GLOBAL WARMING POTENTIAL OF BUILDING CONSTRUCTIONS BASED ON HEAT AND MOISTURE TRANSPORT ANALYSIS

by

Balazs NAGY**, *Martin MAROSVOLGYI, and Zsuzsa SZALAY

Department of Construction Materials and Technologies Budapest, Faculty of Civil Engineering, University of Technology and Economics, Budapest, Hungary

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Global warming potential is one of the most important life cycle assessment indicator, which shows how much heat a greenhouse gas traps in the atmosphere relative to CO_2. In this study, we calculated the global warming potential of a highly insulated building construction detail of a residential nearly-zero energy building based on numerical simulations. To calculate the heat loss of building constructions, which is necessary for estimating the operational energy demand in the use phase of the building, we compared two numerical simulation methods: 2-D thermal simulations and 2-D conjugated heat and moisture transfer simulations. Besides that, we compared the effect of selecting different thermal insulation materials for insulating the building constructions, such as EPS, mineral wool, and wood wool. We then compared the thermal and linear thermal transmittances from the simulations besides evaluating the moisture transmittance behaviour of the constructions. In all examined scenarios, the constructions with mineral wool ended up being the highest impact alternative, while EPS was the lowest for walls and wood wool was for wall corner joints. We also found that including the wall corner joints in global warming potential calculations could increase the overall global warming potential of an average-sized family house by 10%. Our study shows the heat and moisture transfer induced differences between thermal insulations, and demonstrates that heat and moisture transfer modelling-based life cycle assessment indicator of building construction details gives valuable additional information designers to choose the proper thermal insulation.

Key words: *thermal bridge, hygrothermal simulation, heat and moisture transfer, moisture bridge, life cycle assessment, building construction*

Introduction

According to the EU's long-term goal, GHG emissions should be reduced by 80-95% by 2050, compared to the level of 1990 [1]. This ambitious plan requires strict building regulations, therefore, thermal insulation of new and existing buildings is an extremely important field, since it helps reduce the energy demand and decrease carbon emissions. The energy performance requirements of buildings have been constantly tightened in the EU in the past years since the introduction of the recast Energy Performance of Building Directive [2]. From 2021, all new buildings must be nearly zero energy buildings in the EU.

In the EU, expanded polystyrene and mineral wool dominate the external thermal insulation composite system (ETICS) market, while natural-based thermal insulations, such as

* Corresponding author, e-mail: nagy.balazs@emk.bme.hu

wood wool boards account for under 1% of sales [3]. Besides small differences in the aforementioned materials' thermal insulating capabilities, the main difference is in their price, availability, fire and moisture performance as well as in their carbon footprint. In our present research, we focus on this last topic.

Global warming potential (GWP) is one of the most important life cycle assessment (LCA) indicators, which shows how much heat a greenhouse gas traps in the atmosphere relative to CO_2 [4]. In our study, we calculate the GWP of highly insulated building construction details of a residential nearly-zero energy building (nZEB) based on numerical simulations. In this paper, we present the simplest building construction detail: the wall corner. Using this building construction joint, we describe our methodology and compare the results obtained by performing thermal, and heat and moisture transfer (HAM) analysis on wall sections and wall corner joints made of masonry wall and insulated with expanded polystyrene, mineral wool or wood wool thermal insulations. We also show the error made by neglecting a thermal bridge through all life cycle phases.

Literature review

Thermal bridges are the parts of a building construction where multi-dimensional heat flow occurs and heat flow density changes. Heat flow density can vary within a structure, among others, because of changes of materials, geometry or boundary conditions. The effect of a thermal bridge is expressed by the linear thermal transmittance, ψ value, which shows the difference in heat loss of one linear meter of building construction joint compared to the sum of adjoining building elements [4]. In the field of building physics and building energetics, thermal modelling of building constructions and details has been widely used for a long time. Direct heat transfer coefficient, H_d, between the heated or cooled spaces and the exterior can be calculated as the sum of the thermal transmittances of planar elements of the building envelope and the linear as well as the point thermal transmittances of joints responsible for 2- and 3-D (point) thermal bridges according to ISO 13789 [5]. In a detailed evaluation, thermal bridges are calculated by using numerical thermal simulations according to ISO 10211 [6]. Most EU states use simplified methods in their EPC to take the effect of thermal bridges into account, such as tabulated values, basic verification rules or mean U-values [6-8]. In whole building energy performance simulations, as well as in simplified calculations, which often form the basis of life cycle calculations, the effect of thermal bridges is often neglected or taken into account by increasing the surface U-values by an estimated percentage according to the local EPC's [9]. In buildings, an intensive analysis of thermal bridges showed that the ratio of linear thermal transmittance in the energy demand of buildings can vary from 5% (in the case of retrofitting the exterior of the building envelope) up to 40% (in well-insulated single-family houses without proper thermal bridge treatment) [10]. When the design of a building also covers the attentive reduction of the effect of thermal bridges, the ratio of linear thermal transmittance can be reduced under 10% [11].

The HAM modelling of building construction joints is much less common in the scientific literature than *thermal only* modelling, however, the coupled HAM through the envelope has a significant impact on the hygrothermal indoor behavior and energy consumption [12]. There are different validated hygrothermal models available, Liu model can handle near over-hygroscopic region more accurately than Kunzel model [13], although latter also gives reliable results in hygroscopic regions. In recent years, researchers have examined mainly planar structures and modelling of construction joints and thermal bridges using HAM are still in the developing phase. For example, out of 340 publications listed on the website of WUFI, there are only 22 English language papers dealing with the 2-D analysis of building constructions. The possibility of creating multidimensional simulations by using commercial software started in 2000 when the Fraunhofer Institute presented the WUFI 2-D [14] with many applications since then [15, 16]. Besides WUFI, there are other available tools, such as COMSOL MULTIPHYSICS, which is also capable of performing conjugated HAM simulations according to EN 15026 [17]. In our present study, we used COMSOL MULTIPHYSICS and Kunzel model to perform the thermal and HAM simulations on the building construction joints.

The LCA is a scientifically sound method for the *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle* [18]. The LCA can be conducted on the level of the building material, building element or for whole buildings. For insulation materials, numerous studies have been developed and many environmental product declarations are available from different producers [19]. On the building element level, researchers compared the environmental impact of different insulation materials and concluded that insulation is beneficial for the whole life cycle [20, 21]. When a whole building is assessed, mass and energy flows shall be quantified based on a building model according to EN 15978 [22] and ISO 21931 [23]. The level of details is not specified in the standard, and it can be very different in various types of assessments. For example, a *surface* model is sufficient for energy modelling, where thermal bridges are usually handled in a simplified way and the corresponding material quantities may be missing.

Materials and methods

Presented building construction joint

In this paper, we present the calculated GWP of a construction suitable in nZEB buildings where the use phase of the GWP is based on numeric modelling. At first glance, the problem including a wall corner sounds simple, yet the issue of dealing with the excess part of the wall corner is often not taken into account in building simulations and LCA calculations where internal dimensions are frequently used to calculate the energy performance and material quantities of a building. To examine how much GWP is neglected in the usual LCA calculations due to not taking into account the extra heat losses at the joints as well as the amount of material present in the corner, we modelled a usual nZEB wall corner construction in a Hungarian context. The wall corner is built from 30 cm masonry wall (Porotherm 30 N+F) with 15 cm thermal insulation board (either expanded polystyrene, mineral wool or wood wool), 1.5 cm plaster layers on the internal and external sides (gypsum and cement plaster), and 8 mm of dryvit mineral coating with embedded 0.2 mm thick glass fibre fabric on the external surface of the thermal insulation boards, fig. 1.

The sources of the material properties used in the thermal and HAM simulations are listed in tab. 1. We used mostly the WUFI database to obtain thermal and moisture performance properties needed to implement into the models in COMSOL, such as thermal conductivity, density, specific heat capacity, moisture storage function, water vapour resistance factor,

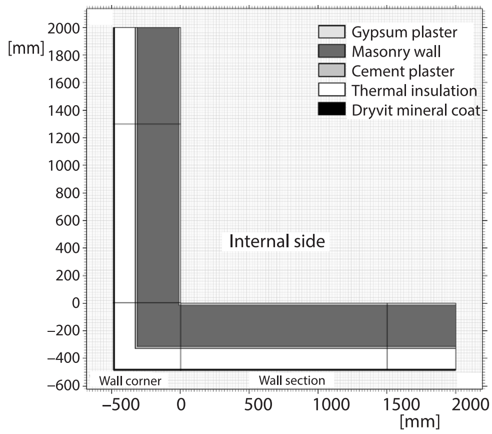

Figure 1. The 2-D model of an nZEB wall corner joint with 15 cm external thermal insulation system

and liquid transport coefficient. For the thermal insulation materials, as well as for the masonry wall, thermal properties are implemented using technical datasheets and ISO 10456 [24] to include the temperature and moisture dependent thermal conductivity as a function.

For the LCA calculations, we included the calculated volume and mass data of 1 m^2 wall construction and the excess amount of material in a wall joint in 1 linear meter of corner based on the geometry presented in fig. 1, where the excess amount of the section is indicated.

Table 1. Data sources of the used material properties

Material	Source of thermal properties	Material name in source	Source of moisture properties	Material name in source	Density [kgm^{-3}]
Gypsum plaster	WUFI DB	Interior plaster	WUFI DB	Interior plaster	850
Masonry wall	Wienerberger + ISO 10456	Porotherm 30 N+F + Fired clay	WUFI DB	Poroton WDF	750
Cement plaster	WUFI DB	Cement plaster	WUFI DB	Cement plaster	1800
Expanded polystyrene (EPS)	Austrotherm + ISO 10456	AT-H80 + Expanded polystyrene	WUFI DB	EPS 15 kg/m^3	15
Mineral wool (MV)	Rockwool + ISO 10456	Frontrock + Mineral wool	WUFI DB	Roxul FacadeRock	135
Wood wool (WW)	Steico + ISO 10456	Protect + wood wool	WUFI DB	Wood-fibre insulation	140
Dryvit mineral coat	WUFI DB	StoLevell StoDecosil	WUFI DB	StoLevell StoDecosil	1400

Thermal and HAM analysis

In the research, steady-state thermal and conjugated HAM simulations were carried out based on [25]. Recent studies showed that dynamic climatic conditions could have a significant effect on the performance of masonry walls [26, 27]. However, steady-state method is selected over the dynamic method in this paper due to a previous study that showed that in Hungarian climate, steady-state HAM simulations give less than 5% difference on the U-value compared to dynamic simulations on South oriented masonry facades in the heating season [27].

Partial differential equations

The PDE shown in eqs. (1) and (2) were implemented into COMSOL MULTIPHYSICS. Equation (1) shows the steady-state heat transfer, in which the first member represents heat fluxes from heat conduction and the second part shows heat fluxes from evaporation fluxes:

$$\nabla \mathbf{q} = \nabla \left\{ \lambda_{\text{eff}} \nabla T + L_v \delta_p \nabla \left[\varphi p_{\text{sat}} \left(T \right) \right] \right\} = 0 \tag{1}$$

The PDE of steady-state moisture transfer is defined in eq. (2), in which the first member of the equation represents the liquid transport of the moisture fluxes, while the second is responsible for moisture fluxes from vapor transport:

$$\nabla \mathbf{g} = \nabla \left\{ \xi D_w \nabla \varphi + \delta_p \nabla \left[\varphi p_{sat} \left(T \right) \right] \right\} = 0 \tag{2}$$

Boundary conditions

Due to the chosen steady-state method, only temperature and relative humidity were taken into account as the basis of the boundary conditions. For the thermal simulations, we used MSZ 24140 [28], which specifies an internal temperature of 20 °C and –2 °C externally, as well as 65% internal and 90% external relative humidity. For the HAM simulations average external data sets of Budapest were obtained from Meteonorm 7 for the standard heating season. According to the meteorological data, the external temperature is 3.92 °C and the relative humidity is only 70% on average in Budapest. Internal conditions of air, and the equivalent vapor diffusion thicknesses of the boundary-layers were set according to EN 15026 [17] normal occupancy. Surface heat transfer coefficients were set based on ISO 6946 [29]. The heat transfer coefficient were $h_{si} = 7.69$ Wm^{-2}K^{-1} for internal and $h_{se} = 25$ Wm^{-2}K^{-1} for external surfaces, while the equivalent vapor diffusion thickness of boundary-layer was set to $s_{d,si} = 0.008$ m on the internal and $s_{d,se} = 0.0023$ m on the external surface.

Linear thermal and moisture transmittance

Thermal transmittance, U-value, shows how much heat could flow through an $A = 1$ m^2 of internal surface of the building element in case of $\Delta T = 1$ K temperature difference:

$$U = \frac{Q}{A\Delta T} \tag{3}$$

The additional heat loss due to thermal bridges of building structures is characterized by calculating a linear thermal transmittance, ψ-value, which shows how much heat could flow additionally due to multidimensional heat flow compared to the surface thermal transmittance. Based on ISO 10211 [6], ψ-value can be calculated from the thermal coupling coefficient, L_{2D}, of the building element separating two spaces (*e.g.* internal and external space), the U_j thermal transmittance and the l_j internal length of the joining building elements:

$$\psi = L_{2D} - \sum_j U_j l_j \tag{4}$$

The thermal coupling coefficient in eq. (4) can be defined as the ratio of the internal surface heat flow, Q, and the temperature difference multiplied by the internal length:

$$L_{2D} = \frac{Q}{l\Delta T} \tag{5}$$

Life cycle assessment

The goal of the assessment is to show the effect of taking into account the joints in an accurate way *vs.* neglecting them on the environmental impact for the whole life cycle. The functional unit in an LCA study could be on mass or volume basis but to analyse building constructions, 1 m^2 is the only basis we can use to compare values relevant to their actual application. Therefore, in our study, the functional unit is 1 m^2 wall construction with 15 cm of thermal insulation as part of the ETICS. As the thickness of the insulation is fixed, the U-values and the corresponding heating energy demand will be different for each alternative. The reference study period is set to 30 years, which coincides with the reference service life of an ETICS system [30]. As an impact category, the GWP100a according to the CML 2001 method was selected. Environmental data used in this study are based on the Swiss ecoinvent v3.5 cut-off database [31]. The ecoinvent data have been contextualized to acknowledge national differences by adopting the Hungarian electricity and natural gas datasets for materials primarily produced in Hungary, using the OpenLCA software. The following life cycle stages were considered according to EN 15804 [32]: A1-3 production stage, A4 transport, A5 construction-installation with cutting waste, C2 end-of-life transport, and C4 waste disposal. Transport distances from the factory to the construction site were based on the number of production plants in the country or the typical import distance. Different materials have significantly varying transportation distance: while only 50 km transportation is needed for masonry wall and 150 km for plasters and EPS, mineral wool requires 350 km and wood wool more than 800 km. For the construction stage (A5), a cut-off waste of 3% was considered for insulation materials and 5% for brick and mortar, due to the lack of other data on the installation process [33]. No replacement is necessary during the reference study period. For waste treatment, standard regional and country-specific ecoinvent data were considered.

After the procedure of thermal and HAM simulations, the use stage is also calculated using B6 operational energy use. The heat transfer coefficient by transmission, H_{tr}, is calculated for the wall and wall construction joint:

$$H_{\text{tr,surface}} = AU \tag{6}$$

$$H_{\text{tr,thermalbridge}} = l\psi \tag{7}$$

The heating energy use in [kWh] is calculated assuming $T_{e,a}$ = 3.92 °C average external temperature in the heating season in Hungary, T_i = 20 °C internal temperature, Δt = 4472 h conventional length of the heating period, as well as a building service system using a condensing gas boiler with a seasonal efficiency of η = 1, for a reference study period of RSP = 30 years, eq. (8). The GWP is then calculated using 0.203 kg CO_2-eq per kWh based on the ecoinvent database:

$$Q_{\text{tr}} = \left[H_{\text{tr}}\left(T_{\text{i}} - T_{\text{e,a}}\right)\right]\frac{\Delta t}{1000}\frac{1}{\eta}RSP \tag{8}$$

Results and discussion

Embodied GWP of the building constructions

Embodied GWP of 1 m² of wall with ETICS

Figure 2 shows the embodied GWP values (A1-A5, C2, C4 life cycle stages) for all the materials of 1 m^2 of wall construction according to the volumes and mass. It is visible in fig. 2 that the masonry wall made of masonry blocks and cement mortar has the highest kg CO_2-eq per m^2 value, therefore, if we want to reduce the carbon footprint of a wall construction, reducing the thickness of the masonry blocks could lead to success. Among the thermal insulation materials, mineral wool is responsible for 27.33 kg CO_2-eq per m^2, which is the highest and more than 2.5 times higher than EPS, which has 11.77 kg CO_2-eq per m^2. This is due to the much higher density of mineral wool. The lowest GWP was calculated for wood wool boards in a wall construction, 7.54 kg CO_2-eq per m^2 and if the construction site is closer to the production facility, this value could

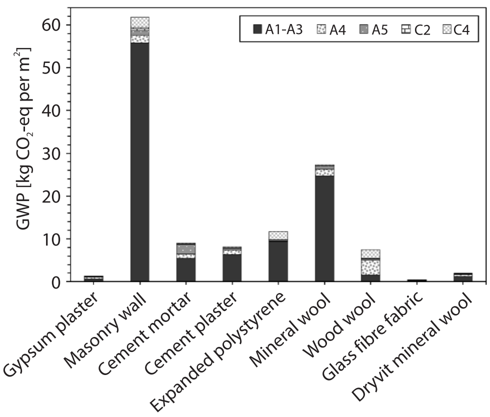

Figure 2. Embodied GWP of the materials of 1 m² wall construction with 15 cm ETICS

be even lower, since transportation was responsible for almost 46% of this value. Glass fibre fabric has high GWP, regardless of the basis. However, we only use 0.2 mm fabric on our façade and 0.165 kg material/m^2 even with a 10% overlap and a 5% cut in waste, so it is no wonder that it produced the lowest value among the examined materials. Therefore, it is pointless to spare the glass fibre fabric for environmental reasons.

After summarizing the components of the wall construction, the GWP is 94.39 kg CO_2-eq per m^2 for the EPS insulated wall, 109.95 kg CO_2-eq per m^2 for the MW based ETICS and 90.16 kg CO_2-eq per m^2 belongs to the wall insulated externally by using wood wool boards. Choosing mineral wool instead of wood wool thermal insulation increases the GWP of a wall construction by 22%, and even choosing EPS instead of mineral wool is 16.5% better considering GWP values of the whole construction. It is visible that wood wool is the most environmentally friendly solution, but if the factory is far away from the construction site, the gains made at the production stage almost disappear in the final results.

Embodied GWP of 1 m of wall corner with ETICS

Studying the joint of the wall constructions, the corners incorporate different volume and mass of materials. The results of the calculations are summarized in fig. 3 for the functional unit of 1 linear meter of wall corner construction. This measure is necessary to be able to add the use stage later, using the linear thermal transmittances. The amount of GWP compared to the different materials change because their geometry changes in a wall corner joint. The external insulation material has the highest value in a construction with mineral wool. In positive wall corners, the external insulating shell contains a greater amount of material, therefore,, its GWP is more significant. The summarized results of the three different types of construction are the following: 37.82 kg CO_2-eq per m^2, 50.42 kg CO_2-eq per m^2 and 34.39 kg CO_2-eq per m^2 for EPS, mineral wool and wood wool, respectively. The difference between the three constructions has increased significantly, a wall corner with 15 cm MW-based ETICS embodies 45.9% more CO_2 than a wood wool insulated construction. An EPS insulated wall corner has 8.9% higher GWP than with wood wool.

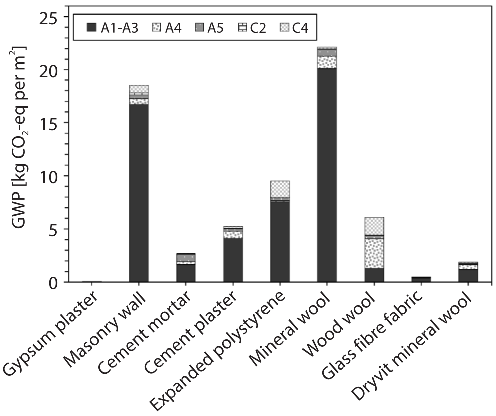

Figure 3. Additional embodied GWP of the materials of 1 linear meter wall construction joint with 15 cm ETICS

Thermal transmittance and whole life cycle values

Thermal transmittance and whole life cycle GWP of 1 m^2 wall

After the calculation of the embodied GWP of the wall construction, we performed thermal and HAM analysis on the building constructions. The *U*-values with different numerical simulations are summarized in tab. 2. It can be seen that the *U*-vales increased if we used HAM simulation, which included not only temperature, but also moisture content, depending on the thermal conductivity of the materials. Despite the low average external relative humidity, *U*-values increased between 3.9-6.1%. These differences occurred because while all the ETICS are constructed as a 15 cm thick layer, EPS has 0.038 Wm^{-1}K^{-1}, mineral wool 0.037 Wm^{-1}K^{-1}, and wood wool 0.042 Wm^{-1}K^{-1} thermal conductivity. Moisture adsorption capabilities and water vapour resistance factors also differ significantly.

Table 2. The *U*-value and GWP_{30} of the wall construction

Method/ETICS	U [$Wm^{-2}K^{-1}$]	A-C [kg CO_2-eq per m^2]	B6 [kg CO_2-eq per m^2]	GWP_{30} A-B-C [kg CO_2-eq per m^2]
Thermal/EPS	0.171	94.39	75.13	169.52
Thermal/MW	0.170	109.95	74.72	184.67
Thermal / WW	0.183	90.16	80.19	170.34
HAM/EPS	0.178	94.39	78.07	172.46
HAM/MW	0.179	109.95	78.34	188.29
HAM/WW	0.194	90.16	85.09	175.24

Table 2 shows that considering a 30-year reference study period for wall construction, the embodied CO_2 content will be larger than 30 years of usage. It is reasonable to say that we need to optimize and reduce the GWP of our materials because as it turns out, in an nZEB ready wall section the A-C stage emits more CO_2 than the complete use stage. The operational energy use is different for the three constructions and also depends on the simulation method. The most interesting point is that after considering the use stage, expanded polystyrene ended up being the most environmentally friendly alternative in both thermal and HAM simulation-based calculations. The GWP_{30} values increase by 1.7% to 2.9% when thermal simulations are compared to HAM modelling, therefore, HAM simulated operation energy use even made the difference larger between EPS and wood wool. The decomposed and stacked GWP stage values for each scenario can be observed in fig. 4.

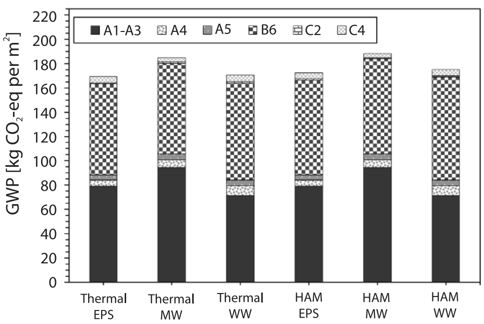

Figure 4. The GWP of the materials of 1 m^2 wall construction with 15 cm ETICS

Linear thermal transmittance and whole life cycle GWP of 1 m of wall corner

The results of the wall corner joint case are summarized in tab. 3. As mentioned before, similar to linear thermal transmittance, the linear GWP_{30} of the thermal bridge areas is often neglected or skipped in LCA calculations. However, if we consider calculating the corner's GWP for the 30-year period, we can see that it could be a significant amount that should not be neglected. The differences between the linear thermal transmittances obtained from a thermal and a HAM simulation vary between 8.4-9.8%, therefore, we can say that in positive wall corners, HAM simulation increases the results more than in planar structures. The temperature profile in the wall corner is lower due to the effect of thermal bridging. In comparison, the moisture profile is higher in the corner mainly because of the relative humidity field, and the latter effect can be called as moisture bridging [25].

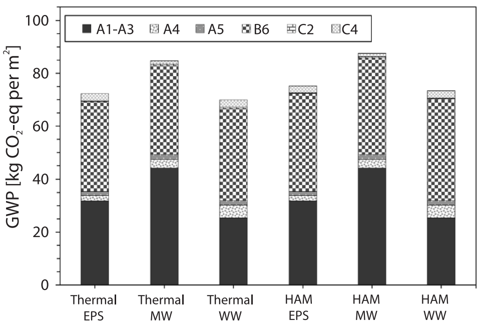

Figure 5. Additional GWP of the materials of 1 meter wall construction joint, 15 cm ETICS

Thermal bridging in the wall corner can be seen in fig. 6 where the isotherm lines draw

Table 3. Linear thermal transmittance and GWP_{30} of the wall construction joint

Method/ETICS	ψ [$Wm^{-1}K^{-1}$]	A-C [kg CO_2-eq per m]	B6 [kg CO_2-eq per m]	GWP_{30} A-B-C [kg CO_2-eq per m]
Thermal/EPS	0.0773	37.82	33.91	71.73
Thermal/MW	0.0768	50.42	33.68	84.10
Thermal/WW	0.0798	34.39	34.98	69.37
HAM/EPS	0.0840	37.82	36.82	74.64
HAM/MW	0.0832	50.42	36.49	86.92
HAM/WW	0.0876	34.39	38.42	72.81

closer to the internal side of the joint in the corner area. Moisture bridging is observable wors in our case using ETICS with low water vapour resistance factor such as wood wool, fig. 7. The relative humidity depends on the temperature of materials, therefore, the thermal bridge affects the relataive humidity field in the corner of the construction, respectively. It is also visible that according to the simulated relative humidity field, the model remained in the hygroscopic region. The moisture bridges at the corners and other building construction joints could reduce the thermal performance as increasing the moisture content in construction materials are increase the thermal conductivity and therefore, reduce the thermal resistance.

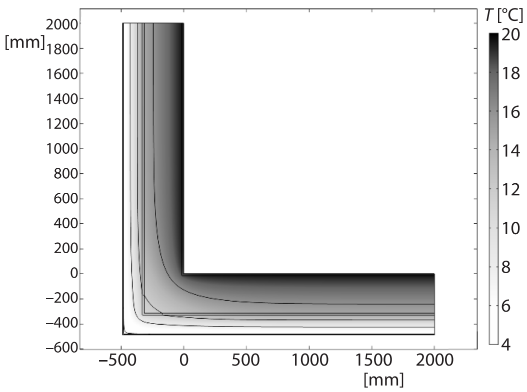

Figure 6. Temperature distribution in wall corner with 15 cm WW based ETICS

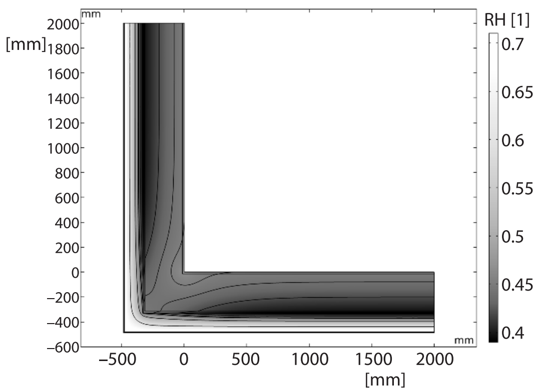

Figure 7. Relative humidity distribution in wall corner with 15 cm WW based ETICS

The summarized GWP_{30} increased by 3.3% to 4.9% due to the switch to the HAM simulation from a thermal approach. It is observable that the highest GWP is produced by the mineral wool yet again, but in this case, expanded polystyrene came in as the second highest, and wood wool offered the lowest solution.

The decomposed and stacked GWP stage values for each scenario can be observed in fig. 5. It is observable that in the case of wood wool-based ETICS, the operational energy use is higher than the production, construction and end of life stages all together. However WW could be significantly better if the considered building construction was located closer to the production facility, which turned out to be a serious issue in Hungary.

Finally, to emphasize the importance of HAM simulations and to consider the GWP_{30} of building construction joints in life-cycle assessment, we can calculate a simple case of a residential building. If we have a rectangular based, 8 m × 8 m internal sized, two levels high, 128 m^2 net floor area family house with four positive wall corners and an inner height of 3 m, then we can count 24 linear meter of wall corner joint and 192 m^2 of wall surface. Considering most of the studies are based on thermal simulations and count only the GWP from 1-D constructions, the total emission can be calculated between 32547.84-35456.64 kg $CO_{2\text{-eq}}$ emission depending on the type of the ETICS. If we consider HAM based LCA calculation, the emission from the walls itself become 33112.32-36151.68 kg $CO_{2\text{-eq}}$, which shows 2% increase only, which could be considered as a small difference that not worth the effort of the more time and resource-intensive HAM simulations over the simpler thermal simulations. However, if we consider adding the GWP_{30} of the wall corner joints too, it increases the HAM based GWP_{30} by around 5% to 35593.52-38990.92 kg $CO_{2\text{-eq}}$. We can state that HAM simulation-based LCA calculation gives around 10% higher GWP_{30} if we consider the effect of only the wall corners, which can be no longer called as a negligible amount. Based on these results, we would like to investigate the impact of all building construction joints in an entire building in our further research.

Conclusions

In this paper, the GWP of different wall and wall corner joint constructions was researched with different thermal insulations and numerical simulation methodologies. Firstly, we calculated the constituent materials' production, construction and end of life stage GWP values on both volumetric and mass basis, and then we calculated the exact values regarding the examined building constructions. To obtain the use-stage GWP, we made thermal and HAM simulations using a multidimensional finite element method. After we performed the analysis, the GWP for a 30-year study period was calculated for each case.

Our study showed that if we want to reduce the carbon footprint of a wall construction, reducing the thickness of the masonry blocks could lead easily to success. The HAM modelling induced differences between thermal insulations, as well as showing that LCA of building construction details based on HAM modelling gives valuable additional information designers to select the proper thermal insulation for their design. In all examined scenarios, mineral wool insulated constructions ended up being the highest GWP alternative. Expanded polystyrene was the most environmentally friendly alternative in both thermal and HAM simulation-based calculations for 1 m^2 of wall construction, but at wall corners, wood wool insulated constructions showed a bit lower GWP than EPS. The additional GWP could be as much as 10% if we consider an average-sized family house just from the wall corners. Therefore,, neglecting the additional material quantities and the thermal bridge effect at construction joints leads to an underestimation of both the embodied and the operational environmental impacts.

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Nomenclature

A – surface, [m^2]
D_w – liquid transport coefficient, [m^{2}s^{-1}]
g – moisture flux, [kgm^{-2}s^{-1}]
H_d – direct heat transfer coefficient
H_{tr} – heat transfer coefficient by transmission, [WK^{-1}]
h – heat transfer coefficient, [Wm^{-2}K^{-1}]
L_{2D} – thermal coupling coefficient, [Wm^{-2}K^{-1}]
L_v – latent heat of evaporation of water, [Jkg^{-1}]
l – internal length of the joining building elements, [m]
Q – heat flow, [W]
p_{sat} – saturation pressure of water vapor, [Pa]
q – heat flux, [Wm^{-2}]
T – temperature, [K]
U – thermal transmittance, [Wm^{-2}K^{-1}]

Greek symbols

δ_a – vapor permeability of still air depending on air temperature, [–]
δ_p – vapor permeability (= δ_a/μ), [kgm^{-1}s^{-1}Pa^{-1}]
η – efficiency, [–]
λ_{eff} – temperature and volumetric moisture content dependent effective thermal conductivity (= $\lambda_{10,dry}\,e^{f_T(T_2 - 10\,°C)}e^{f_\psi(u_2)}$], [Wm^{-1}K^{-1}]
μ – vapor resistance factor, [–]
ξ – differential moisture capacity, [kgm^{-3}]
φ – relative humidity, [–]
ψ – linear thermal transmittance, [Wm^{-1}K^{-1}]

References

[1] ***, European Comission, *Energy roadmap* 2050, Publications Office of the European Union, Luxembourg, Luxembourg, 2012
[2] ***, European Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), *Official Journal of the European Union, L153* (2010), 13, pp. 13-35
[3] Pavel, C. C., Blagoeva, D. T., *Competitive Landscape of the EU's Insulation Materials Industry for Energy-Efficient Buildings*, Publications Office of the European Union, Luxembourg, Luxembourg, 2018
[4] Dodd, N., *et al*., Level(s) Indicator 1.2: Life cycle Global Warming Potential (GWP) User Manual: Introductory Briefing, Instructions and Guidance (Publication Version 1.1), http://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2021-01/UM3_Indicator_1.2_v1.1_37pp.pdf
[5] ***, ISO 13789:2017 Thermal performance of buildings –Transmission and ventilation heat transfer coefficients – Calculation Method, International Organisation for Standardisation, Geneva, Switzerland, 2017
[6] ***, ISO 10211:2017 Thermal bridges in Building Construction – Heat flows and surface temperatures – Detailed Calculations, International Organisation for Standardisation, Geneva, Switzerland, 2017
[7] Erhorn-kluttig, H., *et al*., Thermal Bridges in the EPBD context, *Proceedings*, 30th AIVC Conference Trends in High Performance Buildings and the Role of Ventilation, Berlin, Germany, 2009, pp. 1-6
[8] Kuusk, K., *et a*l., Calculation and Compliance Procedures of Thermal Bridges in Energy Calculations in Various European Countries, *Energy Procedia, 132* (2017), Oct., pp. 27-32
[9] Kiss, B. Szalay, Z., Modular Approach to Multi-Objective Environmental Optimization of Buildings, *Automation in Construction, 111* (2020), 103044
[10] Capozzoli, A., *et al*., A Building Thermal Bridges Sensitivity Analysis, *Applied Energy, 107* (2013), July, pp. 229-243
[11] Pelss, M., *et al*., Thermal Bridge Impact on the Heating Demand in a Low-Energy House, *Scientific Journal of Riga Technical University Environmental and Climate Technologies, 4* (2010), 1, pp. 76-81
[12] Ferroukhi, M. Y., *et al*., Bosschaerts, Impact of Coupled Heat and Moisture Transfer Effect on Buildings Energy Consumption, *Thermal Science, 21* (2017), 3, pp. 1359-1368
[13] Dong, W., *et al*., A Validation of Dynamic Hygrothermal Model with Coupled Heat and Moisture Transfer in Porous Building Materials and Envelopes, *Journal of Building Engineering, 32* (2020), 101484
[14] Holm, A., Kunzel, H. M., The 2-D Transient Heat and Moisture Simulations of Rising Damp with WUFI 2d, *Proceedings*, 12th International Brick/Block Masonry Conference, Madrid, Spain, 2000, vol. 2, pp. 86
[15] Ge, H., Baba, F., Dynamic Effect of Thermal Bridges on the Energy Performance of a Low-Rise Residential Building, *Energy and Buildings, 105* (2015), Oct., pp. 106-118
[16] Orosz, M., *et al*., Hygrothermal Simulations and in-Situ Measurements of Ultra-Lightweight Concrete Panels, *Pollack Periodica, 12* (2017), 3, pp. 69-83
[17] ***, EN 15026:2007 Hygrothermal Performance of Building Components and Building Elements – Assessment of Moisture Transfer by Numerical Simulation, European Committee for Standardisation, Brussels, Belgium, 2007

[18] ***, ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework, International Organisation for Standardisation, Geneva, Switzerland, 2006
[19] Pargana, N., *et al*., Comparative Environmental Life Cycle Assessment of Thermal Insulation Materials of Buildings, *Energy and Buildings, 82* (2014), Oct., pp. 466-481
[20] Tingley, D. D., *et al*., An Environmental Impact Comparison of External Wall Insulation Types, *Building and Environment, 85* (2015), Feb., pp. 182-189
[21] Kalhor, K. Ememinejad, N., Qualitative and Quantitative Optimization of Thermal Insulation Materials: Insights from the Market and Energy Codes, *Journal of Building Engineering, 30* (2020), 101275
[22] ***, EN 15978:2011 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method, European Committee for Standardisation, Brussels, Belgium, 2011
[23] ***, ISO 21931-1:2010 Sustainability in Building Construction – Framework for Methods of Assessment of the Environmental Performance of Construction Works – Part 1: Buildings, International Organisation for Standardisation, Geneva, Switzerland, 2010
[24] ***, ISO 10456:2007 Building Materials and Products – Hygrothermal Properties – Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values, International Organisation for Standardisation, Geneva, Switzerland, 2007
[25] Nagy, B., Stocker, G., Numerical Analysis of Thermal and Moisture Bridges in Insulation Filled Masonry Walls and Corner Joints, *Periodica Polytechnica Civil Engineering, 63* (2014), 2, pp. 446-455
[26] Trindade, A. D., *et al*., Influence of the Climatic Conditions on the Hygrothermal Performance of Autoclaved Aerated Concrete Masonry Walls, *Journal of Building Engineering, 33* (2021), 101578
[27] Nagy, B., Designing Insulation Filled Masonry Blocks Against Hygrothermal Deterioration, *Engineering Failure Analysis, 103* (2019), Sept., pp. 144-157
[28] ***, MSZ 24140:2015 Power Engineering Dimensioning Calculuses of Buildings and Building Envelope Structures, Hungarian Standards Institution, Budapest, Hungary, 2015
[29] ***, ISO 6946:2017 Building Components and Building Elements – Thermal Resistance and Thermal Transmittance – Calculation Methods, International Organisation for Standardisation, Geneva, Switzerland, 2017
[30] Ritter, F., Lebensdauer von Bauteilen und Bauelementen, Ph. D. thesis, Technische Universitat Darmstadt, Darmstadt, Germany, 2011
[31] ***, Ecoinvent: Allocation cut-off by classification, http://www.ecoinvent.org
[32] ***, EN 15804:2012+A1:2013 Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products, European Committee for Standardisation, Brussels, Belgium, 2013
[33] Kellenberger, D., Althaus, H. J., Relevance of Simplifications in LCA of Building Components, *Building and Environment, 44* (2009), 4, pp. 818-825

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