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Assessing the impact of climate change on energy retrofit of alpine historic buildings: consequences for the hygrothermal performance

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Abstract. Climate change will affect future hygrothermal performance of buildings. This could lead to higher risks regarding energy optimization, thermal comfort and historic building conservation depending on the local climate, building construction and retrofit solutions adopted. This paper explores the risks brought by climate change on a typical residential historic building of South Tyrol. The results obtained show that, although the climate warming will reduce the future heating energy demand, an improvement of buildings' energy performance will still be necessary to increase sustainability and ensure their continued use. Natural ventilation would suffice to prevent overheating in the studied location, but a further analysis is needed for warmer alpine regions. Regarding the moisture-related risks for the historic construction, mould growth should be considered when retrofitting a wooden wall and frost damage should be carefully studied in the case of sandstone walls.

1. Introduction

The severity and impact of climate change has been rigorously assessed in scientific literature. According to IPCC's (Intergovernmental Panel on Climate Change) Fifth Assessment report [1], the increase of global surface temperature by the end of 21st century is expected to exceed 2.6 - 4.8 °C compared to 1986-2005 in the most pessimistic scenario. Together with this temperature increase, extreme climate events are expected to occur more frequently. For instance, the length, frequency and intensity of heat waves[1] might increase in large parts of Europe, Asia and Australia. It is also likely that "extreme precipitation events will become more intense and frequent in many regions" [1]. The EEA (European Environment Agency) also confirmed this tendency [2]. However, the changes among different regions will not be uniform. For instance, precipitation will likely decrease in many mid-latitude regions while increase in other regions. Studies carried out in Alpine context have confirmed serious challenge of climate change. The 2018 South Tyrolean Climate Report [3] indicates that the temperature increase during summer periods will be up to 5°C under the most pessimistic scenario by 2100. Besides the temperature increase, extreme precipitations will become more frequent in this Alpine region.

Increased temperatures and changed rain patterns might have great impacts on historic buildings in terms of energy use, indoor climate and moisture safety of buildings' envelope. When combined with retrofit solutions, several risks could threat the conservation and efficiency of historic buildings [4]:

1) Inadequate sizing of HVAC systems leading to energy inefficiency or discomfort.

2) Unsuited retrofit solutions and occupant behaviour combined with increased temperatures in summer might weaken the original passive cooling strategies and exacerbate the risk of overheating.

3) Moisture related risks are likely to increase if more extreme precipitations are found in combination with retrofit interventions that limit the drying capacity of walls.

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[1] Heat waves are excessively hot periods that last for several days or longer, which will cause the overheating of human body.

The retrofit of historic buildings is gaining an increasing attention in Europe. In fact, historic buildings constitute a considerable share of building stocks in Europe where more than 14% of existing buildings were built before 1919, 12% were built between 1919 and 1945 [5], and more than 40% were built before 1960 [6]. Most of these historic buildings have not undergone any energy retrofit. It is estimated that the retrofit of European building stock constructed before 1945 could save up to 180 Mt of CO_2 within 2050 [5] and improve the thermal comfort of occupants. However, considering the possible risks highlighted above, there is a need to investigate further aspects like the specific role of thermal mass and natural ventilation in alpine historic buildings and their combined effect with a changing climate. Additionally, the relationship between moisture dynamics in historic buildings, rain pattern changes and retrofit solutions should be evaluated on regional basis. In conclusion, retrofit solutions should be defined based on aforementioned knowledge and a clear awareness of future risks to maximise energy efficiency, occupant thermal comfort and ensure a proper building conservation.

2. Methodology

The results presented in this study are based on numerical simulations carried out on a reference building designed to be representative of Alpine historic residential buildings. Buildings performance is simulated and compared *before* and *after* retrofit, analysing possible retrofit interventions, as well as in *present* and *future* scenarios, using plausible forecasted future climatic conditions. In this paper, building's performance is assessed according to three parameters: energy demand, indoor comfort and moisture safety of the envelope.

2.1. Reference building construction

The geometry of the reference building is based on (i) the results of the TABULA [7] dataset, for Italy (Climate region E) and the province of Salzburg (Austria), (ii) the database and design guidelines proposed by CasaClima for the province of Bolzano (Italy) [8], and a study of the building stock in the Alpine region of Val Passiria (Italy) [9]. The building, a two-storey single family house with a living room on the ground floor and three bedrooms on the first floor and a total conditioned area of 180 m^2, could be deemed a typical residential house of the Alpine region. Details of the geometry are presented in Figure 1.
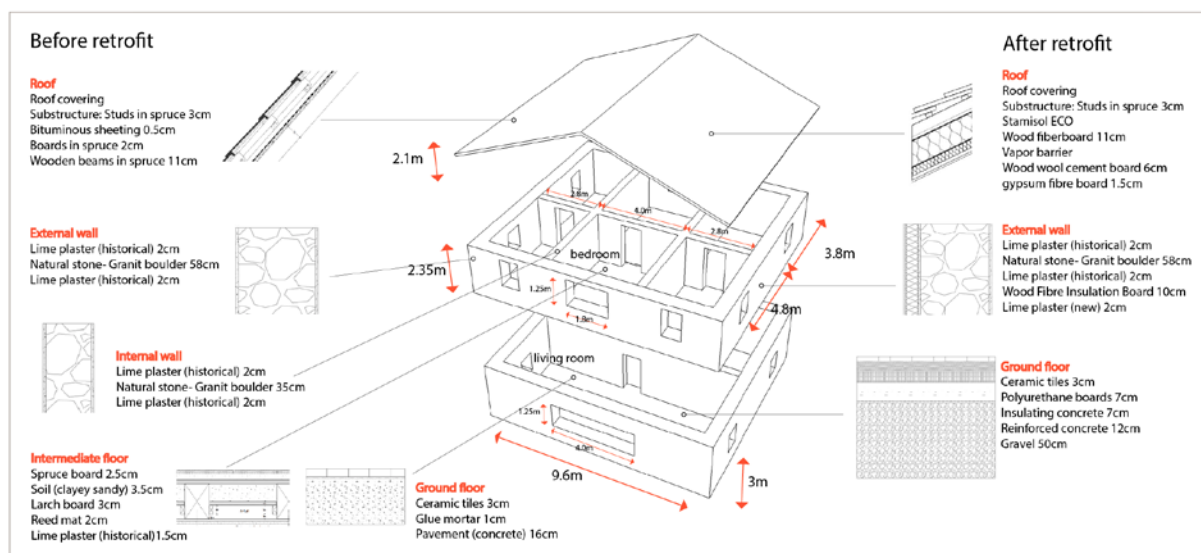

Figure 1 Geometry and construction of the reference building

The building construction and the retrofit solutions are defined based on literature and summary of current practice in South Tyrol [10-12]. The building is constructed with stone masonry walls and wooden pitched roof without any insulation. The main façade of the building (living room and bedrooms) is oriented to the south, with timber framed windows and single glazing. The considered

retrofit solutions are: 1) internal application of insulation on external walls, 2) roof and 3) ground floor, as well as 4) substitution of single glazed windows with double glazing. Details of the original construction and retrofit solutions are presented in Figure 1.

2.2. Future climate data

In order to assess future climatic conditions we used data from EURO-CORDEX initiative which provide high-resolution regional climate change simulations [13]. Within EURO-CORDEX initiative, the global climate projections from CMIP5[2] were dynamically downscaled for the European domain, and here two Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5, were used. These pathways represent two different scenarios, respectively intermediate scenario and business-as-usual scenario.

In the present study, we used the outputs of EURO-CORDEX: five general circulation models (GCMs) and regional climate models (RCMs) combinations. In detail, they are CNRM-CM5 with RCA4, IPSL-CM5A-MR with WRF381P, and EC-Earth (three different initial conditions: EC-Earth-r3i1p1, r12i1p1, r3i1p1) with HIRHAM5, RCA4 and RACMO22E. These five global models are forced by RCP4.5 and RCP8.5 respectively. Therefore, ten climate projections are established (5 GCM-RCM combinations, and for each 2 emission scenarios RCP4.5 and RCP8.5). The model data have been bias-corrected and downscaled for the city of Toblach in South Tyrol, Italy, using quantile mapping. Toblach is selected with the consideration of its abundant precipitation, which may threat conservation of historic buildings. Time series were extracted for precipitation, air temperature, humidity, wind speed, wind direction and solar radiation. The daily meteorological time series were further disaggregated to hourly data by open-source MEteoroLOgical observation time series DISaggregation Tool (MELODIST), see Förster K et al. [14].

The climate projections of final ten models are compared with observed station data of Toblach, and finally model IPSL-CM5A-MR-8.5 is adopted in this preliminary study considering its consistency with observation data in term of temperature and precipitation. In the simulation, *present* scenario is defined with the time span from 2011 to 2017, the longest time period available in the observational data set. The time span of *future* scenario is from 2094 to 2100.

2.3. Computational tool and numerical models

2.3.1. Energy demand and indoor climate calculation models. Energy demand and indoor climate are calculated using EnergyPlus 8.7.0 [15]. The heating energy demand for the building under climate and retrofit scenarios is calculated on the basis of the temperature set point during heating period, while indoor temperature and relative humidity (RH) in summer are calculated in free floating conditions, without any mechanical cooling system.

The assumptions and variables used for the simulations are reported in Table 1. The occupancy, lighting and electric appliances profiles are based on 2014 Building America House Simulation Protocols [16]. Airtightness of the building envelope before retrofit is defined according to literature review: 10 ac/h, at 50 Pa. In the literature, the average infiltration rate of 53 historic houses from Estonia, Finland and Sweden is 8.43 ac/h, at 50 Pa [17]. In UK, the infiltration rate of 471 houses rages from 9.9 to 16.5 ac/h. When restricting the construction year from pre 1900 to 1949, the infiltration rate rages from 10.5 to 16.5 ac/h [18]. The value after retrofit is defined according to CasaClima standard (A): 1.5 ac/h, at 50 Pa [8]. Ventilation rate is defined according to UNI 10339: 1995, based on an average ventilation level of residential buildings with normal level of expectation. The ventilation rate is calculated according to the occupants and area of the room in reference building. A scenario with additional natural ventilation was also established to test the ability of night cooling in mitigating indoor overheating. It is modelled by simplified ventilation calculations in EnergyPlus's Wind and Stack Open Area model. When the natural ventilation is trigged, the opening area of the window is defined as 50% [19].

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[2] The fifth phase of the Climate Model Intercomparison Project

Table 1 Assumptions and variables used for the simulations

Parameters	Value
Heating period	September 15th – April 15th
Heating set point	21°C
Occupants, lighting and equipment profiles	Defined based on *2014 Building America House Simulation Protocols [16]*
Infiltration rate -before retrofit	10 ac/h, at 50 Pa
Infiltration rate - after retrofit	1.5 ac/h, at 50 Pa [8]
Ventilation profile	Defined based on UNI 10339: 1995
Ventilation profile – additional ventilation	Wind and stack open area model

2.3.2 Moisture dynamic models. The hygrothermal performance of the retrofitted wall is calculated by means of numerical simulation with Delphin 6.0. This simulation tool has been validated on several aspects comparing predictions with measurements and tested in numerous studies [20-24].

Both the characteristics of the wall construction and internal and external climates have a significant influence on the hygrothermal performance of the envelope. Table 2 presents the defined wall characteristics and boundary conditions. Wind-driven rain (WDR) is the main source of the moisture influencing the moisture dynamic across the wall. WDR is calculated according to EN 15927-3 [25], where the wall annual index is an important parameter estimating the quantity of water impacting a wall of any given orientation. It takes into account the topography, local sheltering and the type of building and wall [25]. In the simulated reference building, the wall annual index is defined with following assumptions: the reference building located in a farmland with boundary hedges (Terrain category II), on flat ground, and it is a freestanding building with a distance of obstruction over 60 m.

Table 2 Parameters and values used in the hygrothermal simulations

Input parameter	Input distribution
Wall conditions	
Wall orientation (degree from North°)	90 (East)
Wall annual index	0.2499
Reduction coefficient of WDR	0.7
Outdoor boundary condition	
Heat conduction	Convective heat conduction exchange coefficient: 12 [W/m^{2}K]
	Effective heat conduction exchange coefficient: 12 [W/m^{2}K]
Vapour diffusion mass transfer coefficient	7.5e-09 [s/m]
Solar absorption coefficient	0.7
Long-wave emissivity	0.9
Indoor boundary condition	
DIN EN 15026/WTA adaptive indoor climate model	
Surface heat transfer coefficient	Convective + radiative: 8 [W/m^{2}K]
Surface vapour diffusion coefficient	5e-06 [s/m]

2.4. Assessment models

2.4.1 Indoor comfort assessment. Indoor comfort is assessed according to EN 15251 [26], which defines the comfort temperature range in free running buildings as a function of the outdoor temperatures. The approach in the standard is valid for dwellings where occupants can adapt the indoor thermal conditions through window operation or clothing arrangement. Thus, the assessment is carried out in the living room during the occupied hours where occupants could apply adaptive actions.

2.4.2 Frost damage assessment. In this study, the risk of frost damage is identified when two criteria are met: a) temperature is below freezing point of water in pores and b) the degree of saturation (S) reaches to critical degree of saturation (S_{crit}). In Vereecken et al.'s risk assessment [27], the freeze-thaw point is assumed to be -2°C. Different materials have different tensile strength, and so the degree of saturation that will lead to frost damage varies. In the present study, the critical value of granite in South Tyrol is set to 80%, and critical saturation ration of sandstone is equal to 60% according to C. Franzen's study [28]. The critical saturation ratio of plaster is set to 30% according to WTA 6-5 [29].

2.4.3 Mould risk assessment. This study uses the VTT model to assess the risk of mould growth. The model was established to measure mould growth primarily on wood and organic materials [30, 31], and was extended to other materials [32]. It is generally used in research [33, 34].

Mould growth will occur when $RH \geq RH_{crit}$, where RH_{crit} is a function of temperature, RH and time. Mould growth and decay rates relate to temperature, material type, and surface quality. Depending on the mould growth initial condition and growth rate, Mould Growth Index (MGI) represents the condition between no-mould and 100% mould coverage. In this study, the surface of wood fibreboard is defined as sensitive to mould growth and growth rate shows significant relevant decline, and climate board is defined as medium resistant to mould growth and growth rate shows relatively low decline. Mould risk is assumed to exist when MGI exceeds 1 [32].

3. Results and discussion

3.1. Present and future climate comparison

When comparing the annual temperature distribution in present and future scenarios, a general increase is noticeable (Figure 2): the average value raises 3.76°C. However, temperature increase is not constant throughout the year (Figure 3). The maximum increase appears in winter months with an average rise of 5.85°C, whereas in summer, the average increase is 2.06°C. Besides average values of temperature, the daily temperature gradient is an important indicator in defining the potential of night cooling. Figure 4 shows the distribution of daily temperature difference during present and future scenarios. The maximum temperature difference decreases, as well as the interquartile range showing a reduction in the temperature difference between the maximum and minimum daily values.

In winter, the increase of external temperature implies a reduction in heating energy demand, while in summer, a temperature rise may cause indoor overheating. Moreover, due to the drop of daily temperature difference in summer, night cooling effect may be weakened.
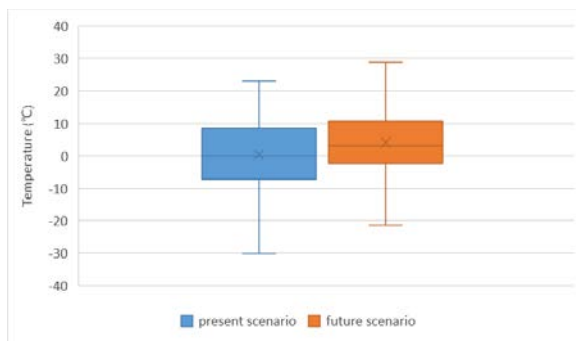

Figure 2 Annual temperature distribution of present and future scenarios
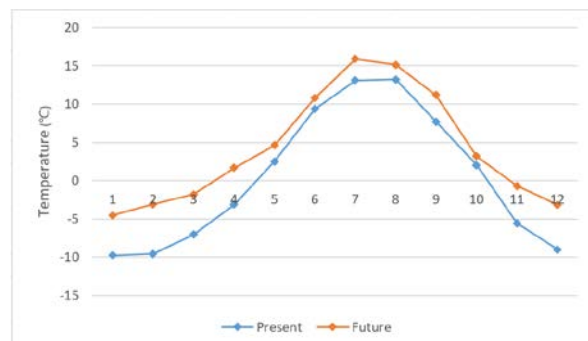
Figure 3 Average monthly temperature in present and future scenarios

The total amount of annual rain increases from 865 mm in present scenario to 993 mm in future scenario (Figure 5), while the annual rain event number decreases from 137 to 131 meaning that the amount of rainfall per event will increase considerably. The distribution of events' duration in future will remain similar. These changes in the rain patterns might lead to higher rain flux on the wall surface. Thus, there may be more water absorbed into the wall which limiting the drying process of the wall.
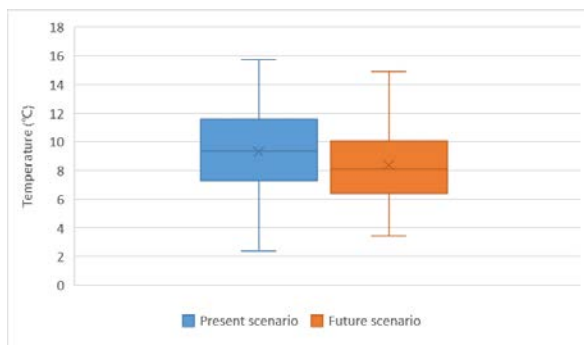
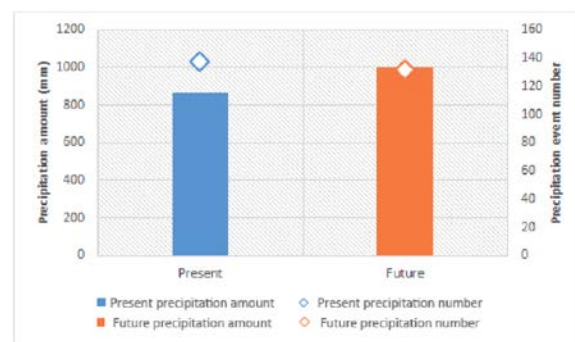Figure 4 The distribution of daily temperature difference of summer months in present and future scenarios

Figure 5 Annual precipitation amount and event number in present and future scenarios

3.2. Energy consumption

Figure 6 shows the average annual heating demand of the reference building in different scenarios. When comparing the energy demand between present and future scenarios, it could be seen that the energy demand in future decreases by 26% in un-retrofitted scenarios and 30% in retrofitted scenarios. This decrease may be explained as a consequence of the increase of outdoor temperature in future scenario that will lower the heating demand in any case. A higher relative reduction of energy demand is reported in the case of retrofitted buildings. This is possibly due to the ability of the insulated building to better preserve heat coming from internal loads that when combined with increased external temperature results in lower energy needs.

When retrofit solutions are applied, heating energy demand in both time scenarios (*present* and *future*) is dramatically reduced. Future scenario exhibits a slight advantage over the present scenario: the retrofit action achieves 86.4% energy saving in future scenario comparing to 85.6% in present scenario. This result shows that also with increased external temperature, retrofit interventions is still an effective way to improve energy efficiency.
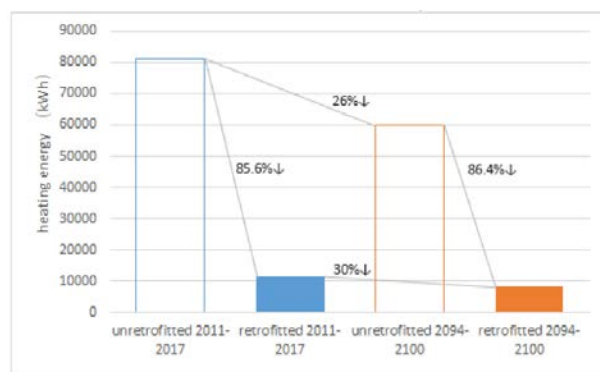

Figure 6 Average annual heating energy consumption of whole building in kWh for retrofitted/un-retrofitted and present/future scenarios
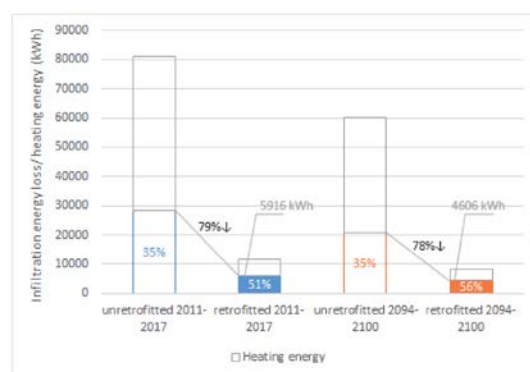

Figure 7 Average annual heat loss due to infiltration during the heating period in retrofitted/un-retrofitted and present/future scenarios (relative contribution to heating demand is shown as percentage)

Figure 7 shows the average annual heat loss due to infiltration during the heating months. Infiltration results in a significant energy loss comparing to total heating energy consumption in all scenarios (on average more than 35% of the heating energy demand). Retrofit solutions can effectively reduce this

infiltration by improving the airtightness of the envelope and cut more than 75% of the energy loss in present and future scenarios. However, the relative weight of energy losses due to infiltration increase in retrofit scenarios. This may due to the reduced share of energy losses across the envelope.

3.3. Indoor thermal comfort

Indoor thermal comfort is assessed according to the adaptive comfort model in EN 15251. As aforementioned, the assessment is carried out on living room where the occupants could apply adaptive action during the occupancy. In addition, the assessment method is applicable: when $10< \Theta_{rm} <30°C$ for upper limit and $15 < \Theta_{rm} < 30°C$ for lower limit without mechanical cooling systems [35]. Where Θ_{rm} is running mean outdoor temperature. Due to the relatively cold summer in Toblach (Figure 3), the applicable hours are only a fraction of the summer period. As shown in Figure 8, the average applicable hours increased from 1290 hours in present scenario to 1520 hours in future scenario. This increase reflects outdoor temperature increase.

When comparing comfort conditions before and after retrofit (Figure 8), there is an obvious change from under-heating to overheating state. The results show that retrofit interventions contribute to indoor overheating not only in future but also in present scenario. However, the overheating caused by the retrofit interventions could be easily relieved with an additional natural ventilation. When an extra ventilation plan is added, the overheating hours decrease and the indoor environment stays within a comfortable range most of the time.

When comparing different time scenarios, the overheating rate in retrofitted buildings grows from present to future scenarios. This is a direct consequence of the temperature rise in the future. On the other side, un-retrofitted building's comfort level worsens in the opposite direction: under-heating. The increase in under-heated hours in the future relates to the unequal increase of outdoor and indoor temperature. The median value of running mean outdoor temperature increase from 15.8 to 18.0 °C (2.2°C), while the median value of the indoor operative temperature increase from 17.7 to 18.5°C (0.7°C). Since the comfort criteria in adaptive method is defined according to outdoor temperature as a linear relationship, the increase of the neutral temperature will be higher than the increase of indoor temperature.

	unretrofitted 2011-2017	unretrofitted 2094-2100	retrofitted 2011-2017	retrofitted 2094-2100	retrofitted with extra ventilation 2011-2017	retrofitted with extra ventilation 2094-2100
▦ Underheat hours	151	411	0	4	0	6
▨ Overheat hours	0	0	94	451	1	6
▪ Comfortable hours in future	1139	1109	1197	1065	1289	1508

▪ Comfortable hours at present ▪ Comfortable hours in future ▨ Overheat hours ▦ Underheat hours
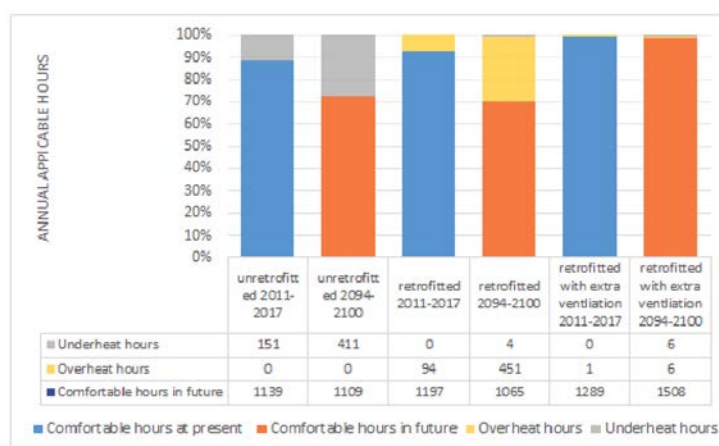
Figure 8 Average annual comfort level in retrofitted/un-retrofitted and present/future scenarios, according to EN 15251 category 2 criteria for buildings without mechanical cooling systems

3.4. Envelope hygrothermal safety

Three internal insulation systems are compared with respect to their hygrothermal performance: 1) wood fiberboard[3] (vapour open system), 2) wood fiberboard with vapour barrier (vapour tight system) and 3)

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[3] The wood fibreboard is produced by Pavatex. http://www.pavatex.com/en/products/wall/pavadentro/

calcium silicate board[4] (vapour open & capillary active system). These three insulation systems are coupled with three wall constructions: 1) granite wall, 2) sandstone wall and 3) wooden wall (pine). These three wall constructions are the most commonly found in South Tyrol. The properties of the insulation materials and wall materials are presented in Table 3. In addition, the sd-value of the vapour barrier used in the simulation is 7.72m.

Table 3 Properties of main construction materials

Materials	Thickness (mm)	λ_{dry} [W/mK]	ρ [kg/m³]	C_p [J/kg·K]	Aw [kg/m²s0.5]	μ_{dry} [-]	θ_{por}[m³/m³]
Granite	580	1.718	2453	702	0.086	53.8	0.095
Sandstone	580	1.973	2043	686	0.024	25.5	0.243
Pine	150	0.186	554	2673	0.016	348	0.654
Wood fiberboard.	100	0.042	150	2000	0.07	3.0	0.981
Calcium silicate board	115.8	0.069	270	1158	1.115	3.8	0.910

To assess the hygrothermal risks, three Assessment Points (AP) are defined: A. High relative humidity in the interface between the insulation and historic plaster, B. Mould risk between the insulation and historic plaster, and C. Frost in the outer historic plaster and 0.5 cm into the wall (Figure 9). To optimise the computational resources, the hygrothermal models are 1-D models (as showed in Figure 9) that simplify the wall construction as a sequence of homogeneous layers.
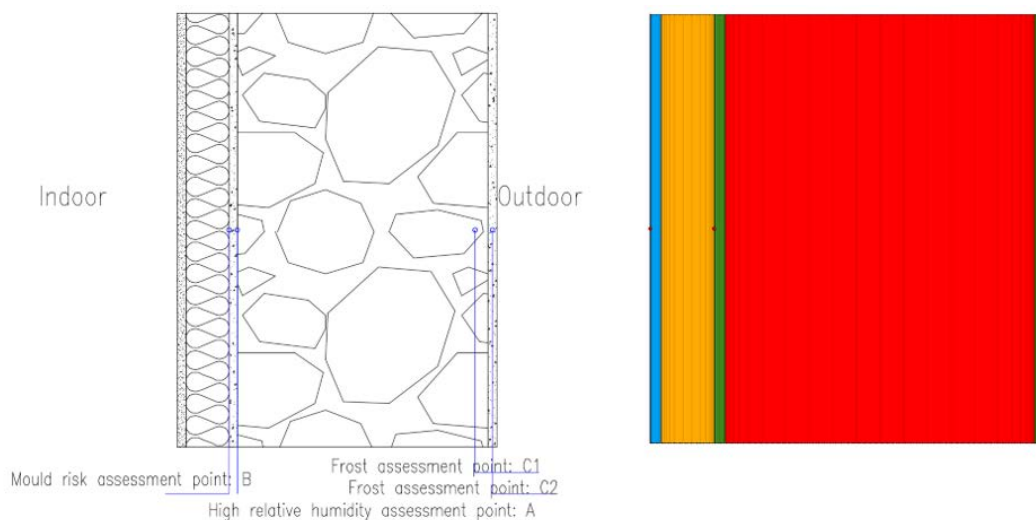

Figure 9 Risk assessment points and example of Delphin simulation model

3.4.1 Condensation risk. RH in the uninsulated wall is mainly depending on indoor RH, and it is relatively low both in present and future scenarios: below 70% for all three wall constructions. However, when climate change is combined with additional insulation, the condition worsened in stone masonry. With vapour open system (wood fibreboard), condensation appears both in granite wall and sandstone wall (in both present and future scenarios) (Figure 10). However, the total condensation hours decrease in future scenarios (e.g. condensation hours of granite wall decrease from 59.6% to 43.2%). With vapour tight system, RH increases with time, which reflects the accumulation of moisture in wall due to the limiting effect of vapour barrier to dry inwards. (Figure 10) Even though there is no liquid water

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[4] The calcium silicate board is produced by Calsitherm Silikatbaustoffe GmbH.
https://www.calsitherm.de/en/applications/internal-insulation/climate-boards.html

accumulated during the simulated period, it could be presumed in later years. With vapour open & capillary active system, there is no condensation in the wall and the fluctuation pattern of RH is similar to the vapour open system, i.e. no accumulation phenomenon observed. Regarding the wooden walls, RH increases in future scenario but does not show condensation risk with any of the three insulation system.
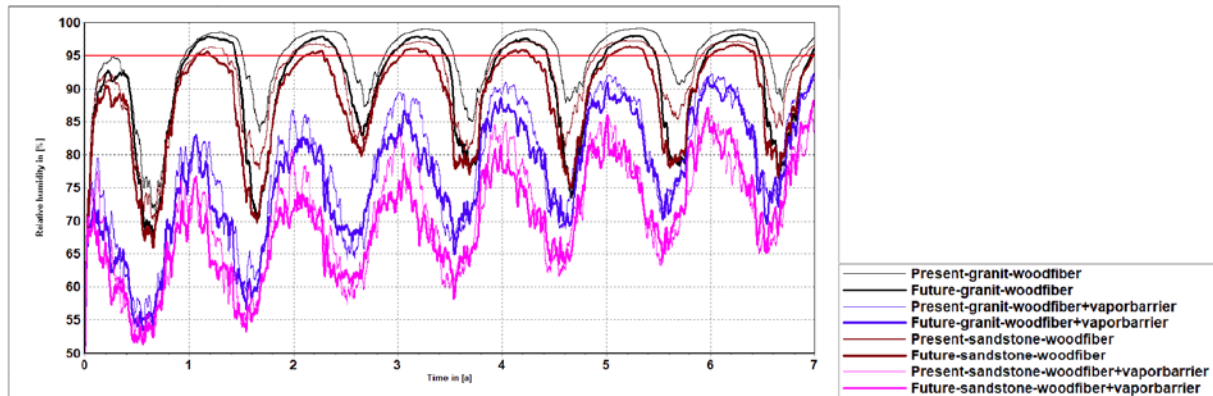

Figure 10 Relative humidity in masonry walls with vapour retard and vapour tight insulation system

3.4.2 Mould risk. No risk of mould growth was found on any of the uninsulated walls. However, with the addition of internal insulation, the risk of mould appearance increased considerably in the future climate scenarios. With vapour open system, the mould index of granite wall and wood wall in present scenario are very low while it will exceed 1 in future scenario. (Figure 11) For wood wall, the mould index in future is higher than 2 implying there will be more than 10% coverage of mould on surface. With vapour tight system and vapour open & capillary active system, there will be mould risk in wood wall in future scenario. The decline of mould on wood material is significant, but the damage caused by mould risk is still probable due to the increased rain quantity in future.
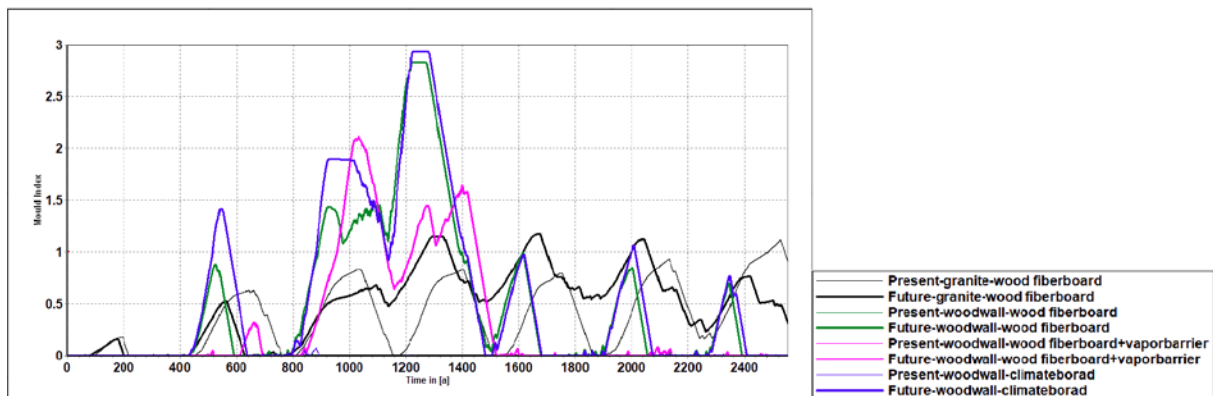

Figure 11 Mould index in granite and wood wall with internal insulation

3.4.3 Frost damage. Both the application of internal insulation and change of precipitation in future will raise the saturation rate. However, climate change has larger impacts: the saturation ratio reaches to S_{crit} due to the extreme rain events. The saturation ratio of retrofitted granite wall could stay below critical saturation ratio in present and future scenarios. Retrofitted sandstone wall is safe from frost damage in present but suffers frost risk in future scenario. The saturation ratio will exceed or be close to critical saturation ratio in future scenario when there is severe rain (Figure 12). The saturation curve results of retrofitted sandstone walls are similar independently of the insulation system. For the external plaster, the application of insulation systems does not increase the saturation ratio. The external plaster of both granite and sandstone wall will be in frost risk in present and future (Figure 13). However, the saturation

ratio surpasses the critical value more frequently in the future, which implies an urgent need for better solutions to protect the historic facade.
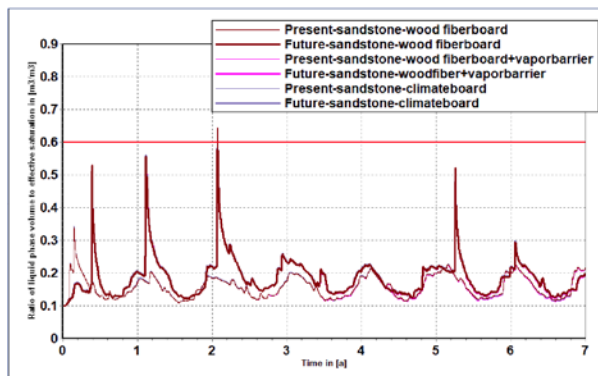

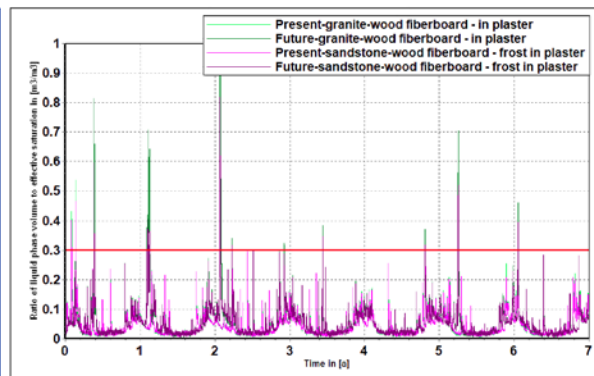Figure 12 Saturation ratio of retrofitted sandstone wall (assessed at AP-C1)

Figure 13 Saturation ratio of external plaster (assessed at AP-C2)

4. Conclusion

The performance of a representative Alpine historic residential building is assessed in terms of energy use, indoor comfort and moisture safety of the envelope under present and future climatic scenarios. The assessment has considered different configurations of wall constructions as well as different possible retrofit interventions.

The results of the simulations demonstrated that the retrofit interventions could significantly improve energy efficiency of historic buildings in both present and future scenarios. Future temperature increase does not compromise the effectiveness of thermal insulation.

A change in climate together with retrofit interventions will result in higher risk of indoor overheating. However, at least in studied case study, this could be effectively reduced by additional natural ventilation. In alpine region, the multifarious terrain results in diverse climate, and studied location has a rather cold climate. Therefore, indoor comfort should be studied before adopting any retrofit solutions.

Climate change and retrofit interventions will also impose moisture related risks to the conservation of historic envelopes. Several solutions that are applied currently often could lead to risks in future. For instance, mould risk is reported in future granite wall with wood fibreboard, as well as wood wall with all three studied insulation systems. Future risk of frost damage is also present in insulated sandstone wall. Retrofit solutions should be carefully studied for compatibility with local building materials and climate.

In conclusion, the present study verified that historic buildings are vulnerable to the changes imposed by climate and retrofit interventions. However, this paper, as a preliminary study, still presents several limitations that should be further studied. For further studies, 1) different future climate projections should be used to have a better understanding of future climate change; 2) different alpine locations should be studied considering the wide climate variations; 3) building performance should be assessed not only in "far" future (around 2100), but also in "near" future (around 2050), which is more instructive for retrofit practices.

References

[1]   IPCC, *Climate Change 2014 Synthesis Report*. 2015: Geneva, Switzerland. p. 151 pp.
[2]   EEA, *Climate change, impacts and vulnerability in Europe 2016 An indicator-based report*. 2017, European Environment Agency: Luxembourg.
[3]   EURAC, *Klimareport Südtirol 2018*. 2018.

[4]   Hao, L., D. Herrera, and A. Troi. *The effect of climate change on the future performance of retrofitted historic buildings: A review*. in *EEHB*. 2018. Visby.

[5]   Troi, A., *Historic buildings and city centres −the potential impact of conservation compatible energy refurbishment on climate protection and living conditions*, in *International Conference Energy Management in Cultural Heritage*. 2011.

[6]   BPIE, *Europe's buildings under the microscope, A Country-by-country Review of the Energy Performance of Buildings*. 2011, Buildings Performance Institute Europe (BPIE).

[7]   *TABULA*. Available from: http://episcope.eu/iee-project/tabula/.

[8]   CasaClima, *Criteri CasaClima: Per l'esecuzione delle prove di tenuta all'aria*. 2015, Agenzia per I'Energia Alto Adige CasaClima.

[9]   *Bozner Aktionsplan für nachhaltige Energie (APNE)*. Available from: http://www.gemeinde.bozen.it/ambiente_context02.jsp?ID_LINK=4527&area=68.

[10]   Bergmeister, K., *Natürliche Bauweisen: Bauernhöfe in Südtirol.* 2008.

[11]   *Die schonsten bauernhofe in Tyrol*.

[12]   Alphouse, *Alpine Building Culture and Energy Efficiency*. 2012.

[13]   Jacob, D., et al., *EURO-CORDEX: new high-resolution climate change projections for European impact research.* Regional Environmental Change, 2014. **14**(2): p. 579-581.

[14]   Förster, K., et al., *An open-source MEteoroLOgical observation time series DISaggregation Tool (MELODIST v0.1.1).* Geoscientific Model Development, 2016. **9**(7): p. 2315-2333.

[15]   *EnergyPlus*. Available from: https://energyplus.net/.

[16]   Wilson, E., et al., *2014 Building America House Simulation Protocols*. 2014, National Renewable Energy Laboratory.

[17]   Eskola, L., et al., *Airtightness, Air Exchange and Energy Performance in Historic Residential Buildings with Different Structures.* International Journal of Ventilation, 2016. **14**(1): p. 11-26.

[18]   D, J., et al. *Airtightness of UK dwellings: some recent measurements* in *COBRA 2004 Proc. Of the RICS Foundation Construction and Building Research Conference*. 2004. London: Royal Institution of Chartered Surveyors.

[19]   Aijazi, A. and G. Brager. *Sensitivity of Passive Design Strategies to Climate Change: Thermal comfort performance of natural ventilation in the future*. in *PLEA*. 2018. HongKong.

[20]   Sontag, L., A. Nicolai, and S. Vogelsang, *Validierung der Solverimplementierung des hygrothermischen Simulationsprogramms Delphin.* 2013.

[21]   A, S.G., *Validation of hygrothermal material modelling under consideration of the hysteresis of moisture storage*, in *Civil Engineering*. 2008, Dresden University of Technology.

[22]   *Delphin-Validation*. Available from: http://bauklimatik-dresden.de/delphin/documentation.php?aLa=en.

[23]   Anlauft, E., et al., *Die energetische Sanierung der Stadtbibliothek Nürnberg - Entwicklung des Energie- und Klimakonzepts mittels hygrothermischer Gebäudesimulation.* Bauphysik, 2013. **35**(4): p. 266-279.

[24]   Kosiński, P., et al., *Thermal Properties of Raw Hemp Fiber as a Loose-Fill Insulation Material.* Journal of Natural Fibers, 2018. **15**(5): p. 717-730.

[25]   EU, *EN 15927-3 Hygrothermal performance of buildings — Calculation and presentation of climatic data Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data*. 2009.

[26]   EU, *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment,lighting and acoustics*. 2007.

[27]   Vereecken, E., et al., *Interior insulation for wall retrofitting – A probabilistic analysis of energy savings and hygrothermal risks.* Energy and Buildings, 2015. **89**: p. 231-244.

[28]   Christoph, F., *Historische Bauwerksteine in Südtirol Verteilung und Verwitterungsverhalten*. 2002, Leopold-Franzens-Universität Innsbruck.

[29]   Preservation, I.A.f.S.a.T.o.B.M.a.M., *Interior insulation according to WTA II: Evaluation of internal insulation systems with numerical design methods*. 2014.

[30]   Hukka, A. and H.A. Viitanen, *A mathematical model of mould growth on wooden material.* Wood Science & Technology, 1999. **33**(6): p. 475-485.

[31]   Hannu, V., *Development of an improved model for mould growth: Modelling.* 2014.

[32]   Viitanen, H., *Moisture and Bio-Deterioration Risk of Building Materials and Structures.* 2011.

[33]   Nik, V.M., A. Sasic Kalagasidis, and E. Kjellström, *Assessment of hygrothermal performance and mould growth risk in ventilated attics in respect to possible climate changes in Sweden.* Building and Environment, 2012. **55**: p. 96-109.

[34]   Hagentoft, C.-E., *Reliability of energy efficient building retrofitting - probability assessment of performance and cost (Annex 55, RAP-RETRO).* Energy and Buildings, 2017. **155**: p. 166-171.

[35]   Normalisation, C.E.e.d., *EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics.* 2007.