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EXPLORING THE INTERPLAY OF CLIMATE AND HYGROTHERMAL RISK FOR INSULATED WALL ASSEMBLIES IN THE IBERIAN PENINSULA

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ABSTRACT

On the road towards an energy neutral building stock, increasingly demanding insulation levels are advised for both new and retrofitted buildings. While centuries of past experience have led to vernacular construction methods suited to local climates, the incorporation of thermal insulation to existing walls fundamentally alters their moisture balance and drying capacity. The impact of insulation assemblies on moisture risk is relatively well studied for cold climates; however, research and case studies are scarce for the warmer climates of Southern Europe, where such highly insulated walls have been unusual up to now.

This paper presents a parametric study evaluating the hygrothermal performance of 3 types of insulated wall assemblies exposed to 5 climates of the Iberian Peninsula. In particular, the influence of climatic parameters on hygrothermal risk is investigated, using transient numerical simulation methods.

Results show that the impact of solar irradiation and wind-driven rain over different orientations can outweigh that of temperature and humidity. Moreover, their combined effect can be either beneficial or detrimental, depending on the interplay of the specific climate and type of assembly. Hence, it has been found that simplified assessment methods that do not consider the impact of wind-driven rain underestimate risk significantly for certain scenarios. Finally, the hygrothermal performance of the assessed wall assemblies is evaluated in the context of Iberian climates, discussing possible improvements.

1. INTRODUCTION

The Energy Efficiency Directive of the European Union [1] identifies the renovation of the existing building stock as crucial to achieving its objectives of reducing energy consumption and greenhouse gas emissions. The addition of thermal insulation to external envelopes is one of the most efficient means to reduce the energy consumption associated with space heating load. In line with this strategy, national, regional and local regulations within the EU require increasingly demanding insulation levels for both new and existing buildings.

As heat and moisture transfer are intrinsically coupled phenomena, the addition of insulation onto an external wall necessarily changes the moisture balance and drying capacity or the original assembly. In this context, insulation materials and strategies that are conceived for modern buildings might not be appropriate for buildings of traditional construction. In the case of historic or traditional buildings, heritage conservation principles often prevent modifications to the exterior of the façade, so as to preserve their architectural character. However, an insulation strategy aimed at preserving the visual appearance of the building might constitute an unwise choice regarding its hygrothermal impact.

Given the inherent link between temperature and relative humidity, cold climates are more prone to moisture-related damage. Consequently, building regulations of Northern European countries tend to have both higher insulation requirements and a more rigorous approach for moisture control, compared to their southern counterparts. In the same way, research works on the hygrothermal performance of building envelopes have mostly focused on cold climates, and studies for other climates are much scarcer. As we step into previously unforeseen insulation levels for Southern Europe, construction practice is experiencing a rapid change that, in the absence of local experience, is often influenced by the more developed principles and conventions from colder countries. However, the suitability of these insulation assemblies might differ for warmer climates. The knowledge of underlying physical processes and the recent development of numerical simulation tools allow for the prediction of their hygrothermal performance. A review of these tools can be found in [2].

This paper presents an exploratory study for insulated external walls in climates of the Iberian Peninsula. The influence of climatic parameters on hygrothermal risk is investigated, considering not only temperature and relative humidity (as assessed by simplified condensation-based assessments), but also the impact of solar radiation and wind-driven rain over different wall orientations. For this purpose, a parametric study has been performed by means of transient numerical simulation, using detailed climatic data for five locations within the Iberian Peninsula, for three different wall insulation strategies.

2. CLIMATES OF THE IBERIAN PENINSULA

The Iberian Peninsula is located to the southwest of the European continent, in a transition zone between temperate and tropical climates. Given the proximity of the Atlantic Ocean and Mediterranean Sea and the variation in topographic relief, significant climatic variances exist within different areas of the peninsula. The first two maps in Fig. 1, which are extracted from a set of digital climatic maps with a 200m resolution [3], portray the variation in mean temperature (left) and annual rainfall (centre). The right image of Fig. 1 shows the distribution of incident solar irradiation, processed from satellite imagery with a spatial resolution of 3 × 3 km [4].

Font [5] divided the Iberian Peninsula into two main climate regions (Fig. 2 left). Green Iberia, in the vicinity of the northwest coast (II), has an Oceanic climate typical of Western Europe, with moderate temperatures and high precipitation. The rest of the peninsula falls into Brown Iberia, a drier area further subdivided in Atlantic (I.1), Continental (I.2) and Mediterranean (I.3) climate regions, depending on seasonal patterns of temperature and precipitation.

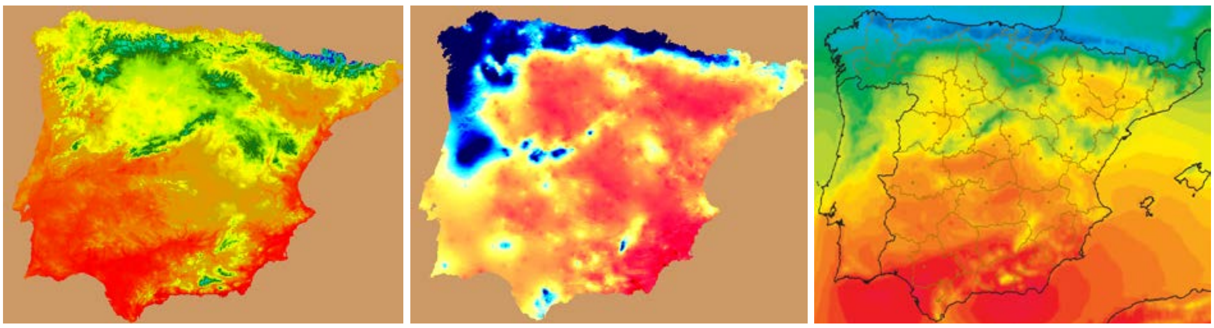

Figure 1: Maps of Iberian Peninsula: mean temperature (left) and annual precipitation (centre) from [3]; mean global irradiation 1983–2005 (right) from [4]

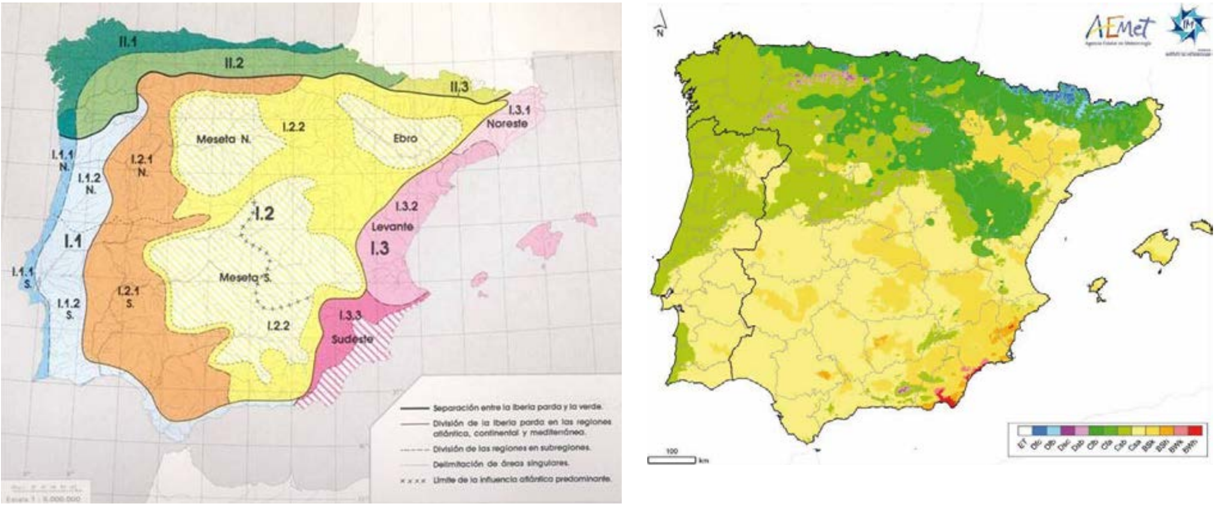

Figure 2: Climatic regions of Iberian Peninsula from [5] (left) and Köppen-Geiger classification in [6] (right)

A joint publication by the meteorological institutes of Spain and Portugal [6] portrays an alternate picture (Fig. 2 right) based on the widely used Köppen-Geiger climate classification, which is based on average monthly values for temperature and precipitation. Most of the peninsula falls into a temperate climate, with no dry season in the north (Cfa, Cfb) and a dry summer period elsewhere. In particular, the southern central plateau and Mediterreanean coastal areas experience a hot summer (Csa), while the northwest and most of the west coast have a temperate summer (Csb). The drier southeast coastal areas are classified as steppe climates (BSk, BSh).

3. METHODOLOGY AND PARAMETER SELECTION

A parametric study has been performed using transient analysis of combined heat and moisture transfer, according to the procedure in EN 15026 [7]. Batch simulations have been run using WUFI Pro 6.1, a software tool developed by Fraunhofer IBP, based on transient calculations of coupled heat and moisture transfer [8]. R programming language (within RStudio 1.0 environment) has been used for post-processing output data and generating graphic outputs.

A number of 135 different scenarios have been simulated, generated from the combination of 3 distinct wall assemblies, 5 external climates, and 9 orientations as described below. The influence of orientation has been explicitly considered in order to evaluate the significance of solar irradiation and wind-driven rain, which are disregarded by the more widely used moisture profile or Glaser method as described in ISO 13788 [9].

3.1. External climate and orientation

Five cities have been selected covering the extension of the peninsula (Fig. 3): Lisbon (west), Madrid (centre), Malaga (south), Barcelona (east) and Bilbao (north). The selection has been based on the availability of data and the representativeness of these locations for populated places in the diverse climate zones of the peninsula. The corresponding climate files, containing detailed data with hourly resolution, have been used as test reference years for hygrothermal simulations. The climate file for Lisbon is provided by FEUP at the University of Porto, and the climate files for Madrid, Malaga, Barcelona and Bilbao are sourced from AEMET, the Spanish meteorological institute.

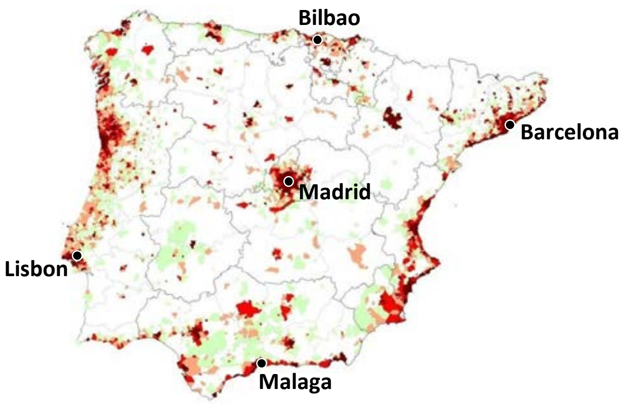

Figure 3: Population density map of the Iberian Peninsula [10] indicating selected locations

Table 1 lists the categorization of these five climates according to the classifications shown in Fig. 2, along with the main climate parameters extracted from the data.

Table 1: Climate parameters of the five locations assessed.

	Lisbon	Madrid	Malaga	Barcelona	Bilbao
Classification by Font [5]	I.1	I.2	I.2	I.3	II
Köppen-Geiger classification in [6]	Csa	Csa	Csa	Csa	Cfb
Mean temperature [°C]	15.6	14.4	18.3	16.3	14.3
Mean relative humidity [%]	74.6	63.0	64.3	66.8	72.9
Rainfall [mm/a]	675	406	313	513	1089

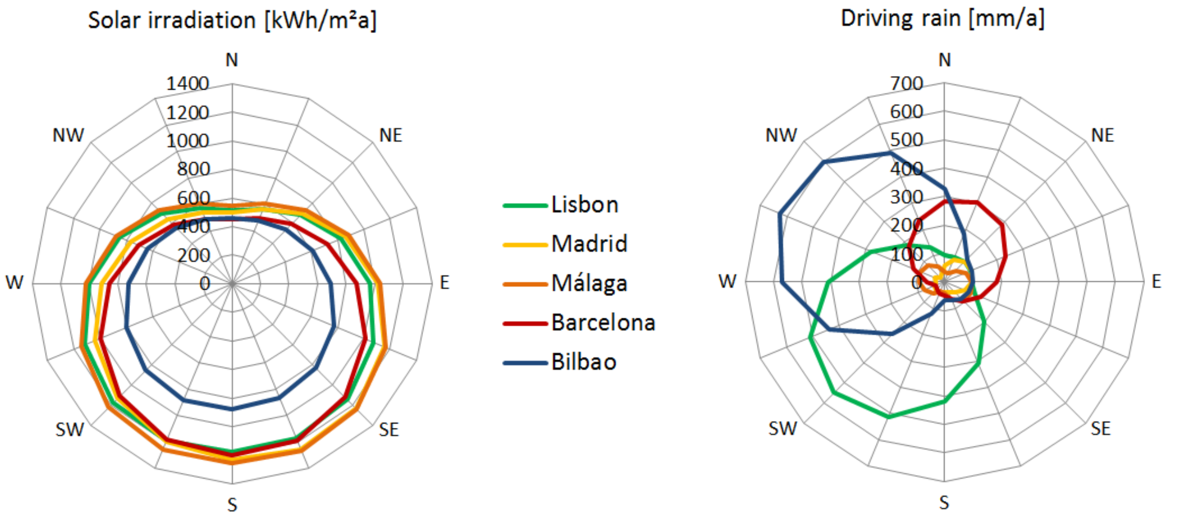

Figure 4: Annual solar irradiation (left) and wind-driven rain (right) incident on vertical surfaces for Lisbon, Madrid, Malaga, Barcelona and Bilbao (source of data: FEUP Uni Porto, AEMET)

The graphs in Fig. 4 show the incidence of solar irradiation and wind-driven rain over vertical walls facing different orientations. The distribution of solar radiation (Fig. 4 left) is broadly symmetrical about the north-south axis, being highest over south-facing walls and lowest over north-facing walls. Bilbao receives a notably lower amount of solar irradiation than the rest of the assessed locations. The incidence of driving rain (Fig. 4 right) varies more significantly and shows a particularly anisotropic distribution, largely determined by the speed and direction of prevalent winds. Among the locations assessed, Bilbao has the highest exposure to wind-driven rain, particularly over northwest- and west-facing walls. The most exposed orientation for Lisbon is southwest, and north/northeast in the case of Barcelona. Madrid and Malaga, which are also the locations with highest solar irradiation, receive a much lower amount of rain over vertical walls.

The eight main orientations have been simulated (N, NE, E, SE, S, SW, W, NW), considering full exposure with no shading or protection, plus an additional 'protected' case with no incidence of rain or solar radiation. The latter has been selected for comparison purposes, as it follows the assumptions of simplified methods where climates are characterised by temperature and humidity only [9].

3.2. Insulated wall assemblies

Three external wall assemblies have been selected, making use of common building materials within fundamentally different insulation strategies:

- An internally insulated solid brick wall (Fig. 5 left), with the brickwork exposed to the external weather, featuring mineral wool insulation and a plasterboard finish to the room side. The addition of thermal insulation to the inner side of solid walls has been widely adopted in the Iberian context, and it is still the only choice for renovations where external appearance cannot be altered.
- A version of the same wall with external insulation (Fig. 5 centre) using a composite system of expanded polystyrene insulation boards with acrylic render. External wall insulation provides a number of advantages (such as protection to existing substrate, low thermal bridging, and reduced disruption to occupants in retrofit works), and despite decades of experience in many European countries, it has only recently been adopted as a common solution within Iberian climates.
- A lightweight insulated wall (Fig. 5 right) containing mineral wool insulation between studs, with a plasterboard finish to the room side and oriented strand boards facing a ventilated cavity behind an external cladding. Such lightweight construction methods, with timber or steel structure, are much more common in northern latitudes but their use is growing in new buildings as they allow for higher insulation levels and faster construction.

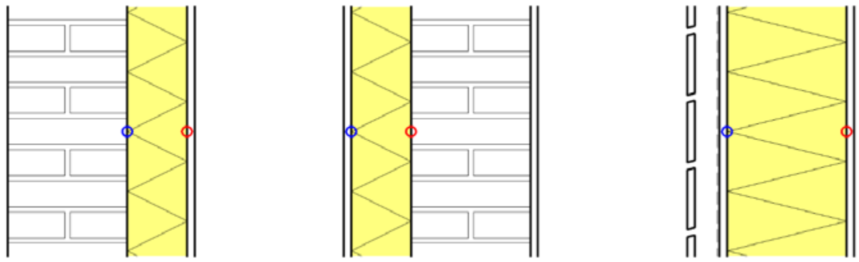

Figure 5: Wall assemblies considered: internal wall insulation (left), external wall insulation (centre), lightweight insulated wall (right) – interfaces assessed for relative humidity are indicated by blue and red circles

The specific wall assemblies considered in this study are not necessarily compliant with current building regulations, and should not be understood as an example of good practice, as none of these has a specific focus on protection against moisture. Indeed, the wall assemblies have been deliberately selected for their vulnerability, in order to explore potential hygrothermal risks linked to each insulation strategy within the assessed climates.
An insulation thickness of 120mm has been considered for the brick wall (both internally and externally insulated), achieving a U-value of 0.27 W/m²K for the insulated wall. As the lightweight wall allows for a greater amount of insulation within a similar overall depth, an insulation thickness of 240mm has been adopted, resulting in a U-value of 0.15 W/m²K.

The relevance of specific hygrothermal risks depends on the type of insulation assembly studied. In order to allow a comparison among the different scenarios, relative humidity has been selected as the critical parameter to be assessed, since it is considered a good proxy for many moisture-related risks such as condensation, mould/algae growth, timber rot or corrosion. The risk of damage from external moisture sources (e.g. ground moisture, roof leaks) is out of the scope of this study.

Concerning condensation, generally the highest risk lies on the cold part of the insulation (usually its outer face, but could be the inner one for warm climates or summer conditions). However, the extent of absorbed rainwater can be more significant than condensation for certain climates and wall assemblies. Therefore, conditions have been assessed both at the outer and inner interfaces of the insulation within each wall assembly, as indicated by blue and red circles in Fig. 5.

4. RESULTS

Results from hygrothermal simulations are graphically depicted below. Fig. 6 portrays the spatial distribution of relative humidity over all orientations, while Fig. 7 shows its variation over time.

Fig. 6 makes use of radial plots for describing the distribution of relative humidity at critical interfaces (marked blue in Fig. 5), for all wall orientations assessed. In every case the radial scale goes from 0% (centre) to 100% relative humidity (outer octagon). The frequency of conditions is indicated by colour intensity: stronger shades represent a higher percentage of time spent above a particular value. The most vulnerable orientations are those with a strong shade of blue approaching the outer ring of the plot, as this indicates a frequent occurrence of high humidity conditions.

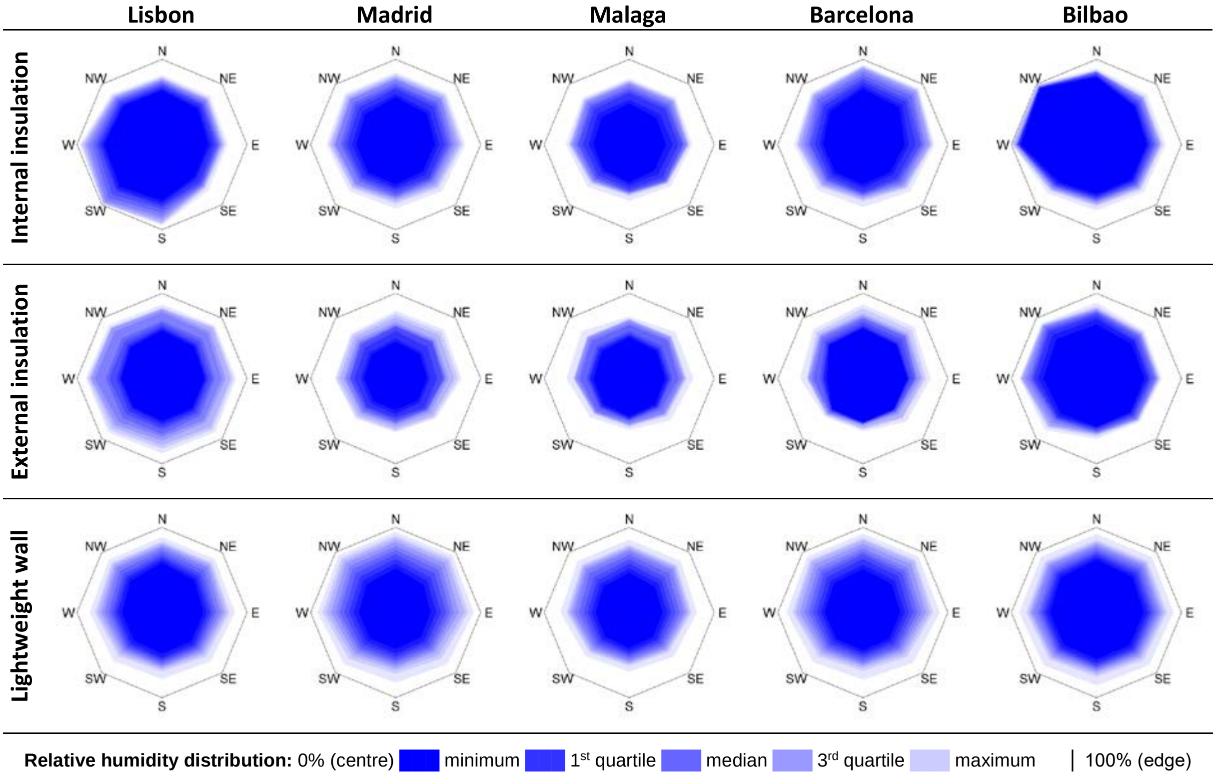

Figure 6: Distribution of relative humidity at critical inferface for different wall orientations – internally insulated wall (top row), externally insulated wall (middle row), lightweight insulated wall (bottom row)

Regarding external climate, Malaga (third column in Fig. 6) is the safest location among the assessed, as humidity at critical interfaces is generally lower than elsewhere, for all three assemblies studied. Conversely, Bilbao (right column in Fig. 6) is the most exposed to risk, as its climate results in the highest humidity at critical interfaces. Nevertheless, the risk associated with each climate is also dependent on the insulation strategy. For instance, Madrid appears to have a lower risk than Lisbon for the insulated solid walls assessed, but a higher risk regarding the lightweight assemblies. This indicates that critical climatic parameters depend on the specific wall assembly considered.

When it comes to insulation strategy, internal wall insulation (top row in Fig. 6) shows the highest risk in all five climates assessed. The safest assembly is the lightweight wall for the rainy climates of Bilbao and Lisbon, while the externally insulated wall better suits the dry and cold winter of Madrid.

The critical orientation for hygrothermal risk depends primarily on the type of insulation assembly:

- For the lightweight wall, north is the most critical orientation in all climates assessed.
- For the internally insulated brick wall, the critical orientation corresponds to the prevalent direction for wind-driven rain.
- For the externally insulated brick wall, the most critical orientation is determined by a combination of solar irradiation and incident rain: among the climates assessed it tends to be close to the north, although wind-driven rain can shift it towards the northeast or northwest.

Fig. 7 shows time-series plots portraying the variation of relative humidity over the yearly cycle, starting in October. In this way, the left half of each chart corresponds to winter conditions, and the right half to summer conditions. Relative humidity values are shown both for critical interfaces (blue in Fig. 5) and inner interfaces (red in Fig. 5). Dark colour shades stand for the 'protected' scenarios with no influence of solar radiation or rain. The lighter shades portray the scenarios exposed to both solar irradiation and wind-driven rain, for the eight main orientations.

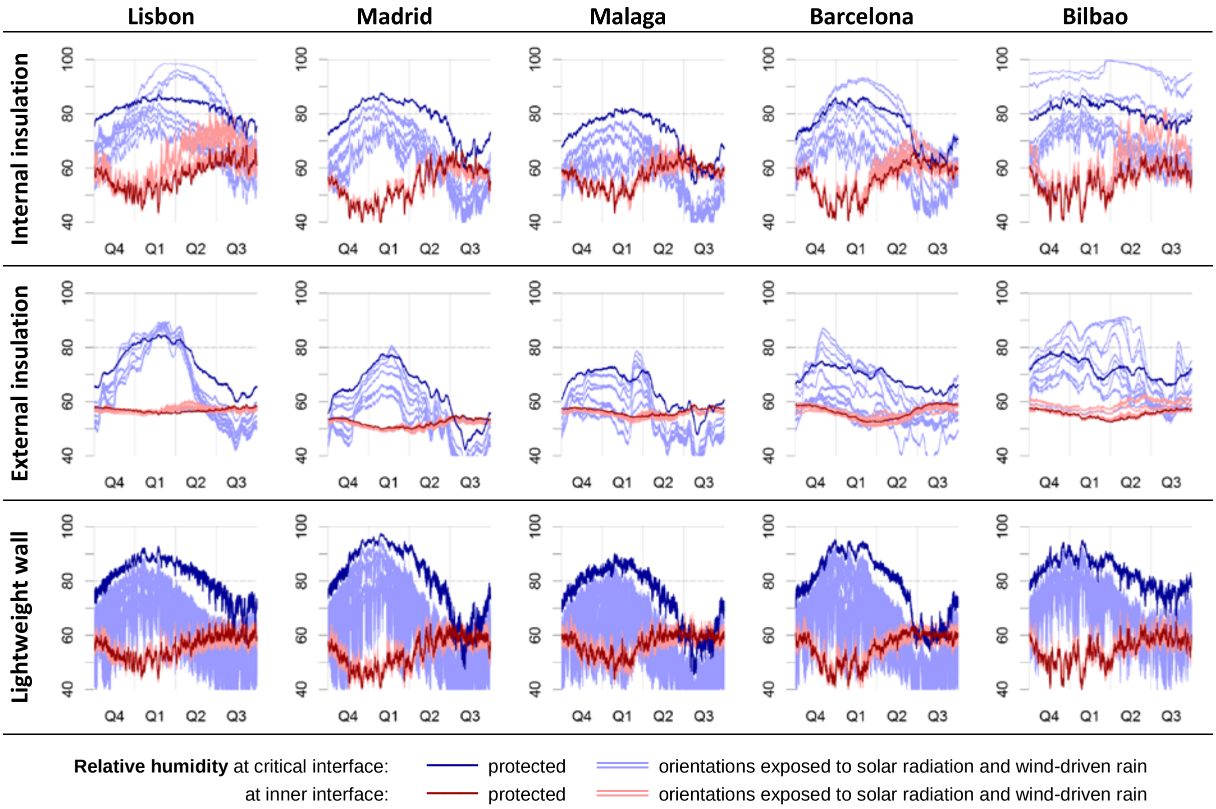

Figure 7: Variation of relative humidity over an annual cycle (starting in October) – internally insulated wall (top row), externally insulated wall (middle row), lightweight insulated wall (bottom row)

Seasonal patterns in hygrothermal performance can be determined from the charts in Fig. 7:

- Generally, for critical locations (blue in Fig. 7), relative humidity peaks in winter, driven by cold temperatures. However, for wall assemblies prone to rainwater absorption, peaks can coincide with a high incidence of wind-driven rain for exposed orientations. An example of

the latter is the internally insulated wall in Bilbao (top right chart in Fig. 7), which has two orientations (north and northwest) with a consistently high relative humidity, maintaining the highest values (95–100%) during the second quarter of the year.
- Conversely, relative humidity at inner interfaces tends to be higher in summer. Values for the considered assemblies are lower than for critical locations and keep at safe levels for most climates. Again, the most concerning cases are the internally insulated walls in Bilbao and Lisbon, as high external temperatures and solar radiation drive the moisture within the wall inwards, reaching values above 80% relative humidity at inner locations.

An additional outcome from this study is the opportunity of comparing 'protected' cases (dark colours in Fig. 7), where external climate is determined by temperature and relative humidity only, with their exposed counterparts (light colours in Fig. 7), which are also affected by solar radiation and wind-driven rain. The impact of the latter two parameters can thereby be inferred from the comparison.
- For the lightweight wall assemblies (bottom row in Fig. 7), all exposed orientations result in lower risk than corresponding 'protected' cases.
- However, for the solid wall assemblies, the 'protected' case overestimates risk for many scenarios but underestimates risk for certain orientations, notably for the scenarios that are most exposed to wind-driven rain (e.g. west and northwest-facing walls in Bilbao, right column in Fig. 7).

5. CONCLUSIONS AND DISCUSSION

A parametric study has been carried out, using transient numerical simulation, to determine the impact of climate parameters on moisture risk for insulated wall assemblies. The hygrothermal performance of three types of wall assemblies has been simulated in five different climates of the Iberian Peninsula. For each case, walls exposed to the eight main orientations (in increments of 45°) have been modelled, plus a 'protected' case with no incidence of solar radiation or rain.

Fundamentally, the moisture safety of insulated walls depends on a successful balance between wetting potential and drying capacity: these are dependent on both climate conditions and wall assembly. This study focuses on determining the influence of the former, which usually cannot be changed. The choice of insulation assembly should then be tuned to the specific climate and exposure and, for the case of retrofits, also to the constraints imposed by the existing substrate.

5.1. Impact of climate parameters on hygrothermal risk

For all assemblies and climates simulated, hygrothermal performance is shown to be highly dependent on exposure and orientation. Results show that the impact of solar radiation and wind-driven rain can outweigh that of external temperature and humidity, which are the climate parameters used by simplified assessments under the Glaser or moisture profile method.

Regarding hygrothermal performance, wind-driven rain increases wetting potential, while solar radiation amplifies drying capacity. The findings of this study show that their combined effect can be either beneficial or detrimental depending on both external climate and type of assembly:
- For the lightweight insulated wall assemblies assessed, risk is predominantly determined by solar irradiation. As the external cladding and ventilated air cavity cope with wind-driven rain, all exposed walls appear to receive a favourable impact from solar radiation, even for north-facing orientations.
- However, for the solid wall assemblies considered, the negative effect of absorbed rainwater can outweigh the positive effect of solar radiation. Simulations for the 'protected' case underrate risk for some scenarios. This underestimation is exacerbated for the climates and orientations with high exposure to wind-driven rain.

Simulation results raise a concern about the suitability of moisture profile methods as simplified hygrothermal assessment tools. Such methods (also known as Glaser or dewpoint methods) [9] are widely used for hygrothermal risk assessments due to its convenience and simplicity, and have been adopted by many regulations and guidance documents. Results from this study suggest that these methods are only conservative for locations with low incidence of wind-driven rain or wall assemblies protected against rain by a capillary break, e.g. a rear-ventilated rainscreen. If rainwater absorption is non-negligible (as is often the case with external and internal insulation of solid walls), moisture risk should be assessed using methods that consider the wetting potential from wind-driven rain.

5.2. Suitability of assessed wall assemblies for Iberian climates

This study does not intend to grade or rank the hygrothermal performance of the assessed insulation assemblies. On the one hand, potential risks and concerns vary depending on the type of assembly and cannot be directly compared, and on the other hand, the suitability of a particular assembly should only be evaluated in relation to a specific climate. However, a brief discussion on their performance within the context of this study is presented below.

The assessed lightweight insulated wall appears to be a safe choice from a hygrothermal point of view when sufficiently exposed to solar radiation. However, during the winter, north-facing or shaded walls experience high relative humidity values at the interface of the insulation with the wall substrate. The performance of this assembly could be significantly improved by adding a vapour control layer to the room side, for controlling vapour ingress and ensuring airtightness. A further improvement could be achieved by specifying a more vapour permeable alternative to oriented strand boards as external sheathing, in order to improve the drying capacity of the assembly.

For the case of external wall insulation, risk is likewise lower for the locations with higher solar radiation. A combination of incident driving rain and low solar radiation (usually near north-facing orientations) can result in high moisture contents in the render, which could potentially lead to algae growth or delamination. In the absence of a capillary break, the main wetting potential may come from wind-driven rain and surface condensation of external air [11]. In such circumstances, a vapour control layer is not necessarily advantageous; the performance of this solution could rather be improved by employing a vapour permeable render (e.g. mineral instead of acrylic) to facilitate the evacuation of moisture. Further protection is offered by rear-ventilated façade assemblies, where the render is substituted by a ventilated airspace behind a rainscreen, thus preventing the absorption of rainwater.

For the internally insulated solid wall assessed in this study, the most significant risk appears to be the accumulation of moisture within the existing wall substrate. Given that the brickwork is directly exposed to the weather, risk is primarily determined by incidence of wind-driven rain, which depends on climate, orientation and exposure. For locations and conditions with high prevalence of driving rain, reducing the wetting potential from rainwater absorption is critical. This could be achieved by applying protective measures over the external surface, such as a pore-lining treatment, an external render or a rear-ventilated cladding. Previous simulation studies suggest that the addition of a vapour control layer could be counterproductive when rainwater is the main moisture load [12]. Furthermore, if changes to the external surface are disallowed by conservation requirements, the appropriateness of insulating the wall should be carefully considered. In such cases, low insulation levels are advised and capillary active insulation materials have been shown to offer the best drying capacity [12, 13].

The hygrothermal influence of the level of insulation (U-value), the material characteristics of existing wall substrate and insulation system and indoor climate conditions is out of the scope of this study. A sensitivity study of these parameters, ideally supported by experimental validation, might be the subject of future work.

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