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In-use conditions of air-tightening materials applied in the air gap of ventilated building envelope constructions: A parametric study for different European climates

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In-use conditions of air-tightening materials applied in the air gap of ventilated building envelope constructions: A parametric study for different European climates

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Abstract. Materials used in the building envelope have to withstand a wide range of varying and harsh conditions over their life cycle. Particular relevance falls upon the materials used for tightening buildings, such as wind barriers and tapes, as air infiltration was found to be responsible for between 10 and 30 % of heat losses of different national building stocks in Europe. However, there is large uncertainty about the conditions a material is exposed to over a building's service life. A validated, hygrothermal model of a zero emission office building in Trondheim, Norway was simulated with 10-year climate files from different European locations: Bergen (NO), Berlin (DE), Oslo (NO), Paris (FR), Rome (IT), Tromsø (NO), and Trondheim (NO). This was done to investigate the temperature and humidity conditions in the ventilated air gap. The results show the total and median values for temperature in the ventilated air gaps of the simulated building's walls and roof for the investigated locations. Moreover, the maximum change compared to the previous hour and the distribution of hours in 5 °C temperature and 10 % relative humidity intervals of the roofing underlay and wall to the west are reported.

1. Introduction

Buildings and building materials are subject to a variety of different climate strains over their life cycle [1] with a high rate of variation in the short time. These can be categorized into solar radiation, ambient infrared radiation, high and low temperatures with temperature changes and cycles, water and moisture, physical strains like snow loads, wind, erosion, pollution from gases and particles in the air, microorganisms, oxygen, and time [1]. In the design process, the natural weathering of the building materials needs to be considered to construct durable buildings. Particular importance falls on materials that are hidden in the wall structures and are therefore inaccessible for inspection. This applies for air-tightening materials, e.g., the wind barrier and adhesive tapes which are a key component for highly energy efficient buildings. In fact, air infiltration was found to be responsible for between around 10 and 30 % of heat losses of different national building stocks in Europe [2–4]. Therefore, knowing the climate strains air-tightening materials are exposed to, can lead to more energy efficient buildings.

In wooden wall constructions, air-tightening materials are usually located in ventilated rain-screen walls that provide drainage, enhance ventilation, and thus enable wetted façade components to dry. However, there is only limited knowledge about the (micro)climatic conditions inside the air gap, as only few long-term studies exist. In order to accurately predict the service life of building components, ISO 15686-1 suggests that ideally, "[…] the microclimate [and] the performance of the component under the intended conditions […]" [5] should be known and that this data is not often available.

Previous work aiming to fill this gap was done for instance by Riahinezhad et al. [6] who measured temperature and relative humidity in the ventilated air gap in a test house in Ottawa, Canada, over 6 years. This was done for the surface temperature on both sides of the air gap in a south-facing brick-cladded façade and below of the roofing underlayment of the roof's air gap. They categorized the hourly-averaged measurements into 5 °C intervals and average monthly temperatures over the measurement period for indicating the occurrence frequency of different (micro)climatic conditions. Other long-term studies that give some indication about the conditions in the air gap of ventilated rain-screen walls are given by Geving et al. [7], and Nore [8].

In this research, a hygrothermal simulation model in WUFI-Pro [9] Ver. 6.5, calibrated with 2 years of measurement data from the air gap of a zero-emission office building in Trondheim [10–12] was used for a parametric study. This parametric study involved simulating the calibrated model from [13] with long-term weather data (10 years) from 7 different locations around Europe: Bergen (NO), Berlin (DE), Oslo (NO), Paris (FR), Rome (IT), Tromsø (NO), and Trondheim (NO). Afterwards, the surface temperatures of the wind barrier in the air gap are categorized into 5 °C steps and the frequency of occurrence among the different simulated locations is compared. According to ISO 15686-1 [5] on *Buildings and constructed assets - Service life planning*, "*extreme levels or fast alterations of temperature"* are among the most common agents affecting the service life of building materials and components. High temperatures are of particular importance, as they increase the reactivity of carbon atoms with oxygen, followed by further decomposition and reaction of the initial products through many stages [14]. Therefore, this study is expected to deliver useful insights to establish better testing schemes, test conditions, and eventually improve the long-term air tightness of buildings.

2. Methodology

2.1. Parametric study

Seven European climates (locations: Bergen, Berlin, Oslo, Paris, Rome, Tromsø, and Trondheim, see also table 1) are used to run a numerical model previously validated in Trondheim climate [13]. The measurements in Trondheim were conducted over two full years at the ZEB Laboratory [10]. For the simulations, long-term climate recordings over 10 years are downloaded from the Open-Meteo Historical Weather API [15] and converted to WUFI weather files. The Open-Meteo Weather API uses the ECMWF ERA5 model and represents a uniform data basis for all locations. After running the simulations, the hourly results for the surface temperature of the wind barrier in the air gap are categorized in 5 °C steps, the relative humidity in the middle of the air gap in 10 % steps. For the present article, the focus is on the results for the south-facing roof and the façade to the West, as it is usually in these parts of the envelope where the highest temperatures in the air gap are reached [16]. Then, the frequency of occurrence of the different intervals among the simulated locations is compared.

Table 1. Average annual heating degree days (HDD) and cooling degree days (CDD), calculated according to [17] for the investigated 10-year period from 2012–2021 and Köppen-Geiger climate type according to [18]. Highest absolute values marked in bold.

	Bergen	Berlin	Oslo	Paris	Rome	Tromsø	Trondheim
HDD	2614.3	2363.6	3021.4	1761.4	931.2	**4137.3**	3279.8
CDD	2.4	109.8	39.0	116.6	**483.0**	2.9	30.3
Köppen-Geiger	Cfb	Cfb[a]	Dfb	Cfb	Csa	Dfc	Dfb[b]

[a] closely borders Dfb
[b] closely borders Dfc
Abbreviations: Cfb (temperate climate without dry season and with warm summer), Dfb (cold climate without dry season and with warm summer), Csa (temperate climate with dry and hot summer), Dfc (cold climate without dry season and with cold summer).

2.2. Model settings and calibration

The building for which the hygrothermal model was calibrated with measurement data in a previous study, was the Zero Emission Building (ZEB) Laboratory (https://zeblab.no). Completed in 2020, the ZEB Laboratory was designed and constructed to provide a research facility allowing for testing new environmentally friendly building components, solutions, strategies, and constructions as well as management processes. It is a 4-storey, ca. 2000 m^2 living office laboratory with glued laminated timber columns, cross-laminated timber floors, stiffening internal walls, and insulated wooden framework in the external walls as load-bearing structure. On the façade to the North, charred wood is used as cladding material, building integrated photovoltaics (BIPV) on the roof (30° inclination towards South), and both BIPV and Alu-PE panels on the remaining facades (see figure 1). In the air gaps of the building envelope, thermocouples of type T (measurement range from -40 to +85°C, with a measurement inaccuracy of ±0.5 °C) are installed at different locations and positions (back of cladding, middle of air gap, and front of wind barrier) for continuous monitoring of the temperature conditions. The calibration results showed that the hygrothermal model was well able to reproduce the conditions measured in the air gap of the building. For that, the setting of the air change rate in the air gap is a major influencing factor. After a parametric evaluation, a ventilation rate of a constant 100 h^{-1} was found to perform best. The results of the calibration, the settings of the numerical model, the sensor locations and accuracies, as well as the material properties are described in detail in [13]. Figure 2 shows the wall and the roof structures.

Figure 1. The ZEB Laboratory viewed from the Southeast (a), and Northeast (b). Photos: © Nicola Lolli, 2021.

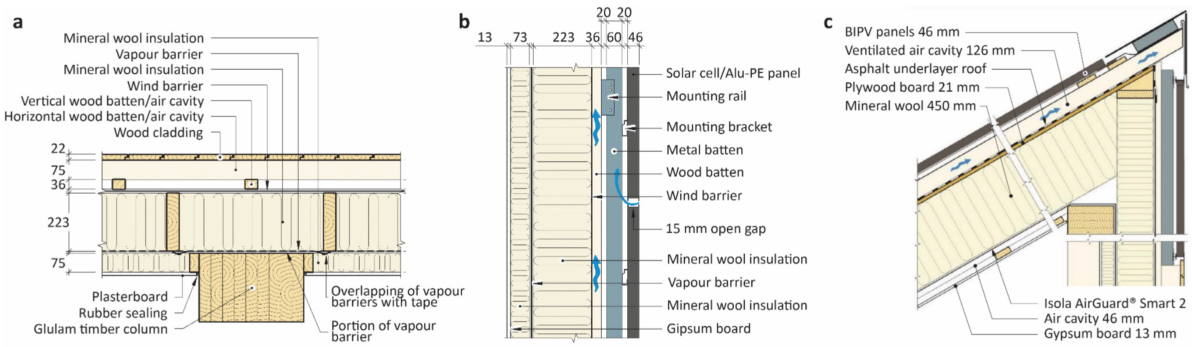

Figure 2. Wall with wood cladding (a), BIPV/Alu-PE panel (b), and BIPV-covered roof (c), from [13].

3. Results and discussion

3.1. Temperature

The simulation results are shown in figure 3 as boxplots for the walls of different orientations (N, S, E, W) and the roof (R) of the reference building at the different locations. It is noticeable that the temperature range at most locations increases when moving clockwise from the North façade towards West and then to the roof. Also, the maximum temperature is mostly occurring at the roof. In Oslo, Tromsø and Trondheim, however, the maximum temperatures and largest temperature ranges occurred at the façade towards West (see table 2). Generally lower solar elevations at these locations' latitudes lead to a more optimal incidence angle on the vertical building envelopes. Moreover, because of long summer days (in Tromsø no sunset between 18.05. and 25.07.) the maximum air temperature at these locations is usually reached in the late afternoon, when the sun is in the West.

Overall, the highest temperature (65.3 °C) was found to occur at the roof when simulating the building with the weather data for Rome, the lowest (-24.8 °C) for Tromsø. The overall largest temperature range occurred when simulating the model with Trondheim weather data (82.6 °C). Table 2 also shows the maximum temperature difference to the previous timestep, both for increasing (ΔT^{+}) and decreasing (ΔT^{-}) temperature. It can be seen that the largest differences in surface temperature at the wind barrier occur at the façade to the West, both for increasing and decreasing temperature. Generally, negative changes are occurring faster than positive changes in the wind barrier's surface temperature. The largest positive and negative changes were found in the simulation results for Paris with 14.2 °C and -24.0 °C. In all locations, the largest difference between the wind barrier's surface temperature and the outdoor air temperature was between 33.0 °C (Bergen) and 35.5 °C (Rome). Only in Tromsø, this largest difference was considerably lower with 29.9 °C. These largest differences to the outdoor air temperature all occurred on the West façade.

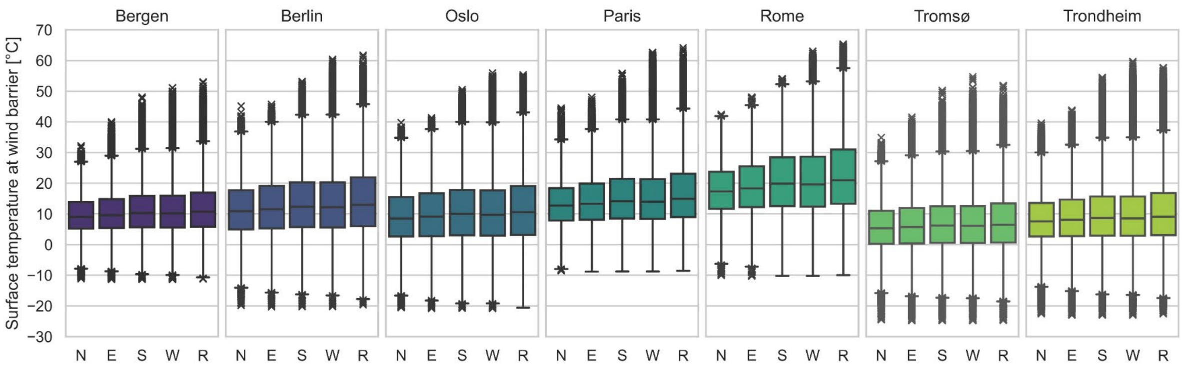

Figure 3. Boxplots of the wind barrier's surface temperature of the different building envelopes in the different locations. Abbreviations: N (North), E (East), S (South), W (West), R (Roof).

Table 2. Maximum and minimum surface temperatures of the wind barrier, as well as the maximum temperature range and maximum change in temperature to previous hour at each location. The building envelope at which the values occurred are given in parentheses. Highest absolute values marked in bold.

Location	Max. temperature [°C]	Min. temperature [°C]	Max. temperature range [°C]	Max. ΔT^{+} to previous hour [°C]	Max. ΔT^{-} to previous hour [°C]
Bergen	53.0 (R)	-11.4 (E, S, W)	64.2 (R)	10.7 (W)	-21.9 (W)
Berlin	61.7 (R)	-20.2 (E, S, W)	81.3 (R)	13.4 (W)	-23.4 (W)
Oslo	56.0 (W)	-20.8 (E, S, W)	76.7 (W)	12.7 (W)	-23.3 (W)
Paris	64.1 (R)	-8.8 (E, S, W)	72.6 (R)	**14.2 (W)**	**-24.0 (W)**
Rome	**65.3 (R)**	-10.2 (E, S, W)	75.3 (R)	13.8 (W)	-23.7 (W)
Tromsø	54.7 (W)	**-24.8 (E, S, W)**	79.4 (W)	13.3 (W)	-19.5 (W)
Trondheim	59.7 (W)	-23.0 (E, S, W)	**82.6 (W)**	11.6 (W)	-22.2 (W)

Abbreviations: N (North), E (East), S (South), W (West), R (Roof)

The percentage of hours in which the surface temperature of the roofing underlay and the wind barrier of the façade to the West falls in each 5-degree interval over the simulated 10-year period is shown in figure 4a and b, respectively. At the roof, notable shares of hours below -10 °C only occur in Oslo, Tromsø and Trondheim, with respectively 1.0 %, 3.2 %, and 1.6 %. On the opposite side of the scale, the largest share of hours in the category above 55 °C result from the simulations for Paris and Rome with respectively 0.2 % and 2.1 %. In fact, the model simulated in Rome shows the highest share of hours in all categories above 20 °C. The categories, in which the highest share of hours for a location occur, are 0–5 °C for Oslo, Tromsø, and Trondheim (18.7 %, 21.8 %, and 21.0 %, respectively), 5–10 °C for Bergen and Berlin, (27.1 % and 18.8 %, respectively), and 10–15 °C for Paris and Rome with respectively 20.7 % and 16.2 %. The results for the façade to the West are very similar. Therefore, they are not discussed individually.

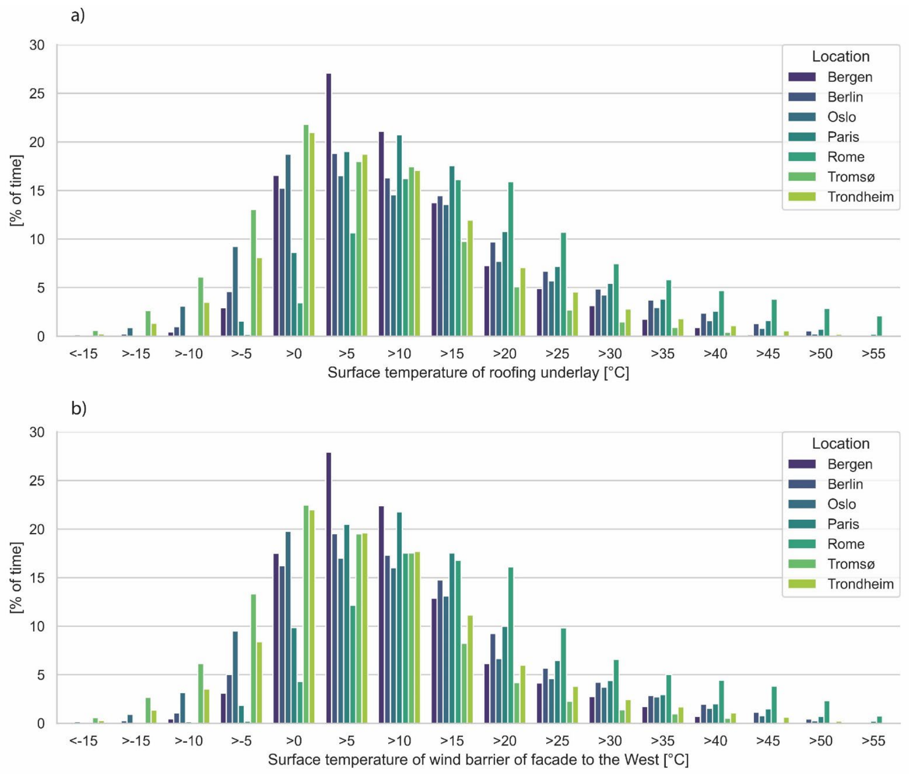

Figure 4. Time percentage of surface temperature of the roofing underlay (a) and the wind barrier of the façade to the West (b) in the temperature categories for the different locations.

Overall, the results for the surface temperature of the wind barrier show a large variation. High temperature levels are an important factor to consider for material durability and ageing. However, the total temperature range and the change of temperature from one hour to the next can also highly stress building materials [5]. While for the Rome simulation the temperature levels are highest (see also figure 3), the total range of temperature is higher in the Norwegian locations (except for Bergen) and Berlin.

3.2. Relative humidity

The simulation results for humidity in the middle of the air gap are shown figure 5. The overall lowest relative humidity occurred in the simulation with Trondheim weather data at the West façade (2.7 %). Yet, a relative humidity reading this low is unlikely in reality. Also during the calibration [13], the numerical model tended to produce a lower relative humidity than measured. When using Oslo weather data, both the highest relative humidity (95.7 % in the roof's air gap) and the largest humidity range (92.7 % at the façade to the West) occurs (see also table 3).

Similar to the results for the surface temperature of the wind barrier in section 3.1, table 3 also shows the maximum relative humidity difference to the previous hour (ΔRH^{+} for increasing and ΔRH^{-} for decreasing). Analogous to table 2 for the wind barrier's surface temperature, the hourly negative change (ΔRH^{-}) for relative humidity in the middle of the air gap is larger than the positive one, reaching up to -35.8 % (Paris), while it is 27.1 % (Rome) in the positive direction.

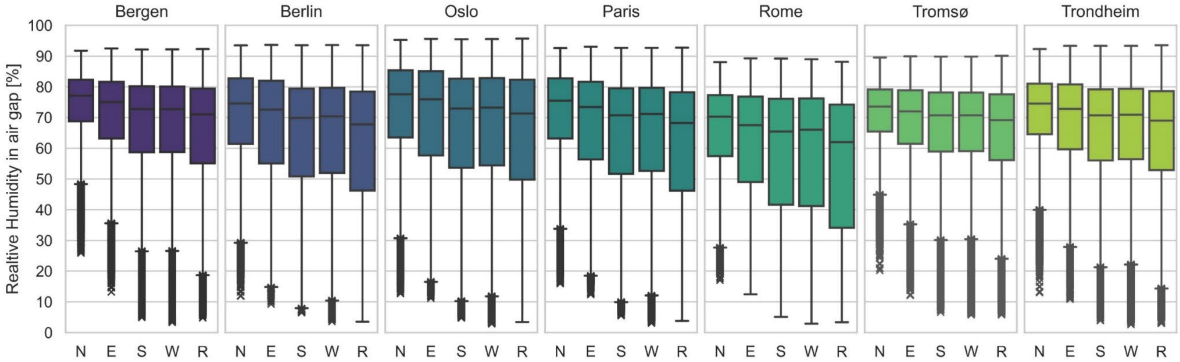

Figure 5. Boxplots of relative humidity in the middle of the air gaps of the different building envelopes at the example building in the different locations. Abbreviations: N (North), E (East), S (South), W (West), R (Roof).

Table 3. Maximum and minimum relative humidity in the middle of the air gap, as well as the maximum relative humidity range. The building envelope surface at which the values occurred are given in parentheses. Highest absolute values marked in bold.

Location	Max. relative humidity [%]	Min. relative humidity [%]	Max. relative humidity range [%]	Max. ΔRH^+ to previous hour [%]	Max. ΔRH^- to previous hour [%]
Bergen	92.5 (E)	3.4 (W)	88.9 (W)	23.0 (W)	-31.1 (W)
Berlin	93.7 (E)	3.6 (W)	90.0 (R)	22.3 (W)	-30.6 (W)
Oslo	**95.7 (R)**	2.9 (W)	**92.7 (W)**	23.6 (W)	-33.6 (S)
Paris	93.0 (E)	3.1 (W)	89.6 (W)	22.4 (W)	**-35.8 (W)**
Rome	89.3 (E)	2.9 (W)	86.0 (W)	**27.1 (W)**	-33.0 (W)
Tromsø	90.1 (R)	5.8 (W)	84.3 (R)	22.4 (W)	-29.5 (W)
Trondheim	93.5 (R)	**2.7 (W)**	90.7 (W)	21.5 (W)	-28.4 (S)

Abbreviations: N (North), E (East), S (South), W (West), R (Roof)

The percentage of hours in which the relative humidity in the middle of the air gap of the roof and the façade to the West is in the different 10-percent intervals over the simulated 10-year period is shown in figure 6a and b, respectively. At the roof, the categories, in which the highest share of hours for a location occur, are 70–80 % for Bergen, Berlin, Paris, Rome, Tromsø, and Trondheim (29.5 %, 24.7 %, 26.9 %, 28.1 %, 31.7%, and 26.7 % of time respectively), and 80–90 % for Oslo with 25.6 % of time. It is furthermore noticeable that in Oslo, the share of hours above 90 % humidity in the roof's air gap is significantly higher than for the other locations (5.7 % against 0.0–1.2 %).

Looking at the distribution of hours in the different categories, two locations set themselves apart: First, Rome, for which the simulation model resulted in significantly more hours in the category between 10 and 20 % relative humidity (11.5 % of time), and consequently only very few above 80 % relative humidity (7.6 % of time). Second, Oslo, for which a considerable fraction of hours was above 80 % relative humidity (31.3 % of time). Otherwise, the distribution of hours for the different locations is rather even. Yet it should be kept in mind that the same relative humidity value at different temperatures can involve highly different absolute moisture contents in the air due to its non-linear ability to "hold" water vapour. Again, the results for the façade to the West are very similar to those at the roof and are, therefore, not individually discussed.

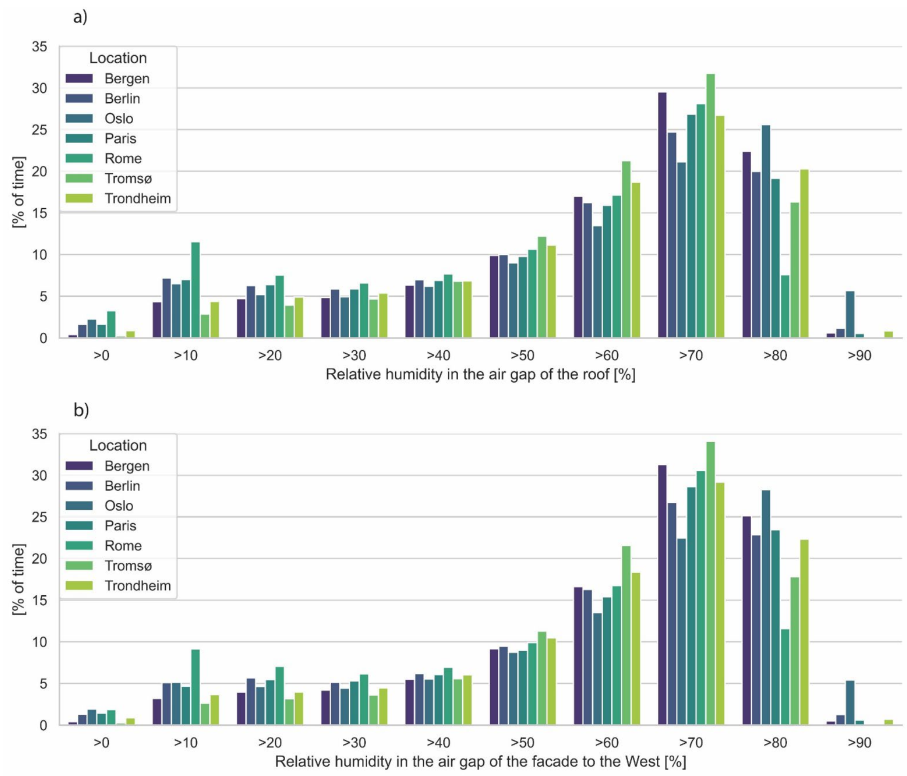

Figure 6. Time percentage of relative humidity in the middle of the air gap of the roof (a) and the façade to the West (b) in the humidity categories for the different locations.

3.3. Limitations

In this study, there are three main limitations to be taken into consideration when interpreting the results. These can likely lead to lower maximum temperatures and temperature ranges than reported in this study. First, the simulations were done in WUFI-Pro [9] Ver. 6.5, which is a one-dimensional, hygrothermal simulation tool. This tool does not allow to select the height of the simulated wall or roof structure above ground, respectively the height of the air gap. As the measurements from [13,16] have been showing, the height of the sensor above ground has a large influence on the temperature. Thermocouples located higher up (at the top of a façade or near the ridge of a roof) measured significantly higher temperatures during times of intense solar irradiation than other sensors of the same building envelope. Second, using hourly weather data buffers especially temperature peaks that can occur in shorter time intervals. Third, the weather data was obtained from reanalysis data using the ECMWF ERA5 [15] with a 0.25° global resolution. Non negligible local effects that can lead to a very unique urban microclimate in the vicinity of a building [19] are lost with this method.

It is important to have in mind that different wall and roof structures or different widths of the air gap will likely lead to significantly different results than those presented in this study. Wind barriers that are located closer or directly adjacent to the roofing/façade cladding material will likely experience higher temperatures and temperature ranges.

4. Conclusions

Planning for high-performance buildings and long-term air tightness requires detailed attention on building materials that are suited for the building's location. In this study, a calibrated hygrothermal simulation model of a zero emission office building was simulated with 10-year climate data from different locations in Europe. In order to accurately predict the service life of building components, ISO 15686-1 suggests that ideally, "[…] the microclimate [and] the performance of the component under the intended conditions […]" [5] should be known and that this data is not often available. The present study aimed to fill this gap by providing a detailed overview of the temperature and relative humidity conditions to expect in the building envelope's air gaps in the investigated locations along with their frequency of occurrence. Based on the results and plastic products' sensitivity to repeated and fast temperature changes, as well as faster degradation at higher temperatures, plastic materials commonly used for making buildings air-tight are expected to be less durable in climates like in Rome and Paris, than for instance in the Nordic countries. Moreover, materials in unshaded facades to the West and roofs are more prone to degradation. This study delivers useful insights to establish better testing schemes, test conditions, and eventually improve the long-term air tightness of buildings.

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