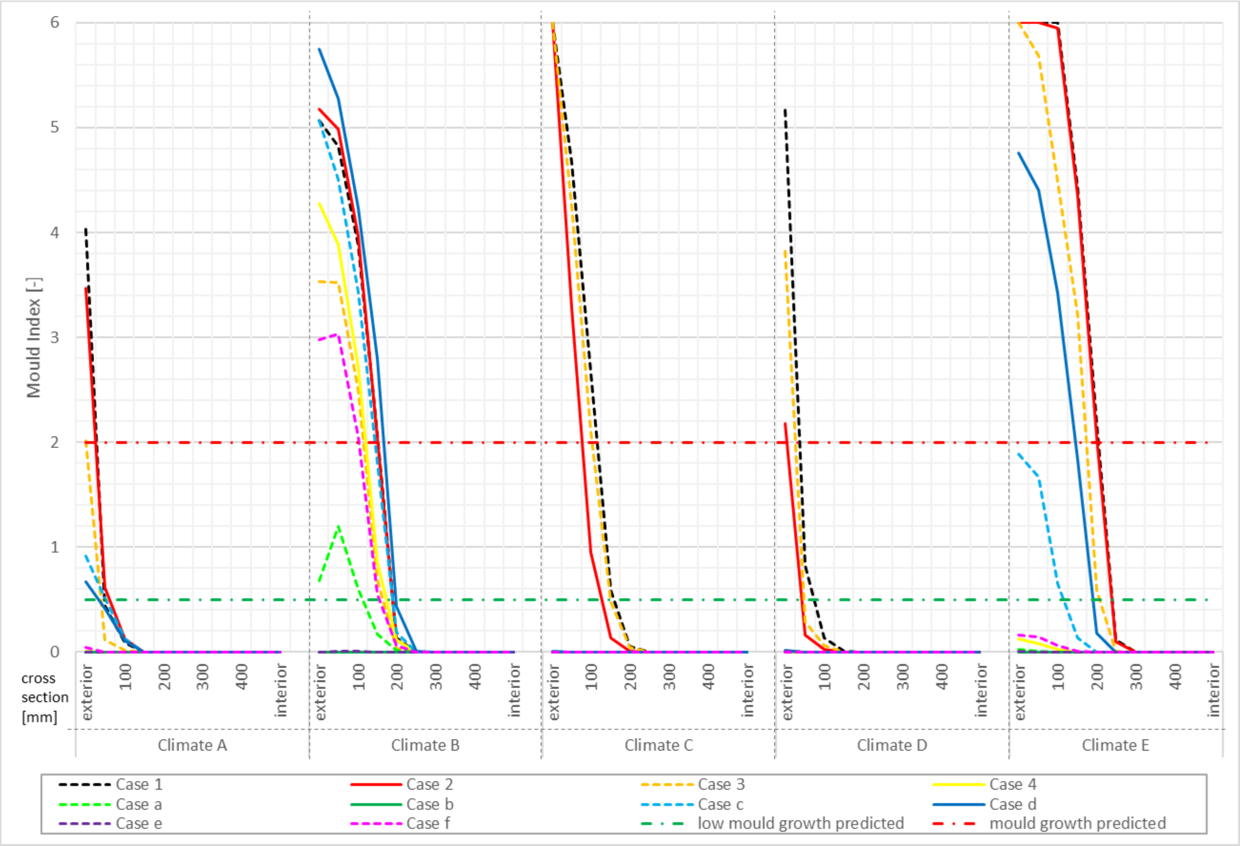
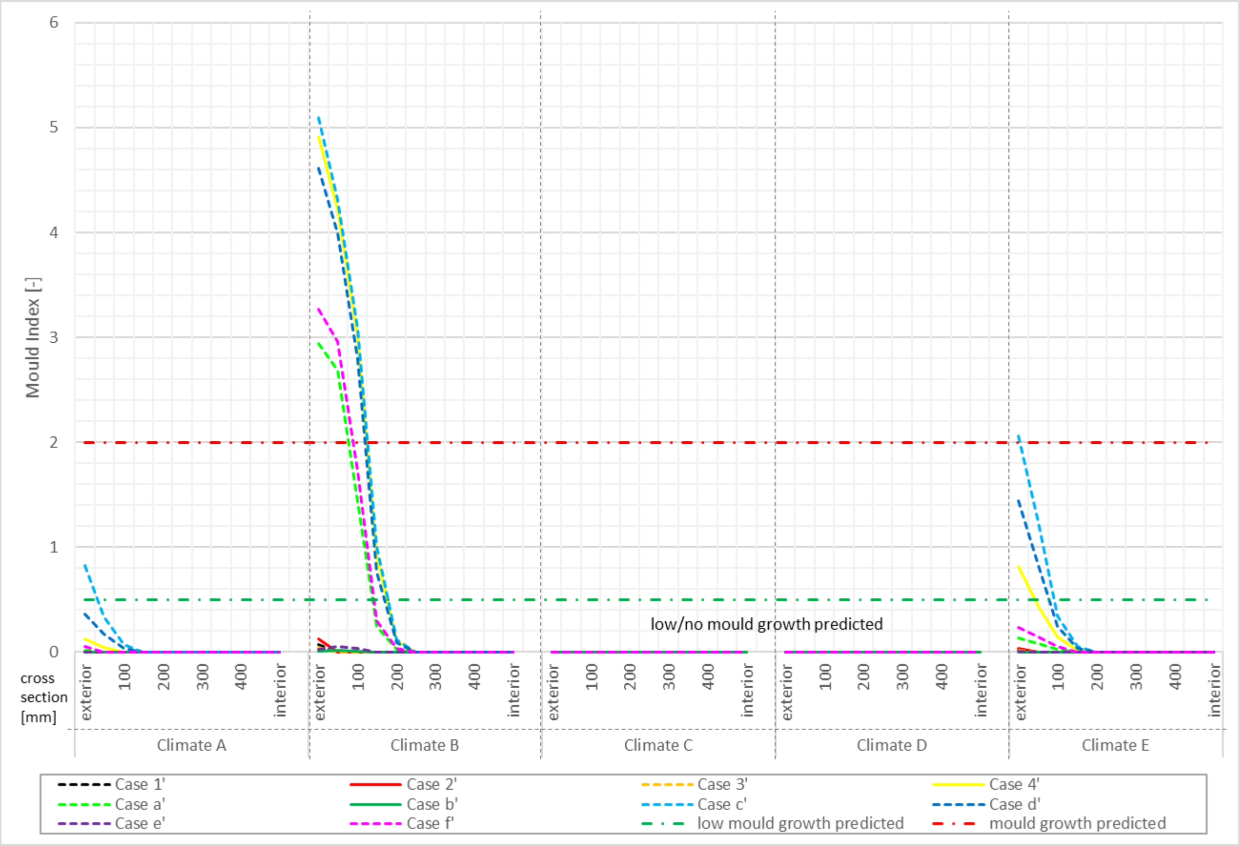


Figure 9 Mould index for different SB wall assemblies (SB layer closest to exterior finish) under simulated climates at 5th year. Markers show mould index under indoor humidity class 3. For reference, mould index under indoor humidity class 4 shown as upper deviation bars and mould index under indoor humidity class 2 shown as lower deviation bars.


Mould Index [-]
6
5
4
3
2
1
0
cross section [mm]
exterior
100
200
300
400
interior
Climate A
Climate B
Climate C
Climate D
Climate E
Case 1
Case 2
Case 3
Case 4
Case a
Case b
Case c
Case d
Case e
Case f
low mould growth predicted
mould growth predicted

(a)


Mould Index [-]
6
5
4
3
2
1
0
low/no mould growth predicted
cross section [mm]
exterior
100
200
300
400
interior
Climate A
Climate B
Climate C
Climate D
Climate E
Case 1'
Case 2'
Case 3'
Case 4'
Case a'
Case b'
Case c'
Case d'
Case e'
Case f'
low mould growth predicted
mould growth predicted

(b)

Figure 10 *Mould index of SB cross section under different case and climate at 5th year* for *(a) cases without cladding, (b) cases with cladding*

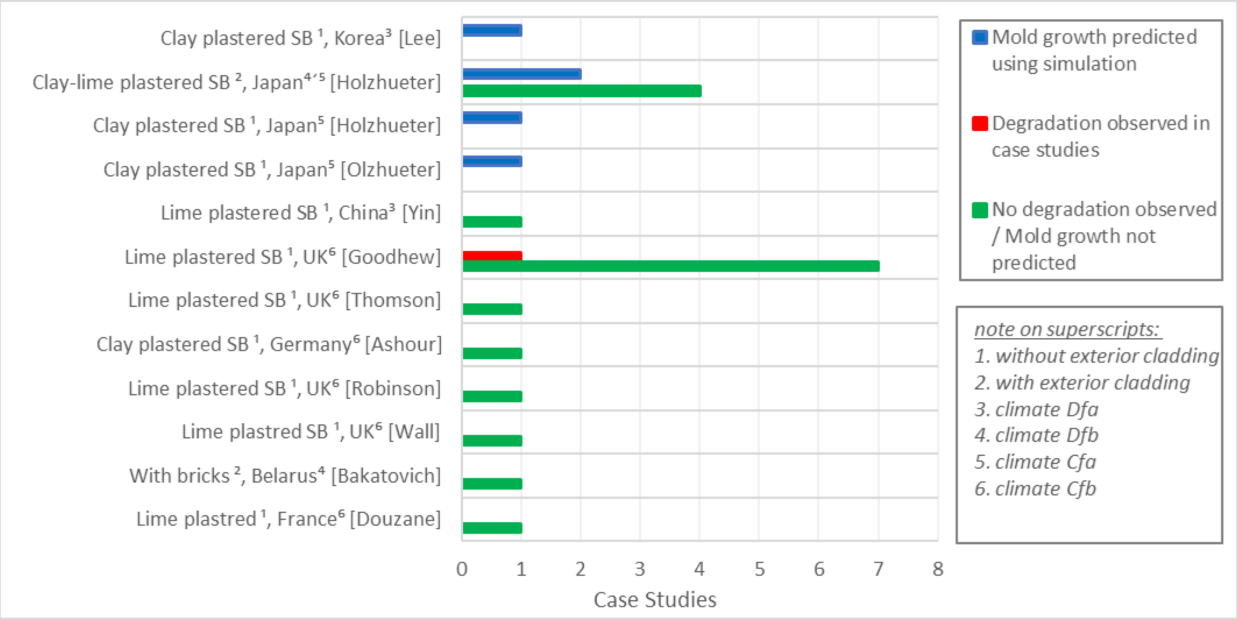


Figure 11 Mould growth comparison with case studies from Lee et al. [32], *Holzhueter et al.* [33] [34] [35], *Olzhueter et al.* [36], *Yin et al.* [37], *Goodhew et al.* [10], *Thomson and Walker* [8], *Ashour et al.* [11], *Robinson et al.* [9], *Wall et al.* [15], *Bakatovich et al.* [38], *Douzane et al.* [7]

3.4. Energy use during operation and embodied emissions

The results from the building energy simulation have shown that the heating and cooling demand for a SB building with different wall assembly designs are not deviating much under the same climate, given a relatively thin layer of wall finishing compared to straw bale cross section. The heat loss through SB walls are in the range of 18% to 25% of the whole building depending on the climates, while heat gain through SB walls are in the range of 3% to 10% only.

The simulated heating and cooling demands are compared to respective average country specific household consumptions, i.e. Statistics Norway (SSB) [39] for climate A and B, Odyssee-Mure [40] for climate C, D and E, and cooling consumption, i.e. Persson and Werner [41] for all climates. The simulated energy demand of SB building is lower than the average household heating or cooling demand in their respective country (Figure 12). In a colder climates, i.e. climate A, B and E, the simulated heating demand is in the range of 12-24% of average household consumption, while in a warmer climate, the cooling demand for climate C is around 41% of the average consumption and 32% under climate D.

Figure 13 show the indoor ϕ profiles of SB building with exterior wall assembly case 1. Due to similar indoor environment profile for all cases under the same climate, only case 1 has been presented here. The indoor ϕ level is recommended to be in the range of 25% and 60% to achieve a comfort level category II IEQ_{II} under EN 16798-1 [18]. Without any mechanical humidification or dehumidification, the designed SB building under climate C showed the worst performance, as the indoor ϕ exceeded the level of 60% for 14.8% of the time in a year, followed by climate D with 13.6% and climate E with 6.4%. In comparison, climate A has experienced only 1.1% during a typical year with indoor ϕ outside the comfort range, followed by climate B with 1.8%. Time series for indoor relative humidity ϕ and air temperature during a year are shown in Appendix B, Figure B4.

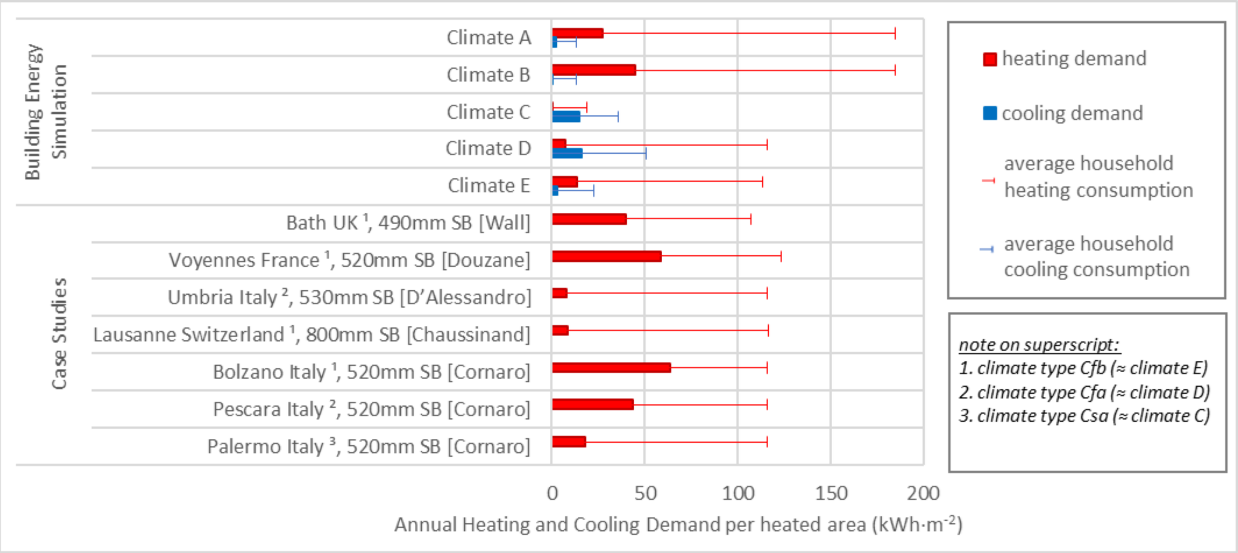


Figure 12 Energy demand under different climates with wall assembly Case 1, in comparison with case studies from Cornaro et al. [16], Chaussinand et al. [14], D'Alessandro et al. [13], Douzane et al. [7], Wall et al. [15]. Upper boundaries show average country specific household heating and cooling consumption.

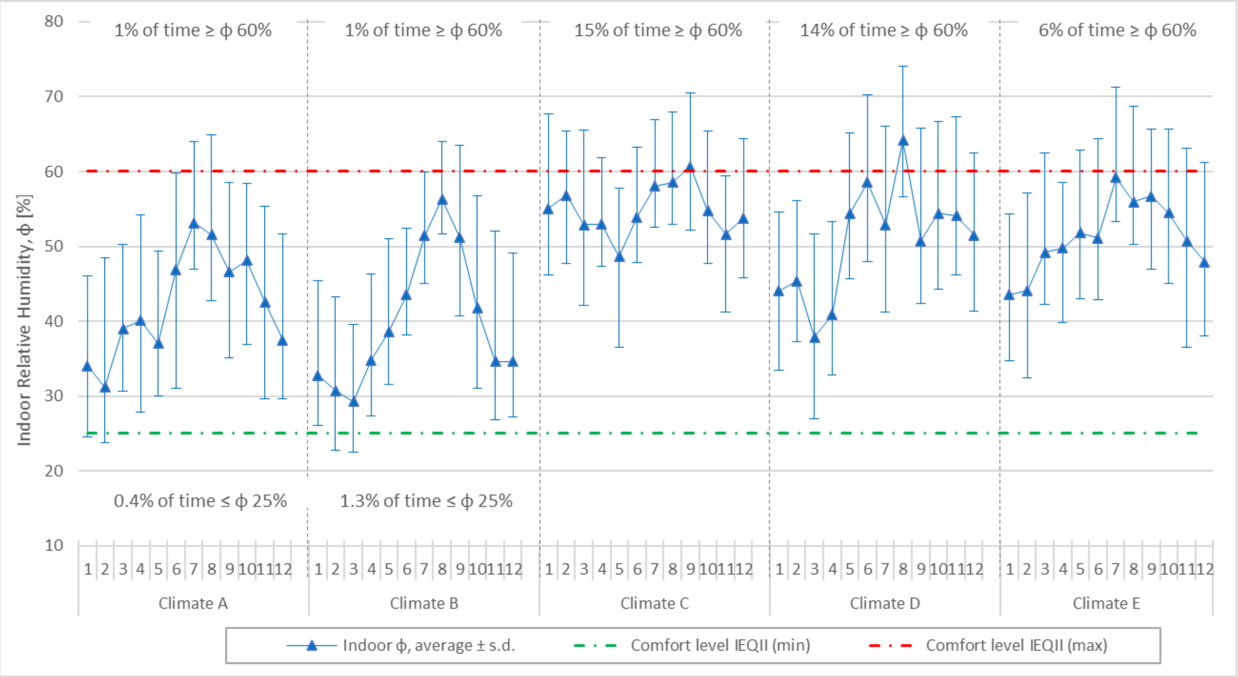
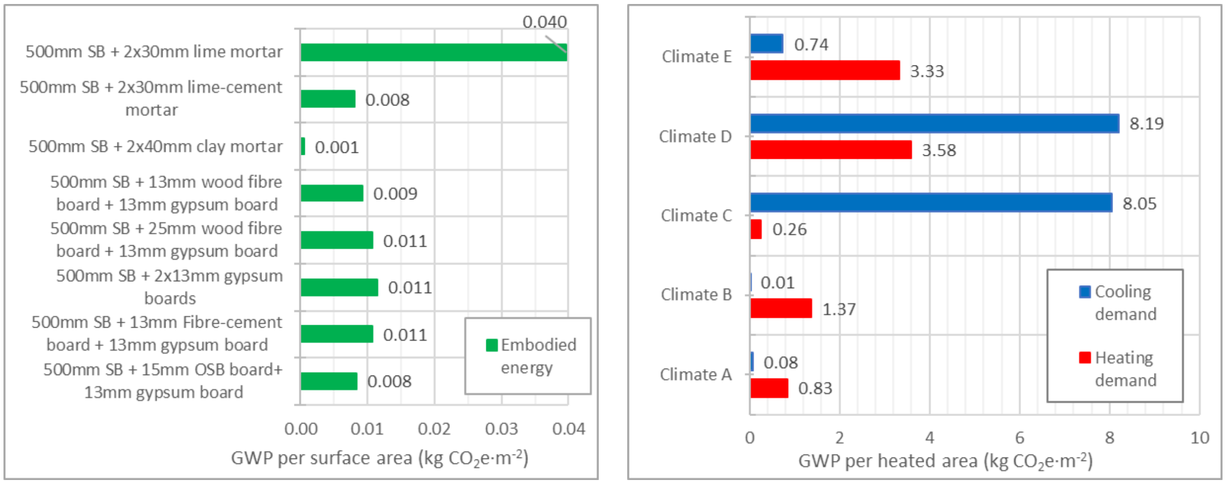


Figure 13 Annual indoor ϕ for wall assembly Case 1. Markers show average ϕ in a year. For reference, maximum indoor humidity shown as upper deviation bars and minimum indoor humidity shown as lower deviation bars. Percentage of simulated time outside the comfort level IEQII limits are highlighted.

A partial life cycle assessment has been done to evaluate the selection of SB finishing, i.e. mortars and sheathing and boards, based on their embodied energy (A1-A3) and the results are shown in Figure 14a. Clay mortar has shown the lowest embodied energy compared to other finishing, while lime mortar has the highest embodied energy. It should be noted that in this study, the GWP of lime mortar is estimated at 0.37kg $CO_2e\cdot kg^{-1}$ [42] and lime-cement mortar at 0.11kg $CO_2e\cdot kg^{-1}$ [43], refer to Appendix B, Table B1. A second assessment has been done on the energy use, i.e.B6, and in particular from heating and cooling requirement under different climates. If assuming all heating and cooling are generated through local electricity grid system, Figure 14b shows the GWP due to heating and cooling demand in the same SB building under different climates, by factoring their country specific electricity mixes.



(a) (b)

Figure 14 GWP (a) embodied energy A1-A3 of different SB finishing per surface area m^2 and (b) part of energy use B6 due to heating and cooling demand per heated area m^2

3.5. Summarizing Result

Based on the findings in this study, recommendations on selecting different exterior finishing layers for straw bale wall under different climate types have been summarized and presented in Table 5, which can be used as a tool to choose the correct straw bale wall finishing under a similar climate profile.

Table 5 Recommendation on selecting of exterior finishing under different climate types

Straw bale wall finishing (exterior + interior) with 500mm thickness of straw bale layer	**Climate Dfb**	**Climate Dfc**	**Climate Csa**	**Climate Cfa**	**Climate Cfb**	**Embodied energy** [note iii]
30mm Lime mortars both sides	H / n [note i]	H / n	H / n	H / n	H / n	5
30mm Lime-cement mortars both sides	H / n	H / n	H / n	H / n	H / n	4
40mm Clay mortars both sides	H / n	H / n	H / n	H / n	H / n	1
Sheathing boards – 25mm woodfibreboard (windbarrier) + 13mm gypsum board	n / n	H / H	n / n	n / n	n / L	2
Sheathing boards – 13mm woodfibreboard (windbarrier) + 13mm gypsum board	n / n	L / H	n / n	n / n	n / n	3
Sheathing boards – 13mm woodfibreboard (porous) + 13mm gypsum board	n / n	n / n	n / n	n / n	n / n	2
Sheathing boards – 13mm woodfibreboard (hard) + 13mm gypsum board	L / L	H / H	n / n	n / n	L / H	2
Sheathing boards – 15mm OSB + 13mm gypsum board	L / n	H / H	n / n	n / n	H / L	2
Sheathing boards – 13mm gypsum boards both sides	n / n	n / n	n / n	n / n	n / n	3

Sheathing boards – 13mm fibre-cement board + 13mm gypsum board	n / n	H / H	n / n	n / n	n / L	3
Annual Heating Demand (kWh·m^{-2})$^{\text{note iv}}$	27.1	44.6	0.5	7.1	13.9	-
Annual Cooling Demand (kWh·m^{-2})$^{\text{note iv}}$	2.5	0.3	14.9	16.4	3.1	-

Notes:

i. Legend: X / Y, where X is straw bale assembly without exterior cladding, and Y is straw bale wall assembly with exterior cladding and ventilated cavity. **n** – no mould growth predicted (recommended, mould index ≤ 0.5); **L** – low mould growth predicted, mould index 0.5 < x < 2; **H** – mould growth predicted (unacceptable / not recommended, mould index x ≥ 2)
ii. Results are based on interior climate as per EN 13788 with humidity Class 3
iii. Embodied energy under A1-A3, ranking from lowest (1) to highest (5)
iv. Minimum 20°C for heating, maximum 26°C for cooling

4. Conclusions

The following conclusions can be drawn on the application of straw bale in exterior wall construction systems:

1. Exterior climate is the most significant factor in determining hygrothermal and energy performance of a straw bale building when other criteria are the same.
2. Under all simulated climates, straw bale layer closest to the exterior side (exterior climate) has the highest level of moisture content, the highest ϕ, and with temperature closest to its dew point, in comparison to other part in its cross section. Low water content is presented in the layer closest to the interior side part of the straw bale cross section. This implies straw bale layer closest to the exterior side will be the most susceptible to mould growth.
3. Straw bale wall with exterior cladding and ventilated cavity will regulate water content inside straw bale throughout a year and prevent any substantial increment of its U-value during heating period.
4. For non-loading straw bale wall, using sheathing board instead of mortar as exterior finishing can regulate water content inside straw bale. However, for climate with high ϕ (e.g. climate B and E), among the simulated material, only low μ sheathing boards, e.g. porous wood fibreboard and gypsum board with thickness around 13mm have been found suitable. Straw bale wallswith other sheathing boards such as hard wood fibreboard, OSB and fibrecement board, i.e. with higher μ, or thicker wood fibreboard, e.g. 25mm, are susceptible to mould growth in humid environment. Both porous wood fibreboard and gypsum board are found suitable for all climates employed in this study.
5. Low cooling and heating demand can be achieved in a straw bale house with 500mm thickness of straw bale layer, in comparison to average household consumption. However, indoor ϕ might exceed the comfort level during cooling period of the year.

The hygrothermal (*Figure 7*) and energy performances (Figure 12) of straw bale wall configurations and building model employed in this study show good agreemtn when comparing to other previously published case studies. Mould growth risks predicted in this study are somewhat higher when compared to the existing case studies (*Figure 11*), however it might be due to the limited sample size in the latter ones. More field studies on straw bale building under different climate types are recommended in order to verify their mould growth risks as presented and discussed in this study.

Appendix A Supplementary notes to section 2

Table A1 software used in this study

Simulation	**Software**	**Remarks**
Hygrothermal Analysis	WUFI Pro V.5.3	Simulation in a five-year period using hourly step. Results at the fifth year will be taken for analysis.
Mould Growth Simulation	WUFI Bio V.3.5	Simulation based on result obtained from hygrothermal analysis.

Energy Simulation	WUFI Plus V.3.1.1.0	Simulation in a one-year period using hourly step, with additional two months initialization period for preliminary calculation.
Life Cycle Assessment	OneClick LCA	Calculation of global warming potential (GWP)

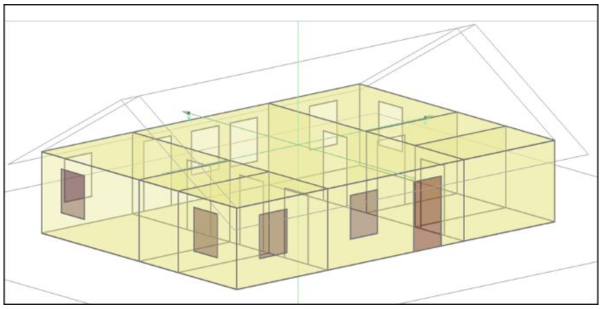
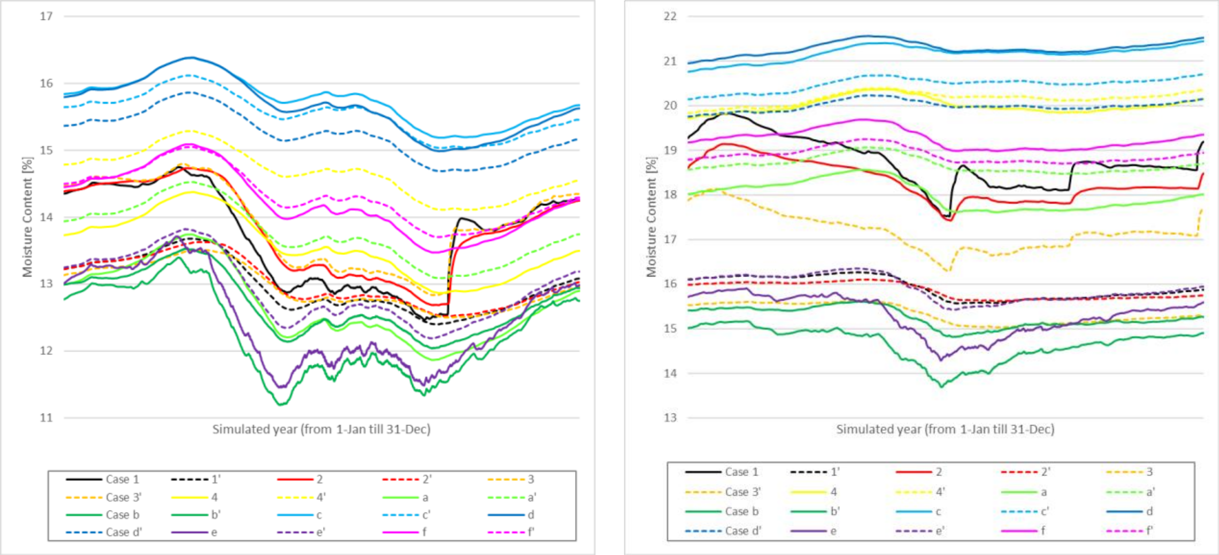


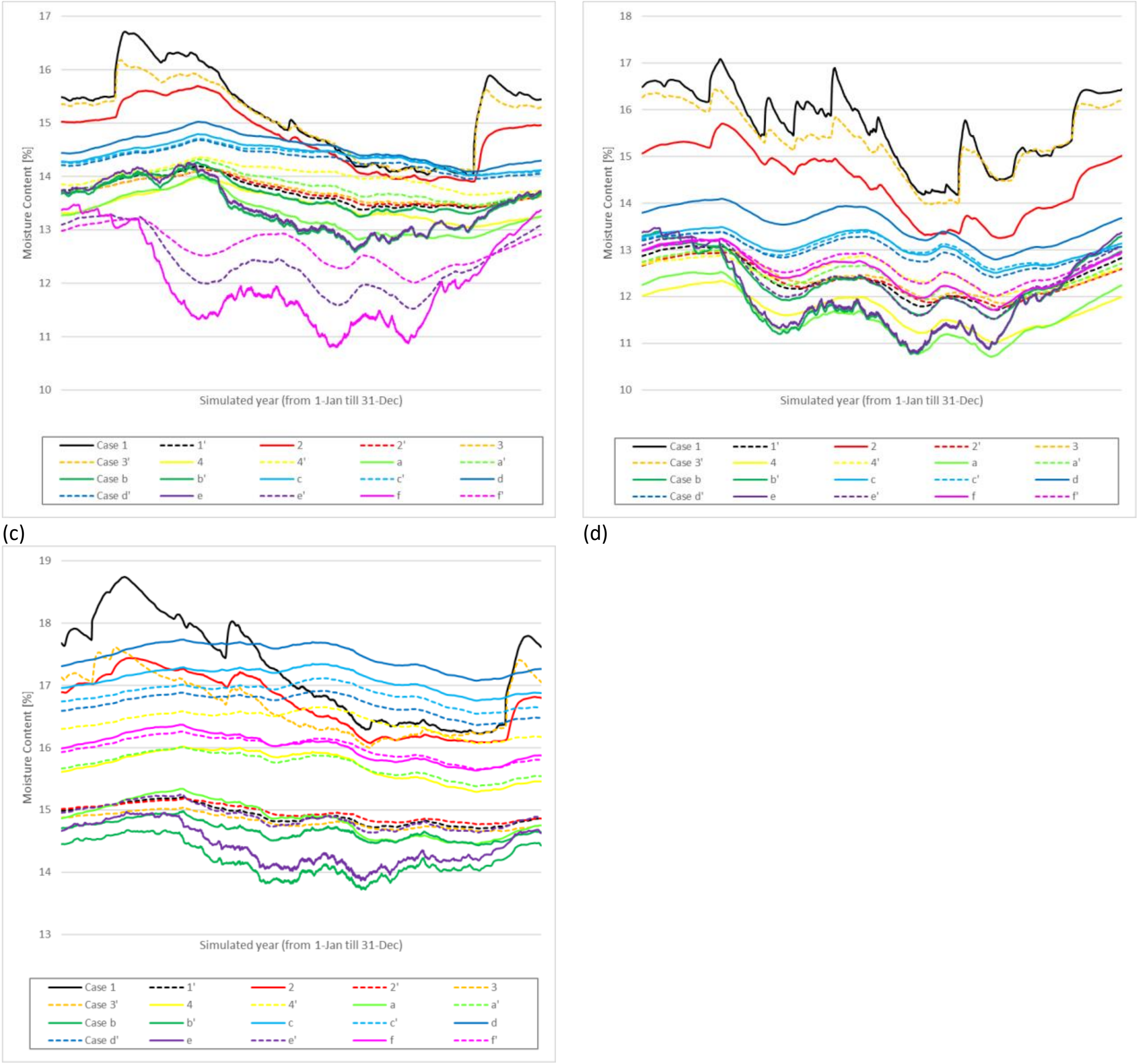
Figure A1 Schematic of simulated straw bale building. Heated region is colored, attic is unheated and excluded from BES.

Appendix B Supplementary notes to section 3



(a)

(b)

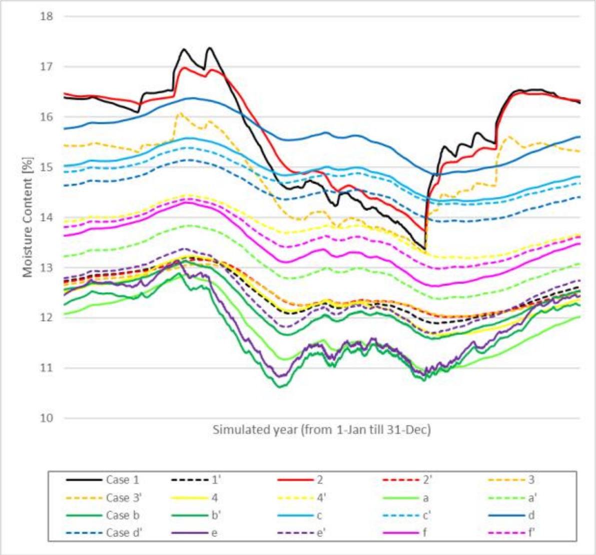


(c)

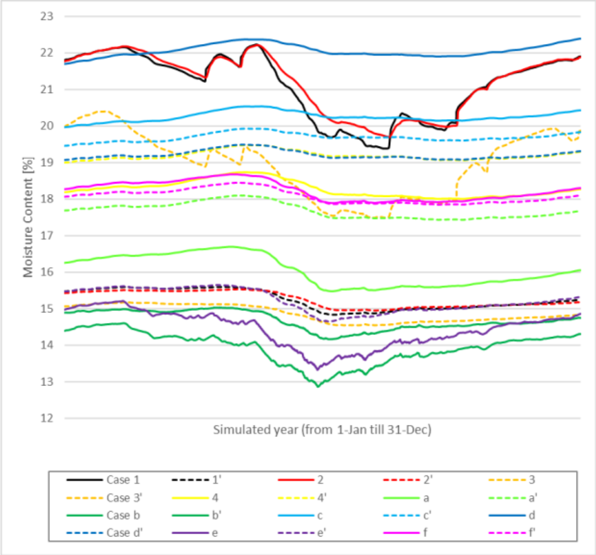
(d)

(e)

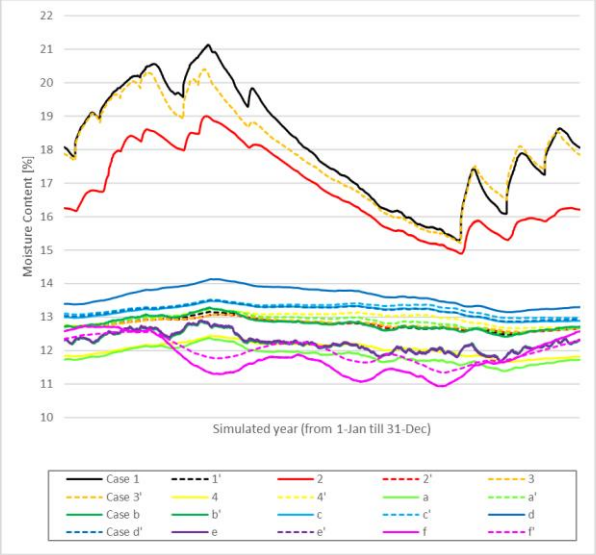
Figure B1 Time series of moisture content w [%] of overall SB cross section of 'north' wall orientation in a year, under different case and (a) climate A, (b) climate B, (c) climate C, (d) climate D, and (e) climate E


18
17
16
15
14
13
12
11
10
Moisture Content [%]
Simulated year (from 1-Jan till 31-Dec)
Case 1
1'
2
2'
3
Case 3'
4
4'
a
a'
Case b
b'
c
c'
d
Case d'
e
e'
f
f'

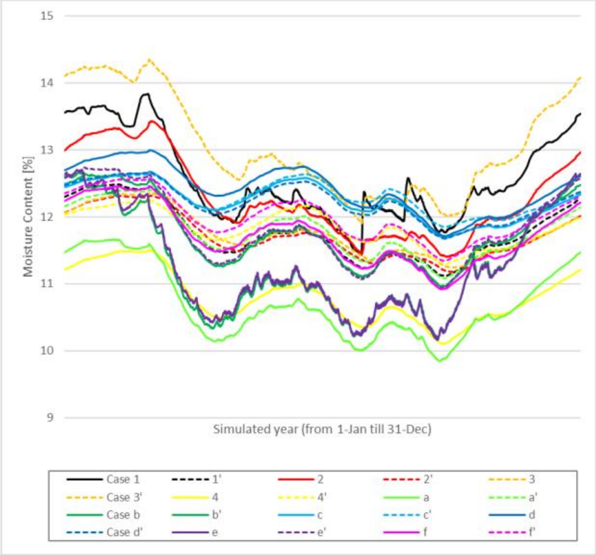
(a)


23
22
21
20
19
18
17
16
15
14
13
12
Moisture Content [%]
Simulated year (from 1-Jan till 31-Dec)
Case 1
1'
2
2'
3
Case 3'
4
4'
a
a'
Case b
b'
c
c'
d
Case d'
e
e'
f
f'

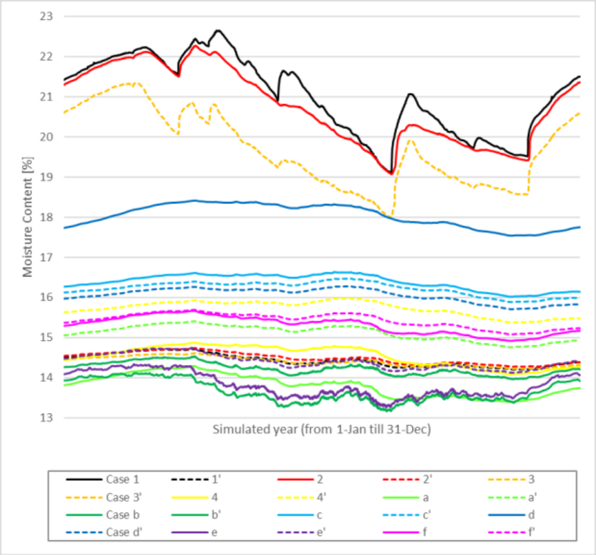
(b)


22
21
20
19
18
17
16
15
14
13
12
11
10
Moisture Content [%]
Simulated year (from 1-Jan till 31-Dec)
Case 1
1'
2
2'
3
Case 3'
4
4'
a
a'
Case b
b'
c
c'
d
Case d'
e
e'
f
f'

(c)


15
14
13
12
11
10
9
Moisture Content [%]
Simulated year (from 1-Jan till 31-Dec)
Case 1
1'
2
2'
3
Case 3'
4
4'
a
a'
Case b
b'
c
c'
d
Case d'
e
e'
f
f'

(d)


23
22
21
20
19
18
17
16
15
14
13
Moisture Content [%]
Simulated year (from 1-Jan till 31-Dec)
Case 1
1'
2
2'
3
Case 3'
4
4'
a
a'
Case b
b'
c
c'
d
Case d'
e
e'
f
f'

(e)

Figure B2 Time series of moisture content w [%] of overall SB cross section of 'south' wall orientation in a year, under different case and (a) climate A, (b) climate B, (c) climate C, (d) climate D, and (e) climate E

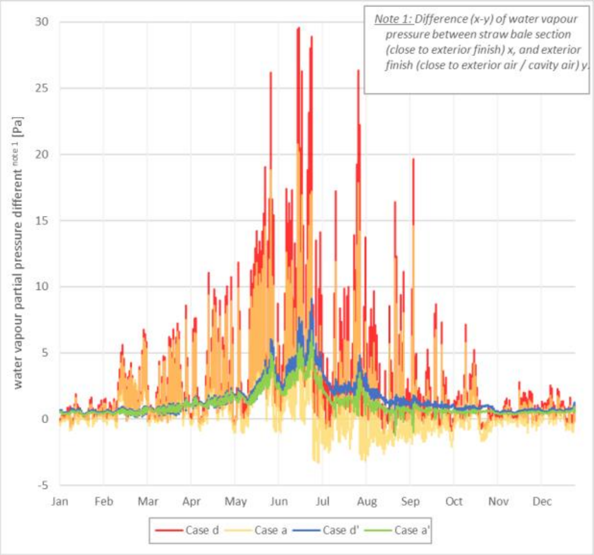
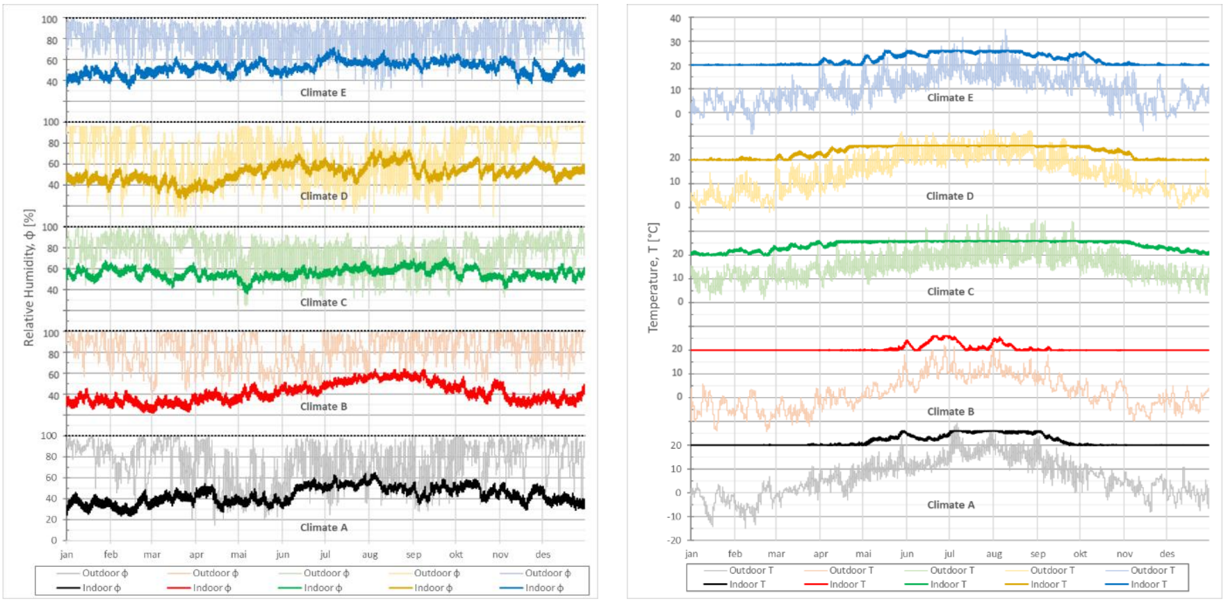


Figure B3 Time series of vapour partial pressure at SB layer (close to exterior sheathing board) and sheathing board (close to exterior air or cavity air) for Case a, a', d and d' under climate B in a year



(a) (b)

Figure B4 Time series under one simulation year in BES for indoor and outdoor (a) ϕ and (b) temperature

Table B1 GWP of materials used in LCA

Material	**GWP [kg $CO_2e \cdot kg^{-1}$]**	**EPD Data Source (main reference: OneClick LCA database)**
Straw bale	0.0658	EPD Baustrohballen Fachverband Strohballenbau Deutschland e.V.
Lime mortar	0.37	EPD Mineralische Werkmörtel: PutzmörtelNormalputz/ Edelputz mit besonderen Eigenschaften Verband für Dämmsysteme, Putz und Mörtel e.V. (VDPM)

Cement-Lime mortar	0.11	Oekobau.dat 2020-II
Clay mortar	0.003	LCA inventory for clay pit operation, Ecoinvent 2014
Gypsum board (interior)	0.29	One Click LCA
Wood fibreboard	0.29	Oekobau.dat 2017-I, EPD EGGER DHF FRITZ EGGER GmbH & Co. OG Holzwerkstoffe
OSB	0.36	One Click LCA
Fibre-cement board	0.82	One Click LCA

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