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# Numerical investigation of mould growth risk in a timber-based facade system under current and future climate scenarios

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**Abstract**. Due to today's sustainability concerns, we must find ways to decrease, the $CO_2$ footprint of the products and systems that are used in buildings. The StaticusCare project, funded by EEA/Norway Grants, emerged from this need, since it aims to decrease the greenhouse gas emissions associated to the construction industry by developing a hybrid timber and aluminium based facade system that will integrate IoT sensors. A decrease of the facade's embodied $CO_2$ footprint of 70-75 % and of the non-renewable energy consumption to 53-56 % is expected. However, it must be ensured that this system has the necessary quality to be installed in the Nordic climates, even for future conditions. Computational models, both at the assembly level as well as at the building level, will be developed. The first level model will allow to perform thorough hygrothermal analysis of the facade system, whilst the second level model will allow to analyse the effect of the system at the building level, i.e. in terms of energy and indoor environment. In addition, this second level model will also be used to obtain the indoor conditions – i.e. temperature and relative humidity – that the first level model needs as an input to run. In order to make this study more comprehensive and, at the same time, determine how differently the facade system will perform under different climates, several representative Nordic outdoor climates will be used in the simulations. Climate change, by means of outdoor weather files, was considered, as well as the effect of moisture penetrating in the tested facade system due to air infiltration or even using timber with a high moisture content due to unprotected storage. It is determined that the tested system is able to properly dry the excess of moisture under current and future conditions. However, if the timber is not properly protected from moisture, then the situation is completely different.

## 1. Introduction

In order to comply with the Paris agreements [1], it is necessary to find ways to decrease the $CO_2$ footprint of the building sector. This can be done using, for instance, building materials that have lower embodied energy and $CO_2$ emissions, such as timber [2]. In addition, the building sector has a large improvement margin on this matter [3].

The *StaticusCare* project emerged from this need. This project aims to decrease the greenhouse gas emissions (GHGs) associated to the construction industry by means of developing a hybrid timber and aluminium based facade system that will integrate IoT sensors, instead of its "solely" typical aluminium facade system [4]. A decrease of the facade's embodied $CO_2$ footprint of 70–75 % is expected, but also of the non-renewable energy consumption, in which a decrease of 53–56 % is estimated [4].

These goals are understandable when we compare the embodied energy and the embodied $CO_2$ of aluminium (201 MJ/kg and 15.08 tonnes of $CO_2$/tonnes of material [2]) with the values for timber (4.60 MJ/kg and 0.35 tonnes of $CO_2$/tonnes of material [2]), which is comprehensible since timber requires much less energy in order to be in the form that can be applied in construction [2]. Finally, the energy consumption will decrease because timber has a much lower thermal conductivity value than aluminium (160 and 0.13 W/m.K [5]), hence the facade will lose much less heat to the outdoor climate than a solely aluminium facade, and less insulation will be needed, resulting in lower embodied $CO_2$ emissions.

A number of research projects and studies have dealt with the weathering and degradation of wooden facades and cladding exposed to Nordic climate [6]. The results show that there is a risk for mould growth due to the exterior climate and in particular the combination of air temperature, relative humidity and solar radiation [7,8]. Various models have been developed to predict the hygrothermal performance of wooden facades and claddings [9], while probabilistic-based methodologies have been suggested [10,11]. The surface treatment of the facade or cladding plays a central role for ensuring the durability of the material and consequently the resilience of the facade system and building.

This study investigates the hygrothermal performance of a hybrid facade system made in aluminium and solid timber. The latter is the innovation of this system as it can be used in large scale facades, by means of building height. Therefore, it is essential to ensure that this system has the necessary quality to be installed in the Nordic climates, in particular for future conditions by considering climate change scenarios [12].

Computational models both at the assembly level as well as at the building level have been developed, but to assess different parameters. The first level model will allow to perform thorough hygrothermal analysis of the facade system, whilst the second level model will allow to analyse the effect of the system at the building level, i.e. in terms of energy and indoor environment. In addition, this second level model will also be used to obtain the indoor conditions – i.e. temperature and relative humidity – that the first level model needs as an input to run in accordance with its respective outdoor climate. The results from the numerical simulations will be validated in a later stage by experimental data obtained in a two-floor test-cell which will be monitored and replicated computationally to assess the energy and indoor climate, as well as the hygrothermal performance of the building elements.

In this study, a cross section of the hybrid aluminium and solid-timber facade system has been studied numerically and its hygrothermal performance has been assessed in a heat, air and moisture transfer tool (HAM), both for current as well as future climate conditions in Norway. Two climate change scenarios have been considered, while three hypotheses have been employed: i) dry construction without air leakages, ii) dry construction with air leakages and iii) wet construction without air leakages. The indoor climate in all simulations has been computed in a separate numerical campaign using building energy simulation (BES) tool.

## 2. Methodology

### 2.1. General considerations

The outdoor weather can, significantly, affect the indoor climate of buildings [13]. This influence is dependent on several parameters, such as the composition of the assemblies as well as the hygrothermal properties of building materials or ventilation rates, among others [13]. This means that a facade system, such as the one studied here, can fail in accordance with the building's location.

To account for the outdoor conditions variation and, at the same time, to determine if this type of facade system can be applied through the different climates in Norway, the present study simulates the developed hybrid facade under different Norwegian climate conditions. Norway was divided in nineteen regions, which correspond to its previous county division. Each region has a climate that was assumed that characterized the whole region, which is a simplification since the climate can vary considerably within the county. The models' orientations were chosen in accordance with the highest WDR for current conditions, which does not mean that they do not differ in the future since, for some cases, the differences between lead orientation were small. In addition, it is not possible to assess the performance of the facade system without dividing it in section since a one-dimensional software was used, which can lead to the uncountability of some phenomena.

In addition, climate change, by means of outdoor weather files, will also be considered using files from Meteonorm [14]. This will enable to determine the effects of climate change and, if necessary, make the appropriate changes to the facade system, depending on the location and climate change scenario [15]. Finally, the Meteonorm limitation in terms of producing climate change weather files for locations with a latitude higher than 65° N, limited the performance assessment. These limitations will be delt with in future publications.

Two other assessments will be carried out to try to identify the facade system limits, i.e. due to water infiltration and using wet timber in the construction site. A total of 306 simulations will be run, 153 in each software.

This study follows a methodology to assess the risk of mould growth in a newly developed hybrid facade system (Figure 1). For this purpose, a whole-building model of a typical office building was built in WUFI®Plus to obtain the indoor climate for the several tested locations. Then, the obtained indoor climate conditions were used in WUFI®Pro as inputs, i.e. boundary conditions, in order to perform a hygrothermal analysis of the assemblies and assess the risk for mould growth using the *mould index*. Finally, the results were presented by means of mould risk maps.

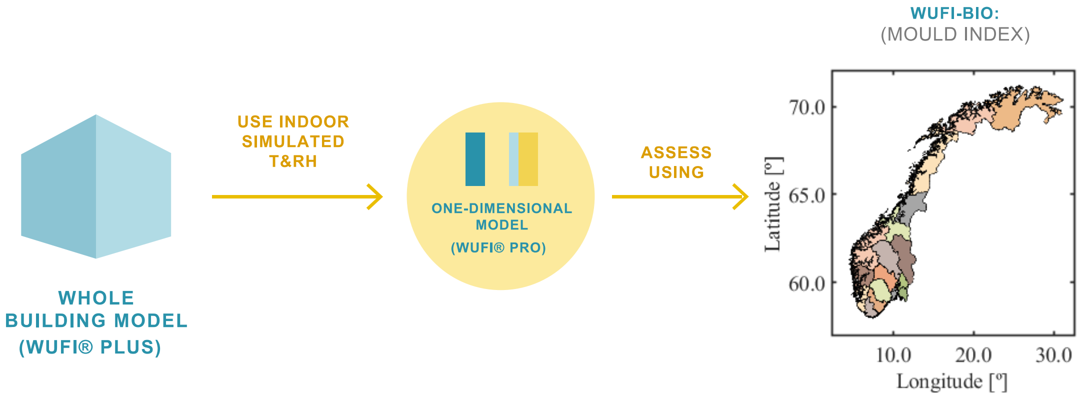


Figure 1 – Overview of the methodology used in this manuscript

The simulations were carried out for both current (i.e. beginning of the 21st-century) and future conditions using two climate change scenarios – RCP 4.5 and 8.5 – for one time-frame – far future, FF. A significant part of this process was carried out using code developed in MATLAB to ease the data transfer processes significantly. This option had the effects of increasing the time efficiency considerably and, at the same time, decrease the occurrence of errors associated to monotonous activities considerable [16].

In addition, to determine the "limits" of the section, two other assessments were carried out: 1) *infiltration of water through the exterior surface* and 2) use *timber with in-built moisture* in the construction site. The first assessment is carried out using the *air infiltration IBP model* for an air leakage rate of 0.6 $h^{-1}$ at 50 Pa [17], which will be used to simulate the infiltration of moisture and its effects on the facade. The second assessment is carried out by increasing the *initial relative humidity* of the timber parts from 60 % (considered "dry" timber) to 80 % (considered "wet" timber), which will be used to simulate the use of unprotected timber in the construction site.

Each of these assessments were carried out for the previously described time frames and climate change scenarios, hence it encompasses 51 hygrothermal simulations in WUFI®Plus and another 51 simulations in WUFI®Pro. In total, these three assessments encompass 153 simulations in each software.

## 2.2. Outdoor weather files for current and future conditions

To account for the outdoor conditions variation in the Nordic region and, at the same time, to determine if this type of facade system can be applied through the different climates in Norway, the present study simulates the developed hybrid facade under different Norwegian climate conditions.

The outdoor weather files were download from the meteorological database Meteonorm [14]. In addition, to determine how climate might affect the hygrothermal performance of the facade system, future weather files were also downloaded from the software. Two RCP scenarios were considered, i.e. RCP 4.5 (an intermediate scenario [18]) and RCP 8.5 (an high GHGs emission scenario [18]) and for one time-period, i.e. far-future (2090-2100). The current weather works as a reference that allows to compare the results from different RCP scenarios [19].

Norway was divided in nineteen regions (Figure 1) and for each of these regions, the weather station that exists in Meteonorm that is nearest to the county's administration centre was assumed to be representative of that region, which can be consulted in Table 1. This table also presents the current weather conditions for each of these locations, in terms of air temperature and relative humidity, solar radiation, wind speed and rain. It is visible that the annual temperature and the global radiation averages are rather low, although both the rain and the relative humidity have rather moderate/high values. For instance, Bergen stands out in terms of precipitation, since its annual sum is 2392 mm.

It is important to mention that Meteonorm has a limitation in terms of producing climate change weather files for locations with a latitude higher than 65° N. This affects the Northern region of Norway of Finnmark, Norland and Troms. Hence, the climate change was not considered for these locations.

Table 1 – Overview of the several selected climates, in terms of annul mean temperature (°C) relative humidity (%) and global radiation (kWh/m$^2$), and total rain (mm) for current conditions

| Nr | Norway county | "Meteornom" station | Temp. [°C] | RH [%] | Rad. [W/m$^2$] | Wind [m/s] | Rain [mm/a] | Orient. |
|---|---|---|---|---|---|---|---|---|
| 1 | Akershus | Ås | 7.1 | 0.74 | 108.7 | 3.06 | 693 | SE |
| 2 | Østfold | Rygge | 7.3 | 0.76 | 112.5 | 3.37 | 689 | E |
| 3 | Aust-Agder | Torungen | 8.4 | 0.79 | 117.1 | 6.51 | 870 | SW |
| 4 | Buskerud | Fagernes | 3.7 | 0.74 | 108.4 | 1.74 | 542 | S |
| 5 | Finnmark | Vardo | 2.7 | 0.83 | 81.3 | 6.05 | 494 | S |
| 6 | Hedmark | Roros | 1.4 | 0.78 | 103.8 | 2.77 | 897 | NW |
| 7 | Hordaland | Bergen | 8.4 | 0.74 | 89.3 | 3.43 | 2392 | S |
| 8 | Møre of Romsdal | Molde | 7.6 | 0.74 | 100.5 | 3.75 | 902 | NW |
| 9 | Nord-Trøndelag | Namsos | 5.8 | 0.76 | 100.7 | 4.29 | 635 | S |
| 10 | Norland | Bodo | 5.6 | 0.75 | 91.3 | 6.38 | 1017 | SE |
| 11 | Oppland | Vest | 3.9 | 0.75 | 109.8 | 1.16 | 578 | S |
| 12 | Oslo | Blindern | 7.1 | 0.72 | 111.2 | 2.65 | 676 | S |
| 13 | Rogaland | Stavanger | 8.6 | 0.76 | 107.4 | 4.53 | 1539 | N |
| 14 | Sogn og Fjordane | Sogndal | 4.8 | 0.73 | 101.9 | 2.96 | 623 | SW |
| 15 | Sør-Trøndelag | Trondheim | 6.2 | 0.73 | 102.2 | 3.98 | 776 | W |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 16 | Telemark | Lyngor | 8.4 | 0.74 | 118.0 | 4.70 | 914 | S |
| 17 | Troms | Tromso | 3.6 | 0.78 | 84.0 | 4.33 | 752 | S |
| 18 | Vest-Agder | Kristiansand | 7.9 | 0.76 | 115.8 | 3.70 | 1166 | SW |
| 19 | Vestfold | Ferder | 8.6 | 0.76 | 117.6 | 7.09 | 672 | S |

### 2.3. Whole-building and one-dimensional model

A generic office building of seven floors was built in WUFI®Plus (Figure 2a) to determine the indoor climate in accordance with the nineteen selected locations (Table 1). The developed model only simulates the indoor climate of the last floor (ca. 150 $m^2$) due to its higher precipitation load [20], whilst the other floors were assigned as attached zones, i.e. they have similar indoor climate. Aside from the hybrid facade (i.e. front facade), the other facades were assigned as adiabatic surfaces (Figure 2a).

The internal gains, ventilation rates and temperature setpoint strategy are in accordance with the recommendations of the Norwegian specification SN-NSPEK 3031:2021 [21] for these buildings, in terms of heat, moisture and $CO_2$ loads due to occupants, lighting and technical equipment.

Subsequently, a one-dimensional model of a section of the hybrid facade system was develop in WUFI®Pro to assess its hygrothermal performance and determine the risk for mould growth. This model was fed by the WUFI®Plus in terms of indoor conditions in accordance with the outdoor conditions.

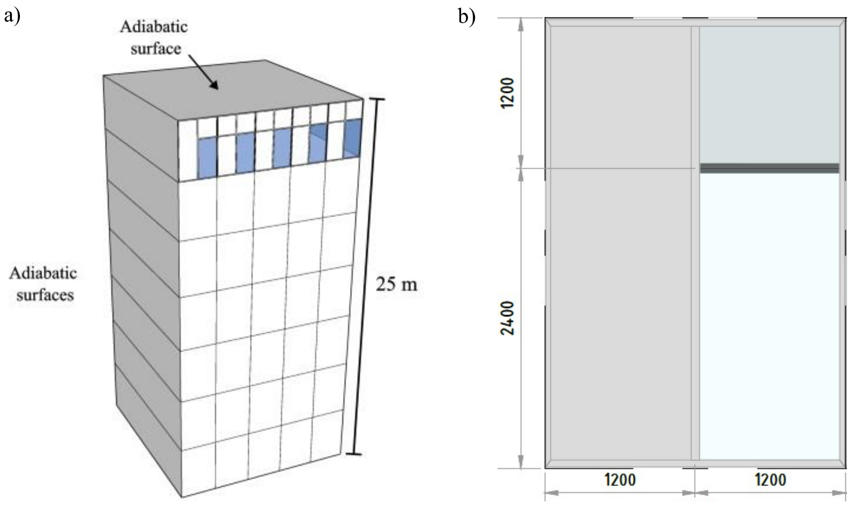


Figure 2 – Generic office building (a) and hybrid timber and aluminium façade unitized block (b)

The hybrid timber and aluminium facade is composed by units (Figure 2b), which are constituted by the following layers: a) Frames - made from glue laminated timber beams and aluminium profile; b) Opaque zone - bended tin sheet, mineral wool insulation, external finishing: Powder coated external aluminium tin sheet and enamelled glass; c) Transparent zone - triple glazed glass unit. Figure 3 is the simulated assembly section of the hybrid unitized facade system.

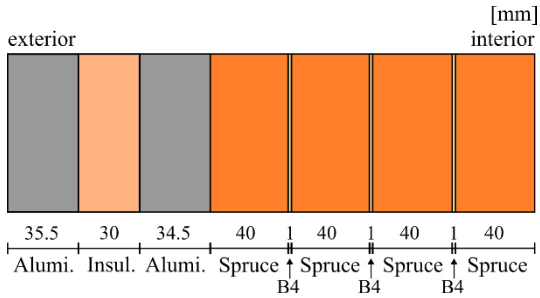


Figure 3 – Simulated section of the hybrid unitized facade system

In both models, the outdoor weathers are the ones describe in subsection 2.2 and the simulated material are the ones that exist in the WUFI material database, with some changes been made in accordance with specific materials that will be used in the facade assembly (Table 2). The models' orientations were chosen in accordance with the highest WDR for the current conditions (Table 1).

Table 2 – Hygrothermal properties of the materials used in the WUFI models, respective layer thickness and thermal resistance for the simulated section of the hybrid unitized facade system

| Material (ext. →int.) | Thick. [d, m] | Hygrothermal properties | | | | | Thermal resistance | |
|---|---|---|---|---|---|---|---|---|
| | | Bulk density | Porosity | Heat capacity | Thermal conduct. | Vapour diff. resist. factor | | |
| | | [ρ, kg/m³] | [ε, m³/m³] | [cp, J/(kg.K)] | [W/(m.K)] | [μ, -] | [W/m²K] | [%] |
| Aluminium | 0.070 | 2,700 | 0.001 | 900 | 200 | 50,000 | 0.00 | 0.0 |
| Polyisocyanurate insulation | 0.030 | 32.5 | 0.999 | 1,470 | 0.024 | 72 | 1.25 | 50.1 |
| Spruce (4 layers) | 0.040 | 390 | 0.750 | 1,600 | 0.13 | 108 | 1.23 | 49.4 |
| Glue (3 layers) | 0.001 | 1,200 | 0.001 | 1,800 | 0.25 | 6,000 | 0.01 | 0.5 |

### 2.4. Mould risk maps

The data – temperature and relative humidity – obtained from the simulations inside the wall system was analysed using the WUFI®Bio to, in accordance with the occupant exposition class, determine the mould growth risk for each of the nineteen simulated locations. The mould risk was assessed using the *mould index* [22] which is subdivided into seven levels: level 0, which corresponds to "no growth", and level 6.0, which corresponds to a "tight coverage". The safety-limit is dependent on the occupant exposition class: 1.0, if it is an "indoor surface or positions in contact to indoor air"; and 2.0, if it is an "surface inside constructions without direct contact to indoor air" [22].

The mould index of the nineteen simulated locations for each of the selected time frames (subsection 2.2) are presented in map form. This allows to, more easily, assess the risk of mould growth for this type of facade system in accordance with the location. These maps were developed in MATLAB using code developed by the authors specifically for that purpose. This option allows for a greater flexibility when assessing and handling the data, and, at the same time, it is more time efficient and less prone to errors.

## 3. Results and discussion

### 3.1. Mould risk for current and future conditions – RCP 4.5 and RCP 8.5

One section of the under develop facade system was assessed in terms of mould risk for the nineteen Norwegian selected regions (Table 1) for two climate change scenarios – RCP 4.5 and RCP 8.5 in the far-future. The results of this assessment are present in the form of risk maps (Figure 4).

It is visible that the selected facade section does not show risk of mould growth since all regions have a green color, i.e. no growth [22]. This occurs for the current climate (Figure 4a) as well as for both climate change scenarios – RCP 4.5 (Figure 4b) and RCP 8.5 (Figure 4c).

This leads to the notion that this section is not under risk of mould growth for this study parameters, which is due to the facade exterior impregnable protection that prevents water to come in the facade and the interior protection, which prevents moisture to come in the facade. In addition, due to the facade composition, the interior temperature is high, which reduces the risk of mould growth.

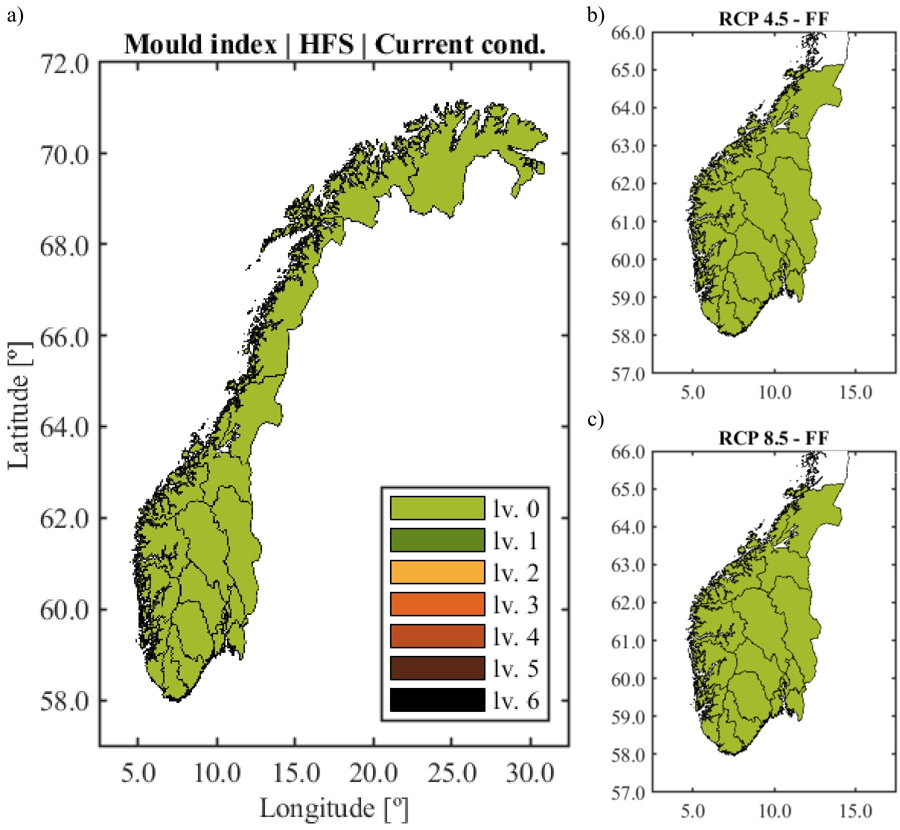


Figure 4 – *Mould index* map for current conditions (a) and in the far future (FF) for RCP 4.5 (b) and RCP 8.5 (c) for the hybrid facade system (HFS)

## 3.2. Testing the facade system under more demanding conditions

### 3.2.1. Air infiltration

The tested facade section is water-vapour resistant as a whole, but it also has a water-vapour repellent interior surface (a $S_d$-value of 0.5 m), which does not allow the absorption of moisture that originates from the indoor climate. In addition, the exterior surface is water repellent, since is a non-hygroscopic material, which does not allow the driving rain to penetrate into the facade.

However, due to construction details, it is possible for moisture to migrate from neighbouring sections, through air leakage paths, driven by convection. To account for this possibility, a moisture source due to air infiltration was considered using the IBP model. An air leakage rate of 0.6 $h^{-1}$ [17] was assumed, which due to the office area (150 $m^2$) and volume (ca 443 $m^3$), corresponds to an envelope infiltration q50 of 1.73 $m^3/(h.m^2)$.

It is visible that the facade is able to dry the simulated excess of moisture by air infiltration, which means that there is no risk of mould growth under the simulated conditions, currently (Figure 5a) nor are they expected in the future for either of the selected scenarios under the simulated conditions (Figure 5b and c). Note, although, that for a higher moisture infiltration rate the facade might behave differently.

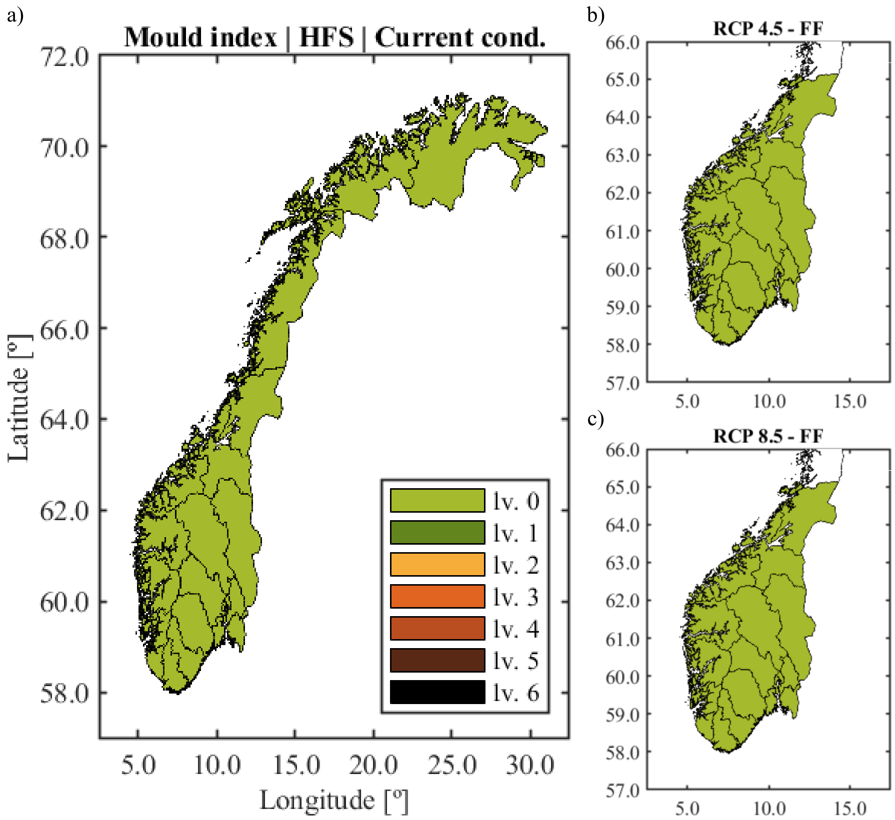


Figure 5 – *Mould index* map for current conditions (a) and in the far future (FF) for RCP 4.5 (b) and RCP 8.5 (c) for the hybrid facade system (HFS) with air infiltration

### 3.2.2. Initial moisture content

These simulations were conducted to determine the effects of keeping the timber parts of the facade system in areas of the construction site that are unprotected from the outdoor loads, e,g. rain, although the current recommendations on this matter [23]. These effects are determined by inputting a higher initial moisture content in the timber parts of the tested section in WUFI. A value of 80 % was adopted, which corresponds to ca 58 kg/m$^3$ in the simulated timber and reflects a wet substrate, instead of the typical value of 60 %. The latter corresponds to timber in "dry state" and for the simulated timber it corresponds to a water content of 41 kg/m$^3$.

It is visible that by increasing the initial moisture content from 60 to 80 % there is a major increase of the risk of mould growth (Figure 5a and Figure 6a), which demonstrates the importance of properly storing timber. The situation goes from "no growth" throughout Norway (Figure 5a) to "tight coverage" in two years after the beginning of the simulation for most of Norway (Figure 6a) with the exceptions being Akershus, Aust-Agder, Hordaland, Rogaland, Møre of Romsdal and Vestfold. Eventually, the facade is able to dry the moisture excess, and, consequently, the mould risk decreases, but the damage has already been done. The period that the facade needs to start showing signs of drying, which can take up to four years, varies in accordance with location. The largest periods are attained by Vest-Agder and Sør-Trøndelag, which correspond to ca. four and three years, respectively.

It is visible that climate change has the effect of decreasing the risk of mould growth due to the corresponding higher temperature and lower relative humidity. This occurrence is more significant for RCP 8.5 scenario due to its higher GHGs emissions.

Although the *mould index* manages to drop to 4.0 in some regions – Akershus, Oslo, Møre of Romsdal and Vestfold – for this scenario in the far future, it still corresponds to a situation of "visual coverage". Although the risk decreases, it still remains, which shows the importance of properly storing timber that will be used in the built environment. The exceptions to the risk decrease are Finnmark, Hedmark, Norland and Troms regions for both tested climate change scenarios that remain in level 6.0.

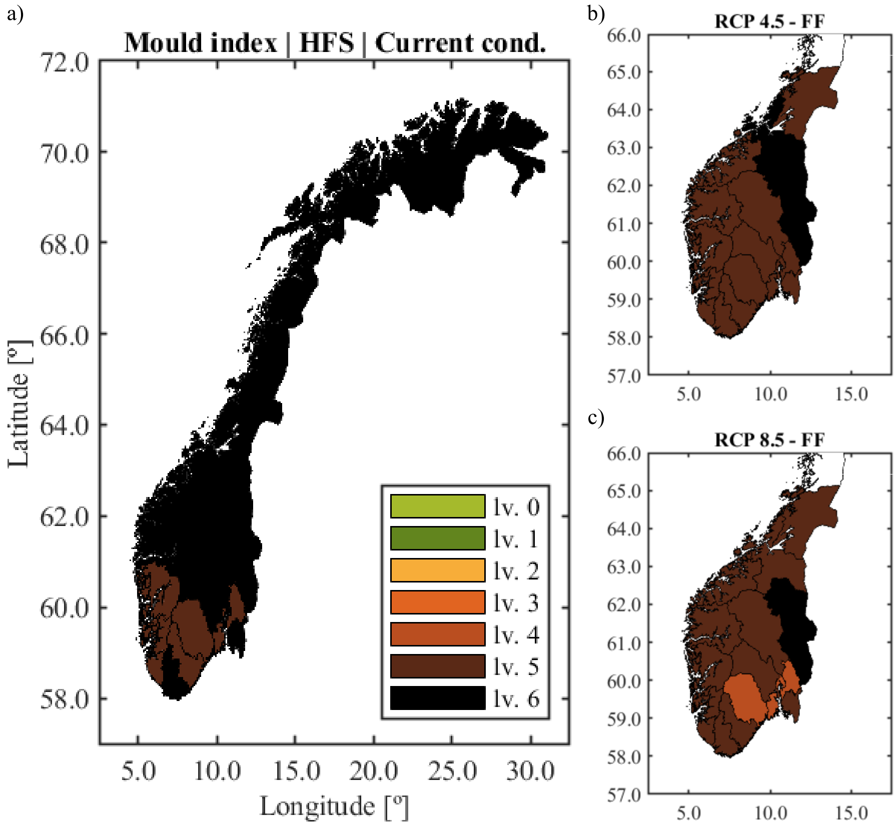


Figure 6 – *Mould index* map for current conditions (a) and in the far future (FF) for RCP 4.5 (b) and RCP 8.5 (c) for the hybrid facade system (HFS) with wet timber

## 4. Conclusions

This paper presents the assessment of hygrothermal performance of a new hybrid facade system (HFS), composed by both aluminium and timber, by means of heat, air and moisture transfer (HAM) simulations. The assessment methodology is based in using WUFI Bio to assess the risk of mould growth in accordance with the building location. The interstitial conditions in the facade system are obtained from WUFI®Pro simulations, which are feed in terms of indoor climate by means of WUFI®Plus simulations. This study encompasses nineteen locations in Norway.

The study was carried out for current climates as well as future climates, i.e. RCP 4.5 and 8.5 in the far future. In addition, two other assessments were carried out to try to identify the facade system limits, i.e. due to water infiltration as well as using wet timber in the construction site.

It is visible that the tested facade system is able to properly dry the excess of moisture within in current conditions as well as in future conditions, since for the tested climates and conditions there is no risk of mould growth. However, if the timber is not properly protected from moisture, then the situation is completely different. The worst-case scenario for the mould index is quickly attained in most regions of Norway, whilst for the other parts of the country the situation is also problematic, but to a lesser extent. This clearly shows the importance of properly storing timber. Finally, climate change is able to attenuate this situation in some of the tested regions, since the temperature inside the wall increases and the relative humidity decreases, but the risk of mould growth still remains.

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