EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

Comprehensive report on the further development of the EnerPHit building certification criteria and procedures within the 3encult project (task 7.4)

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Project Coordinator	Alexandra Troi EURAC research, Viale Druso 1, 39100 Bolzano/Italy Alexandra.troi@eurac.edu
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Author(s)	Zeno Bastian, Dr. Juergen Schnieders, Dr. Benjamin Krick, Tanja Schulz
Co-author(s)	-
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1 Introduction and general overview

1.1 “EnerPHit”: A voluntary standard for advanced energy retrofit

While the EPBD and its national adaptations set mandatory requirements for the energy demand of new buildings and renovations, there are also a number of additional voluntary energy standards. Some are present only on local or regional level, e.g. for municipal funding programs, whereas other standards are valid nationally, in all of Europe or even world-wide. The Passive House standard was defined in the 1990s by the Passive House Institute in Germany. It is now widely applied to buildings all over the globe, from the mild climate of Portugal to hot and humid Shanghai or Minnesota’s freezing cold winters. For all locations the Passive House standard combines very high energy efficiency with excellent user comfort at minimal life cycle costs.

Figure 1: EnerPHit seal

In many European countries the building renovation market has gained the main market share in the recent past. However, when old buildings are renovated, it is often difficult to achieve Passive House standard. Typical reasons for this are unavoidable thermal bridges as well as a general building design, which was originally not optimized for energy efficiency. For such buildings, the Passive House Institute (PHI) introduced the EnerPHit[1] standard in 2010. The basic principle is to modernize all relevant parts of the building with Passive House components. This way almost all advantages of the Passive House standard can be realized in retrofits, even if the heating demand is not reduced all the way down to the Passive House limit of 15 kWh/(m²a).

Typical Passive House components, which are required for EnerPHit retrofits in cool, temperate climates like Central Europe include an efficient heat recovery ventilation system, windows with triple glazing and insulated frames, more than 200 mm of thermal insulation and a very good air-tightness. Thermal bridge effects should be mitigated as best as possible within reason. The benefits of these measures for the building owner and occupants include:

[1] EnerPHit stands for “**En**ergy Retro**fit** with **P**assive **H**ouse Components“

- Warm indoor surface temperatures, preventing condensation and mould and ensuring a much more even temperature distribution inside, contributing to optimal thermal comfort.
- Improving air-tightness prevents structural damage caused by the exfiltration of humid indoor air into exterior building components. Uncomfortable drafts caused by the infiltration of cold outdoor air are also avoided.
- Comfort ventilation with heat recovery tangibly improves air quality with positive health effects, and helps reduce mould risk by reliably removing moisture.
- Using Passive House components in a modernization can reduce heat demand by more than 90 percent. Carbon emissions for building heating are reduced to the same extent, if not more.
- The sum of all energy saving measures results in a yearly financial profit for owners and residents.

1.2 Further development of the EnerPHit certification scheme in the 3encult project

After a pilot phase the first version of the EnerPHit certification criteria officially came into effect in spring 2010, half a year before the start of the 3encult project. However, certification of energy retrofits with Passive House components was completely new at that time. Therefore the certification criteria were restricted to building types with which Passive House Institute had already gained extensive experience in the years before (see [John 2002], [Kaufmann 2009a], [Kaufmann 2009b]). This included residential buildings in cool, temperate (Central European) climate. Buildings that are predominantly insulated from the inside were excluded at that time. One reason was the greater effort and knowledge for the building certifier necessary to evaluate the structural longevity of interior insulation. The other reason was that heating demand values too far from Passive House standard should be avoided during the first run.

One of the 3encult tasks was to create certification criteria and procedures for energy retrofit of historic and listed buildings including buildings that have interior insulation measures applied. Instead of creating entirely new criteria, PHI decided to extend the existing EnerPHit criteria for application to historic buildings. The goal also was to be able to use the criteria for evaluation of the eight 3encult case study buildings. However, these were mainly nonresidential buildings, not yet covered by the EnerPHit criteria (museums, schools, offices and university buildings). Moreover some of them were located outside of Central European climate (warmer climates of Spain and Northern Italy as well as a colder elevated alpine location in Appenzell, Switzerland). For this reason amongst others the EnerPHit criteria had to be extended to nonresidential buildings and other climate zones.

The further development of the 3encult criteria was carried out in two phases with the release of a new version of the EnerPHit criteria at the end of each phase.

1.3 Phase 1

1.3.1 Nonresidential buildings in cool, temperate climate

One of the main differences with effect on the energy balance of nonresidential buildings compared to residential buildings is the amount of internal heat gains (IHG), which is generally considerably higher. Other factors, such as the ventilation air change rate are often of comparable height in residential and common nonresidential buildings such as educational and office buildings as shown in [Bastian 2012]. The question arose if and how this was to be reflected in the EnerPHit criteria. High internal heat gains lower the heating demand in an unrefurbished building, thus reducing the potential for savings by energy efficiency measures such as thermal insulation. However first evaluations showed that improving the energy efficiency to the level of Passive House components is economically viable also in buildings with higher IHG. Later this was systematically analyzed for Central European climate in [Bastian 2012] showing that the EnerPHit component requirements were only not recommendable in buildings with extremely high IHGs above 12 W/m². This could be confirmed on an international level within the 3encult project: For typical non-residential use like offices or schools the optimum changes very little as compared to dwellings. Thus there was no reason to lower the component requirements for nonresidential buildings. Moreover very high IHG are often a sign of inefficient electricity use. This might (should) be improved in the future. Therefore it would not make sense to base the efficiency standard of the building envelope which should last approx. 50 years on possibly excessive IHGs.

The second question was related to the alternative certification procedure based on the heating demand. Would the limiting value of 25 kWh/(m²a) also make sense for nonresidential buildings with higher IHGs. The answer was quite simple. For many retrofits of nonresidential buildings also the 25 kWh/(m²a) are a relatively low value, too, which takes quite some effort to achieve. However, there is also the case of a large and compact office building with little shading in winter. Such a building might, in extreme cases, reach the 25 kWh with relatively unambitious measures such as only 14 cm of wall insulation. In this case, however, the clause in the criteria that says that EnerPHit certification is only applicable to buildings which cannot reach the Passive House standard due to restrictions caused by the existing construction comes into effect. This implies that a building that could reach Passive House standard just by using standard Passive House components (with the same efficiency standard as the EnerPHit component requirements) cannot receive EnerPHit certification.

Based on the above considerations the scope of the EnerPHit criteria was extended to nonresidential buildings without the necessity of any other related changes. At this time (spring 2012) the criteria were still valid for cool, temperate climate only. There was no requirement for the cooling demand yet, as this is of lower importance in cool, temperate climate.

1.3.2 Buildings with interior insulation

The installation of interior insulation requires high standards of planning and execution, in order to avoid moisture-related damage. This also has to be checked during the certification process in order to avoid certification of faulty buildings. Frequently hygrothermal simulations are used to predict the successful functioning of the interior insulation. During the certification process the certifier has to decide if a hygrothermal simulation is required. He/she also has to check the hygrothermal simulation reports provided for the certification. This is not an easy task, considering that hygrothermal simulations depend on a lot of parameters and assumptions, and considering that there are no simple rules for the interpretation of the simulation results. Not all Passive House / EnerPHit certifiers have a sufficiently high level of experience in hygrothermal simulation. Therefore a guideline on how to evaluate interior insulation systems and simulation reports was necessary. This was created by PHI following an extensive research process. It is included in chapter 6.

In the published version of the certification criteria there is no requirement to prove that exterior insulation has not been possible in a specific building. Instead the decision if exterior or interior insulation is most suitable for their house is left to the building owner and architect. EnerPHit-certified buildings with predominant use of interior insulation can have a heating demand of more than 60 kWh/(m²a). This is tolerated as for these specific buildings reaching much higher efficiency levels would not be economically feasible.

1.3.3 Historic and listed buildings

It is clear that many historic buildings cannot be fully renovated with Passive House components without compromising their cultural heritage value. On the other hand many energy efficiency measures indeed are compatible with historic buildings. Frequently these measures, when applied with care, can even help preserve the historic substance. A heat recovery ventilation system, for example, lowers the relative humidity of the indoor air in winter thus preventing moisture-induced damage.

The EnerPHit approach is based on the evaluation of individual components also and especially in the case of historic buildings. Each component with EnerPHit requirements has to be evaluated for parallel requirements from cultural heritage protection authorities. In case of conflicts, the heritage protection requirements prevail. However, for all other components, the EnerPHit component requirements have to be applied as far as compatible with the heritage protection requirements. This way it is ensured that the optimal efficiency standard possible under the heritage protection restrictions is achieved.

As a second rule exemptions from the EnerPHit specifications are only permissible if minimum standards regarding thermal comfort, prevention of moisture-induced damage and mould growth as well as healthy living conditions in general are met. These absolute minimum requirements are listed in the certification criteria and include minimum U values for the thermal envelope (e.g. a minimum U value of 0.85 W/(m²K) for external walls). If the existing construction does not meet these requirements and an improvement is not possible, EnerPHit certification has to be declined. The reason is, that EnerPHit is not only meant to be an energy saving standard, but also a standard that offers high comfort and living quality.

1.4 Phase 2

At the end of phase 1 updated EnerPHit criteria, including requirements for listed, nonresidential buildings in cool, temperate climates with interior insulation were published and came into effect. However, the extension to other European climates was still missing. The criteria for cool, temperate climate had been based on the certification criteria for Passive House components (component certification). Such criteria were not available for other climates at the start of the 3encult project.

Thus as a prerequisite for Europe-wide EnerPHit certification Passive House component requirements for all European climates had to be defined. These requirements had to ensure that the corresponding components were cost-efficient over the life-cycle. Moreover the efficiency had to be good enough to prevent moisture, mould growth and impairment of thermal comfort. Full component certification criteria with detailed requirements on testing procedures etc. were, however, not necessary for the further development of the EnerPHit criteria. The basic requirements such as a U value or heat recovery efficiency were sufficient.

1.4.1 From international component requirements to certification criteria

The Europe-wide component requirements were determined using an economic optimization process, which also took into account requirements regarding thermal comfort and prevention of moisture-induced damages as boundary conditions. The process and its results are explained in detail in chapters 1 - 4.

The optimization was based on 1289 climate data sets for Europe (geographic resolution of 1°) and resulted in a set of cost-optimal component s for each location. This high resolution was important for receiving exact and reliable results in the first step. However, it would have been unwieldy for use in general certification criteria. A further step of simplification was required which reduced the many single locations to 7 climate zones with common sets of component requirements each. This process and its results are described in chapter 5.

In a last step the simplified requirements had to be integrated into the EnerPHit requirements for practical application in building certification. Some of the defined component requirements were not necessary for the building certification criteria and could be omitted. This included

- requirements for the window U value without installation thermal bridges (only the installed state is relevant for EnerPHit certification),
- airtightness requirements for single components such as doors (these are covered by the overall airtightness requirement for the whole building),
- electric efficiency of ventilation systems (covered by the overall primary energy requirement)

Strategies for summer comfort and lower cooling demand derived from the economic optimization process were simplified in order to give the designer more freedom of choice.

Some special issues that had to be solved when integrating the international component requirements into the EnerPHit criteria are described in the following sections.

1.4.1.1 Ventilation heat recovery efficiency in cooling climates

The heat recovery efficiency value given in the Passive House component certificate takes into account the heat emission of the fans, the leakages and the transmission heat losses through the casing. The resulting value is correct for application in the heating season. In this case the heat emitted by the fans is an additional benefit.

However, if the heat recovery system is used for recovering coolness, the fans' heat emission is unwanted. In the PHPP a correspondingly lower heat recovery efficiency value has to be used for cooling.

1.4.1.2 Limitation of solar heat loads and night-time ventilation

From the economic optimization process specific measures such as anti-sun glazing, fixed window overhangs and temporary shading devices (blinds) resulted. However these were optimized for the specific situation in the example buildings used for the calculations. Other buildings can have other shading situations, window fractions etc. which may also be different from window to window in the same building. Thus a more flexible requirement was needed.

The solution to this was to determine a general threshold above which the installation of anti-sun measures would be economic (in buildings with active cooling) regardless of the shape and location of the specific building. The related analysis resulted in a value of 100 kWh/(m²a). As a rough rule, it can be said that if the solar irradiation on 1 m² of glazing during the cooling period is higher than this value, anti-sun measures will be economic. This is true regardless of the type of measure (e.g. installation of blinds or overhang) as higher investment costs for one measure are made up for by corresponding higher sun blocking efficiency resulting in an overall comparable economic viability.

Most anti-sun measures will have a negative effect on electric energy demand for lighting as also some of the visible light spectrum will be blocked. The electricity demand is, however, already covered by the overall primary energy requirement. Thus there was no need for an additional requirement regarding visible light transmission of anti-sun measures.

For buildings and locations which allow for passive cooling, the requirement of a maximum of 10 % overheating (fraction of times with indoor temperatures above 25 °C) was adopted from the Passive House criteria. This is not an energy criterion but a comfort criterion and thermal comfort in an EnerPHit building should not be considerably lower than in a Passive House. How this criterion is met, wether with nighttime ventilation, shading or other passive measures is up to the designer. The requirements for solar load limitation only apply to buildings with active cooling.

Nighttime window ventilation can also help reduce the (active) cooling demand in some climates. However the contribution of nighttime ventilation to the reduction of the cooling demand will normally not exceed a few kWh/(m²a). The reason for this is, that nighttime ventilation is only useful if a) there is a cooling demand at all, b) the nights are nevertheless cool enough and c) the outdoor air is not too humid. For buildings and locations with a cooling demand above 15 kWh/(m²a) the relative influence of nighttime ventilation is generally low.

Moreover it would be quite difficult to specify exact requirements for nighttime window ventilation as a large number of different window configurations is possible, which would lead to very different achievable air change rates. Additionally nighttime window ventilation is frequently impeded by several practical obstacles such as traffic noise, danger of burglary etc.

For all of the above reasons, a requirement for nighttime window ventilation for buildings with active cooling has not been included in the EnerPHit component requirements.

1.4.1.3 Airtightness

Airthightness cannot be correlated with specific costs (except for the cost of the airtightness test) as it is a general quality requirement for all buildings. High levels of airtightness can be achieved with careful planning and execution, rather than with financial investments. Therefore a fixed airtightness requirement of 1.0 h^{-1} was defined for all climate zones. This requirement had already proven to be realistically achievable in Central European EnerPHit projects, whereas the Passive House requirement of 0.6 h^{-1} would be to demanding most of all in smaller projects.

1.4.1.4 Primary energy requirement

The current EnerPHit criteria use the energy requirement of 120 kWh/(m²a) from the Passive House criteria, but with an additional allowance for the extra heating demand:

$Q_P \leq 120\ kWh/(m^2a) + (Q_H - 15\ kWh/(m^2a)) \cdot 1.2$

The general factor of 1.2 takes the primary energy factor of fossil fuels (1.1) as well as the performance factor of the heat generator into account.

In the new version of the criteria, the primary energy factor for the cooling demand also needed to be taken into account. It was added to the requirement formula as below:

$Q_P \leq 120\ kWh/(m^2a) + [(Q_H - 15\ kWh/(m^2a)) \bullet 1.2\ ]^* + [Q_C - Q_{C,\ Passive\ House\ requirement}]^{**}$

*only to be added if $Q_H - 15\ kWh/(m^2a) > 0\ kWh/(m^2a)$

** only to be added if $Q_C - Q_{C,\ Passive\ House\ requirement} > 0\ kWh/(m^2a)$

This means that any heating or cooling demand that exceeds the Passive House requirements is added to the primary energy demand as an extra allowance. For cooling there is no additional factor (like the 1.2 for the heating demand) as for the cooling demand the primary energy demand roughly equals the final energy demand (primary energy factor of electricity very roughly equals the seasonal performance factor of the cooling devices).

1.5 Outlook

For the final public version of the EnerPHit criteria a shift from evaluation according to primary energy factors (PE) to renewable primary energy factors (PER) is foreseen, parallely to the same change in the Passive House certification criteria. This will probably make the above primary energy requirements obsolete.

Additionally there will probably be three classes of EnerPHit: “basic”, “plus” and “premium”. Like the new Passive House classes, these will depend on the efficiency of the technical systems and on the amount of renewable energy generation.

2 Economic analyses as a basis for certification criteria

2.1 Definition of the task

For the certification of energy efficient modernisations of preserved historic buildings it seems appropriate to link the requirements for building components with economic considerations. The position of the economic optimum is of central importance for practical implementation. Certification criteria must also be based on this economic optimum.

The data basis and methodology for the following considerations were first applied in [Feist 2011] for defining an economically optimum new construction in any chosen climate. The methodology was refined for the analyses documented here and adapted to the situation with listed historic buildings; on account of the project framework, these analyses are largely limited to Europe. In order to help the reader understand the reasons behind this, relevant parts of the text from [Feist 2011] have been reproduced or adopted with slight changes below.

2.1.1 Climate data

In order to be able to generate a set of climate data for any point on the surface of the Earth, it is important to obtain the corresponding data at low cost and little effort from a single source. Satellite data from the NASA, which are continually available via the EOSWEB interface ([NASA 2009]) without cost and which were processed by the Passive House Institute, are ideal for this purpose. Among other information, these data sets include daily mean values for the temperature, solar radiation and air humidity over a period of 23 years.

This data has a spatial resolution of 1 degree, which equates to a distance of up to 111 km. We use 1289 data sets for the areas of land in Europe which are located west of 35° East.

The spatial resolution of the data is not adequate everywhere. Systematic errors can be expected particularly in mountainous regions such as the Alps, where the climate can change drastically within the distance of a few kilometres. The climate also changes radically near coasts within the space of a grid cell. On the other hand, Germany for example has a considerably finer resolution with ca. 40 grid points compared with the 15 test reference years used by the German Meteorological Service.

This data has the great advantage that it is widely available, covers a long period of time continuously and is derived from the same source. It is thus ideally suited for comparative investigations. The amount of data which would have accumulated with a higher resolution could only have been processed with a great deal of technical effort.

The usability of the available satellite data was checked in detail in [Feist 2011]. According to the adaptation and processing carried out by the PHI, overall correlation with the data from other sources can be described as satisfactory. The three-day mean deviation in the temperatures is usually less than 1 K compared to other sources; global radiation values vary by less than 10 W/m². The data was therefore used without modification, with one exception: for outdoor temperatures around 0 °C and mid-latitudes, global radiation according to EOSWEB was typically higher by 10 to 20 % than according to other sources. For these cases, global radiation was reduced by 20 % in order to remain on the safe side in this respect.

Hourly data was first generated based on algorithms in [Duffie 2006] and [Meteonorm 2010] using the data basis with daily values, which was downloaded from the EOSWEB server, dividing global radiation into direct and diffuse radiation. From the hourly data we generated data sets for calculations with the Passive House Planning Package (PHPP, see [PHPP 2007]). The following examinations are based on these data sets.

2.1.2 Methodology for calculating economic feasibility

If buildings and components are optimised from an economic point of view with reference to their energy demand for heating and cooling, then the necessary extra investment should be put into relation to the saved energy costs. The most appropriate method for this is that known as the net present value method, where each expenditure or income within the life cycle of the building is discounted to the beginning of the period under consideration using the chosen capital interest rate. This takes into account the fact that because of the interest due on the capital, costs which are incurred at a later point in time (here: energy costs) are weighted as being less than the costs which arise at the beginning of the period under consideration (here: investment for construction). More information about this method can be found for example in [Kah 2008], [Feist 1997], [Feist 2005] and [Feist 2013].

Since the cost of products for construction, labour and energy varies greatly in different countries in Europe, such considerations can only serve as a guideline. Research on energy and construction costs for the affected countries was far beyond the scope of the present study in any case; other optimums may result in individual cases and at current prices.

Uncertainties in the boundary conditions only play a smaller role in the conclusions drawn here; for example, as shown in [Kah 2009], the influence of variations in the boundary conditions on the *position* of the economic optimum is small. The optimum itself is decidedly flat especially with reference to the insulation thicknesses, so that the insulation thickness can be varied in the order of ± 30 % starting from the optimum, without appreciably influencing the economic optimum (see also [Kah 2009]).

For preserved historic buildings, the costs for an energy efficient renovation in individual cases may be considerably higher than those for new constructions, for example. However, as a rule the costs due to building preservation are likely to be independent of the chosen insulation thickness; they are incurred as soon as insulation is carried out. In the following study, as in the case of a new construction, only the costs for additional thermal insulation will therefore be assessed. Whether completely dispensing with improved thermal protection is more cost effective in a specific case cannot be decided with universal validity, just as it cannot be decided whether the historic monument can be better preserved with or without additional thermal protection.

The chosen cost estimates are based on the assessment of the authors with reference to average prices throughout the period under consideration. Economies of scale due to the higher number of items, also for products which were exotic up till now, have already been priced in. The fact that such effects greatly distort the price is apparent from the situation in Germany for example. In the mid-nineties shortly after insulating double glazing practically became standard due to legal requirements, this became available at the same price as the previously common double glazing without low-e coating and inert gas filling; today, the latter is only available at significantly higher prices as a special product. A similar trend is now apparent for low-e triple glazing; in the future this can be expected for low-e quadruple glazing.

2.1.3 Example buildings

The energy demand for the variants of two sample buildings as described below was determined for each location using the Passive House Planning Package [PHPP 2007].

The calculations were first carried out in accordance with [Feist 2011] on the basis of the geometry and orientation of the end-of-terrace house in Darmstadt-Kranichstein (Germany), which was built to the Passive House Standard. The building faces exactly south and is moderately shaded; most of the windows are on the south side (30 m² south-facing windows with a living area of 156 m²). Details of this building are provided in the sample file in [PHPP 2007]. The new construction situation was assumed for this building in which any type of e.g. shading and glazing can be chosen, and the heating or cooling system respectively depends on the building characteristics. This building is identified below as **Type I**.

Obviously, the described new construction situation is atypical for the modernisation of preserved historic buildings. In spite of this, the results are valuable for the present task since the sensitivity of the results and any specific features of the modernisation become clear in comparison with the calculations described below for preserved historic buildings.

Figure 1: One of the example buildings for the economic assesment: Wilhelminian apartment house in Ludwigshafen, Germany before (left) and after (right) refurbishment (Images: Osika GmbH)

In order to accommodate the special situation arising in modernisations of preserved historic buildings, an existing building in a city location was considered. This was an east-west oriented triple storey Wilhelminian style house as part of a row of buildings in Limburgstraße in Ludwigshafen (see [Schnieders 2005]). Inevitably, the results obtained for this were completely different on account of the different geometry and the decreased available solar radiation. Apart from this, unavoidable thermal bridges remain after the modernisation, more so with interior insulation than with exterior insulation. These were taken into account as an overall value. In addition, as described further below, some boundary conditions were selected differently from those in the case of a new construction. This represents the building **Type II**.

Two further questions were examined for the Type II building:

- The effects of interior insulation instead of the standard exterior insulation in a complete refurbishment.
- The position of the economic optimum in case only one building component (e.g. the windows or the roof) can be modernised due to building preservation reasons, while the existing building otherwise remains the same. The typical historic interior insulation was also presumed here.

With Wilhelminian style buildings like Type II, preservation orders often only apply for the specially designed facade on the street side, while it is possible to use exterior insulation for the plain courtyard façade (rear façade) of the building. This situation is covered by both extreme cases "interior insulation only" and "exterior insulation only" and will not be examined separately here, also because the optimum insulation thickness is barely influenced by the level of thermal protection of the remaining building (see Section 2.2.2).

Altogether, four variants were considered for each location:

1. Type I, new construction, south-facing
2. Type II, existing building, exterior insulation
3. Type II, existing building, interior insulation
4. Type II, existing building, modernisation of single building components only

2.1.4 Boundary conditions for the economic feasibility calculation

The boundary conditions summarised in Table 1 to Table 4 were used for the calculations. All prices are retail prices including VAT. The present value of the energy service "comfortable temperature-controlled interior space" is obtained from the invested costs and the capitalised energy costs over the 40-year period under consideration. The house is cost-optimised if this value is minimal.

The glazing types shown in Table 2 were used successively for each individual location. A modern Passive House window frame with a good level of thermal protection and 90 mm facing width was used all throughout[2], this can be manufactured at the same price as ordinary frames and therefore will soon represent the economic optimum in any case. This level of thermal protection is also achievable with preserved historic buildings; the "SmartWin historic" window developed in the context of the 3encult project results in almost

[2] Another improved window frame which is not commercially available yet was assumed with vacuum and quadruple glazing for Type I: U_f = 0.45 W/(m²K), frame width 70 mm, extra costs € 20/m².

the same window U-value (for example, the difference is 0.03 W/(m²K) for the windows of Type II).

Four ventilation strategies were examined for each of these glazing types:

a) Exhaust air system without HRV/ERV, with night-time ventilation via tilted windows across several storeys (n = 0.46 h^{-1} for a temperature difference of 1 K)
b) Exhaust air system without HRV/ERV, without night-time ventilation
c) Supply and extract air system with 90 % HRV, with night-time ventilation as above
d) Supply and extract air system with HRV as above and 80 % ERV, without night-time ventilation

The economically optimum U-values of the opaque exterior building components were determined for the best ventilation strategy in terms of cost. Apart from this, an economically optimal level of airtightness was specified for the new construction case Type I, whereby an overall amount of € 5 per square metre of living area was set for improvement from n_{50} = 0.6 h^{-1} to 0.35 h^{-1} and from 0.35 h^{-1} to 0.25 h^{-1}. In principle, values worse than 0.6 h^{-1} were not permitted here in order to guarantee faultless functioning of the ventilation system, structural integrity etc. Better values were interpolated or extrapolated using a hyperbola. The n_{50} value was always 1.0 h^{-1} for the refurbishment case Type II; it is not possible to achieve better values in existing buildings reliably. The economic optimums of U-values and airtightness depend on the length of the heating or cooling periods and thus on the mechanical systems of the building and the quality of windows used, therefore they must be redefined for each variant.

The first economic optimum is obtained in this way. If passive cooling is not sufficient for the thus calculated building, then shading equipment in accordance with Table 4 is additionally taken into account in the comparison[3].

Finally, a search was made for a functioning Passive House for the new construction variant Type I. If the heating load or the sensible cooling load of the building which was optimised as previously described was higher than 10 W/m², then thermal protection was improved for the cases with supply air and extract air systems in such a way that both these limits were undercut. In this case a discount was made for a simplified building services system (supply air heating or cooling) according to Table 3. Since as a rule the Passive House Standard cannot be achieved for preserved historic buildings on account of the specific boundary conditions, this procedure was not carried out for Type II.

[3] For Type II, it was assumed all throughout that there is temporary shading on the outside. This is generally the case in existing buildings in Southern European climates, for colder climates shading is less relevant in any case.

Table 1: Boundary conditions of the economic analysis

Real interest[1]	2.5 %
Usage period of exterior building components	40 years
Price of additional insulation for wall and basement ceiling[2], λ = 0.035 W/(mK)	€ 1/cm/m²
Price of additional insulation for roof	€ 0.50/cm/m²
Price of additional wall insulation in case of interior insulation[3]	€ 7/cm/m²
Average price of final energy[4]	9.2 cents/kWh
Efficiency factor of heat generator	92 %

1 This is a typical value for the mortgage interest rate, taking into account the rate of inflation (see [Feist 2013]).

2 The basement ceiling can in principle be insulated at a low price similar to that for the roof; however, there is often insufficient space available, so one would have to use materials with a smaller thermal conductivity, which costs even more than exterior wall insulation. With the value set here, we have adopted the middle course between the two.

3 A loss of living area has been priced in for interior insulation. With an overall price of € 1500 per m² living area and a room height of 2.50 m, this gives an additional square meter price of € 6 per centimetre of thermal insulation. In principle, the approach for loss of living area would only be justified from the point when the interior surface temperature allows the placing of furniture next to the exterior wall, otherwise a gain in living area would have to be assumed as a matter of principle. However, like the general increase in residential quality due to increased comfort, this has not been taken into account here so that the ascertained insulation thicknesses are rather too low.

4 The average real price during the period under consideration, inc. taxes and duties. If local energy prices are significantly lower, this is either due to subventions, or the locally produced energy could have been sold more profitably on the world market. In such cases, this has to do with a macroeconomic rather than a microeconomic analysis, but price adjustments during the usage period of a building are particularly likely in these cases. Further increases in energy prices during the period under consideration have not been included since in the long term, the substitution of increasingly scarce fossil fuels with renewable energy sources for a price slightly higher than the current price level is likely. Useful cooling energy for cooling and dehumidification is included with the same price as that for heating energy.

Table 2: Properties of the examined glazing types

Abbreviation	Glazing type	U-value [W/(m²K)]	g-value [-]	Costs [€/m²]
2ISO	Insulating double glazing	2.74	0.78	45
2LE	Low-e double glazing	1.13	0.62	55
3LE	Low-e triple glazing	0.58	0.49	75
3LE+	Low-e triple glazing w/ high transmittance	0.69	0.62	80
4LE	Low-e quadruple glazing[1]	0.36	0.41	95
4VAK	Low-e quadruple vacuum glazing[2]	0.20	0.46	180
2SPG	Solar protective double glazing	1.04	0.19	65
3SPG	Solar protective triple glazing	0.57	0.19	85
2SPGX	Double solar protective glazing extra[3]	1.04	0.10	65
3SPGX	Triple solar protective glazing extra[3]	0.57	0.10	85

1 This product is already commercially available, but only on a made-to-order basis at considerably higher prices.

2 This product is already commercially available; two double vacuum glazing units have been joined into quadruple glazing with a conventional space between the two which is filled with argon gas. The technical data is provided by the manufacturer, the assumed price refers to production on a large scale.

3 This type of glazing is not common. In order to provide a good level of colour reproduction, the daylight transmission factor cannot be significantly higher than 0.2 for physical reasons. This type of glazing was not considered for the existing building Type II.

Table 3: Cost assumptions for mechanical services in € per square metre living area

	Costs [€/m²]
Extract air or supply air system	15
Supply air and extract air system with HRV	40
Additional costs for ERV	5
Heat or cold air distribution, in case heating or cooling load is greater than 10 W/m²	20

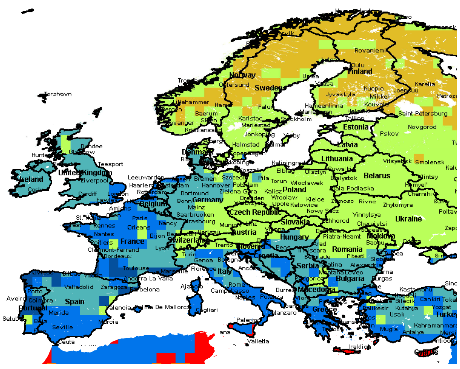
Table 4: Properties of the examined shading devices

No.	Type of shading	Reduction factor for g-value	Costs [€/m²]
1	Overhang, 1 m deep	geometric	40
2	Temporary shading inside[1,3]	0.7 … 0.9	15
3	Temporary shading outside[2,3]	0.25	80
4	Overhang & temporary shading inside[3]	combination	55

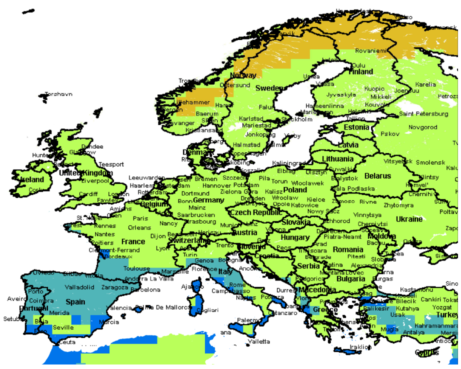
1 The effectiveness of shading on the inside depends on the type of glazing
2 The reduction factor takes into account partial use to a certain amount
3 Not in combination with solar protective glazing

2.2 Results

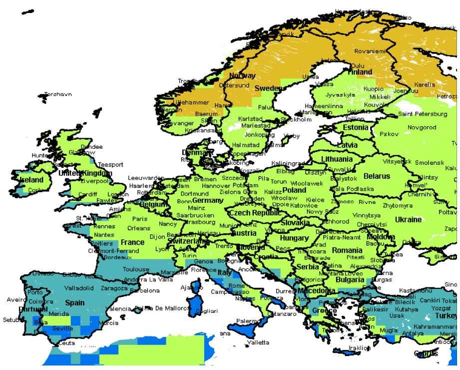
2.2.1 Glazing



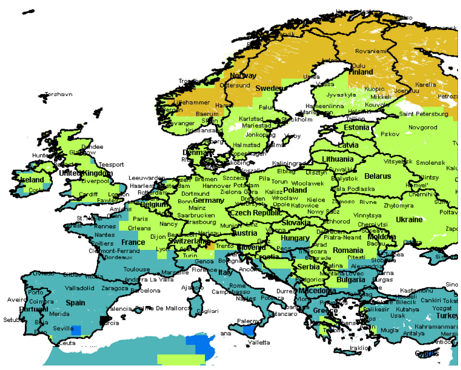
Glazing type, exterior insulation, Type I



Glazing type, exterior insulation, Type II



Glazing type, interior insulation, Type II



Glazing type, rest of building not modernised, Type II

Figure 2: Optimum glazing types. SPG: Solar protective glazing, VIG: vacuum insulation glazing, LE: low-e glazing. See also Table 2.
The image resolution corresponds with the available climate data sets, each pixel represents a climate data set. Interpolation between the pixels as performed in the following sections does not make sense for the glazing types.

Which glazing type is cost optimal depends greatly on the boundary conditions. Other optimums often apply for Type I, which is the south-facing, unshaded, newly built terraced house, in contrast with Type II, which is the modernised apartment house in a city location. The differences are partly due to the different geometry and partly due to the fact that a cost reduction was assumed for Type I if the Passive House Standard could be achieved, while this was not the case for Type II.

Even for Type I, solar protective glazing is of practically no interest in Southern Europe, since the reduction of the heating demand with simultaneous solar protection in the summer by combining clear glass with movable shading devices has proved superior. Solar protective glazing as an alternative for new construction is only possible in the far South of the region under consideration. For Type II, solar protective glazing was not taken into consideration due to building preservation reasons, as already mentioned above.

To the east and north of Germany, low-e quadruple glazing represents the cost optimum for Type I in the long term. This result is given by the calculation even for Austria and Switzerland; however, when interpreting the result, it should be noted that the climate data apply for medium elevations, while in the Alps built-up areas often exist only in the valleys, where temperatures are higher.

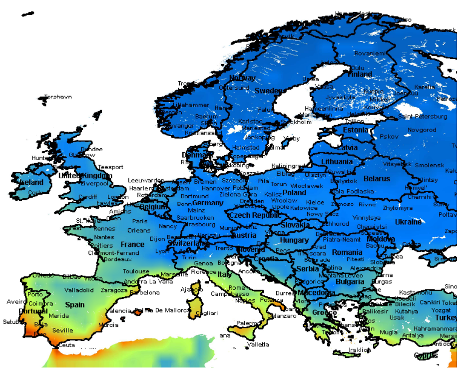
Low-e quadruple glazing is the optimal solution for the strongly shaded Type II building not only in Eastern Europe, but also in Germany, large parts of France, and the British Isles. The fact that the range for quadruple glazing stretches even further with simultaneous optimisation than that for separate optimisation (i.e. if the other components of the building remain at the old level), which is apparent in the two lower illustrations with Southern Europe or the west of France, is explained by the longer heating periods for the case with separate optimisation. Phases with high available solar radiation increasingly occur in the heating period due to this, so that glazing types with a high g-value become more favourable despite their higher U-values, and the triple glazing scores better than the quadruple glazing.

For the new construction case, very inconsistent recommendations for glazing result in France, Spain and Italy. Here the optimal glazing type depends greatly on the climatic details as well as the type of building, because depending on the situation, even small differences in the solar gains, heat losses and investment costs will lead to a different cost optimum.

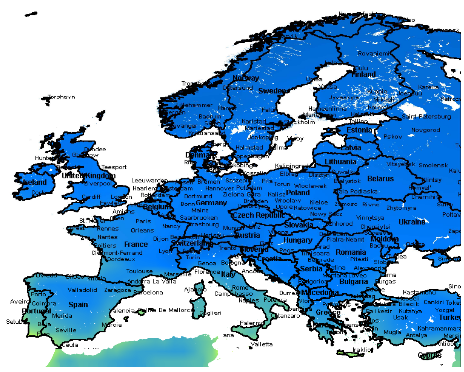
This situation is illustrated using Paris as an example. Here the cost optimum new construction has low-e triple glazing (3LE) with shading on the inside; however, for the glazing types 3LE+ and 4LE, variants also exist with lifecycle costs which are less than 10% higher. The ratios in existing buildings are similar (Type II, interior insulation): the most favourable variants for the glazing types 2LE, 3LE, 3LE+ and 4VIG have lifecycle costs which are less than 5% higher than the cost optimal variant with 4LE.

The certification requirements in such regions should be based more on the slightly higher U-values (triple glazing here), since otherwise a solution which is not cost-effective would be required at least in some cases, especially as quadruple glazing units aren't yet available at the long-term prices assumed here and frequently aren't economical at the moment.

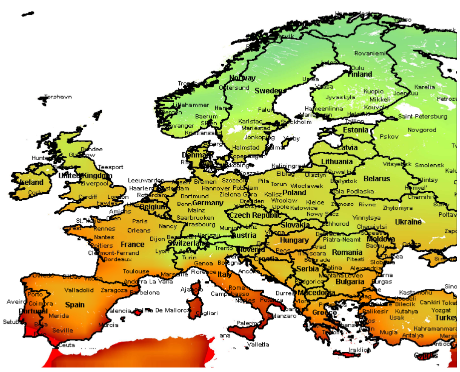
2.2.2 Insulation of the exterior wall



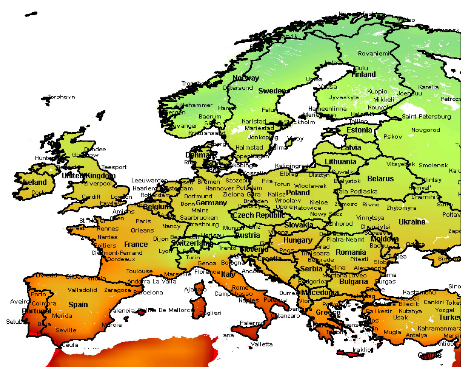
U-value of exterior wall, exterior insulation, Type I



U-value of exterior wall, exterior insulation, Type II



U-value of exterior wall, interior insulation, Type II



U-value of exterior wall, interior insulation, rest of building not modernised, Type II

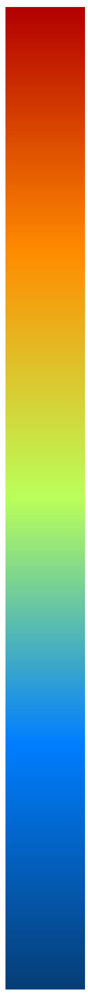


Figure 3: Optimum U-values of walls

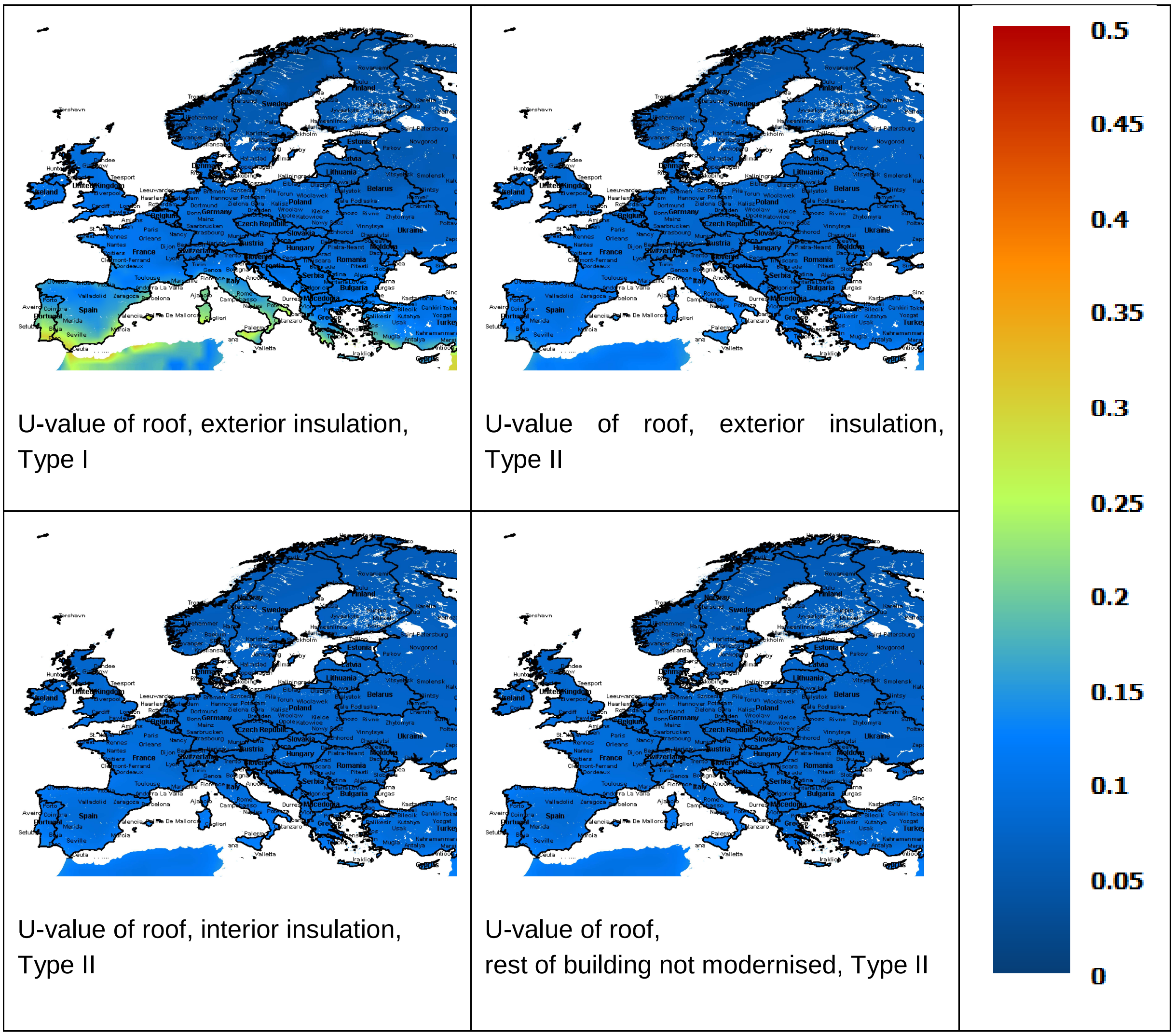
For the new construction case Type I, relatively moderate U-values of up to 0.4 W/(m²K) result in Southern Europe. Here the potential utilisation of passive solar gains is clearly noticeable; the heating period becomes so short that a good level of thermal insulation is no longer worthwhile, nor is it necessary. The situation is different with the Type II building, that is rather unfavourable with reference to passive solar energy utilisation, where the cost-optimal level of thermal protection in Southern Europe becomes lower than in northern latitudes on account of the mild temperatures, but not to the same extent.

In contrast, in Scandinavia where available solar radiation is low in any case, the more compact building envelope is particularly advantageous so that even a lower level of thermal protection results in the economic optimum for Type II.

With interior insulation, only smaller insulation thicknesses make sense on account of the allocated loss in living area.

The lower two illustrations show an important result: the interior insulation in the otherwise unchanged existing building requires only slightly better U-values than the interior insulation in the completely refurbished building; the differences in the length of the heating period are hardly noticeable in this respect. To a large extent, this will also be confirmed further on for other building components; this implies that requirements on a component-by-component basis can very well be reasonably formulated in spite of the interaction between the components because they are almost independent of the rest of the building.

2.2.3 Insulation of the roof



U-value of roof, exterior insulation, Type I

U-value of roof, exterior insulation, Type II

U-value of roof, interior insulation, Type II

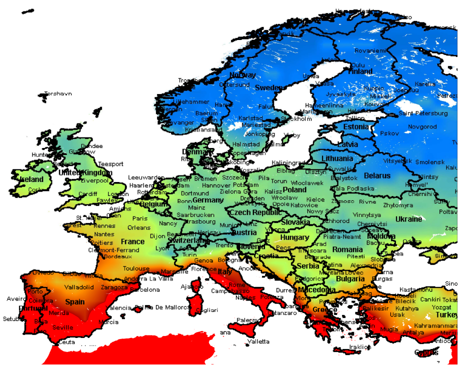
U-value of roof, rest of building not modernised, Type II

Figure 4: Optimum U-values of roofs

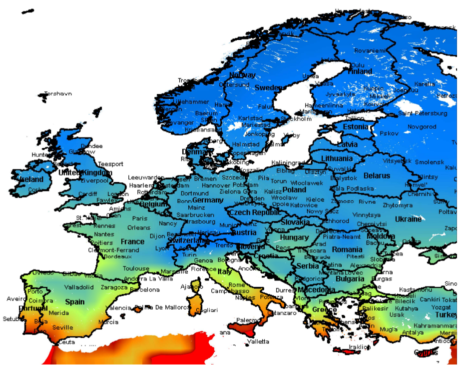
The results for the roof are similar to those for the exterior wall. Again, much more insulation is required for the house Type II in the sunny climate than for the solar house

Type I. Whether the exterior wall is insulated on the outside or the inside hardly affects the optimal level of thermal protection of the roof.

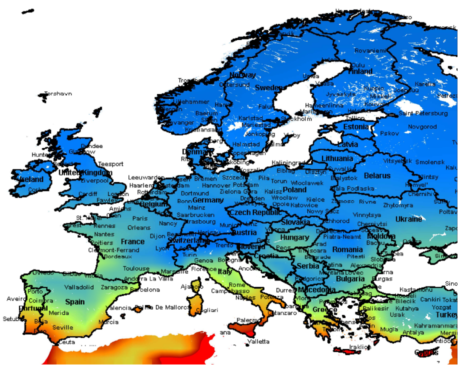
2.2.4 Insulation of basement ceiling



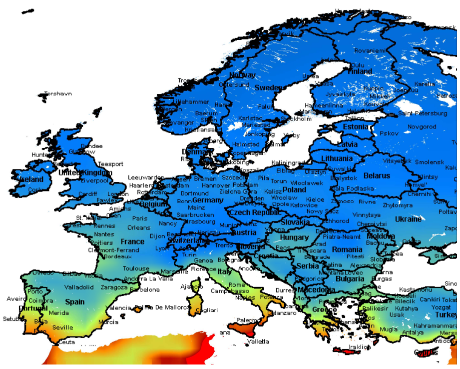
U-value of basement ceiling, exterior insulation, Type I



U-value of basement ceiling, exterior insulation, Type II



U-value of basement ceiling, interior insulation, Type II



U-value of basement ceiling, rest of building not modernised, Type II

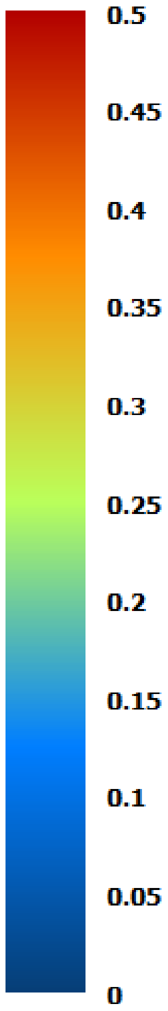


Figure 5: Optimum U-values of basement ceilings

For the basement ceiling, a lower level of thermal protection than for the exterior wall and roof makes economic sense on account of the insulating effect of the soil. Near the southern borders of Europe, with a good level of thermal protection of the rest of the building and possibly even higher solar gains (Type I), insulating the basement ceiling/floor slab will hardly be worthwhile.

2.2.5 HRV / ERV

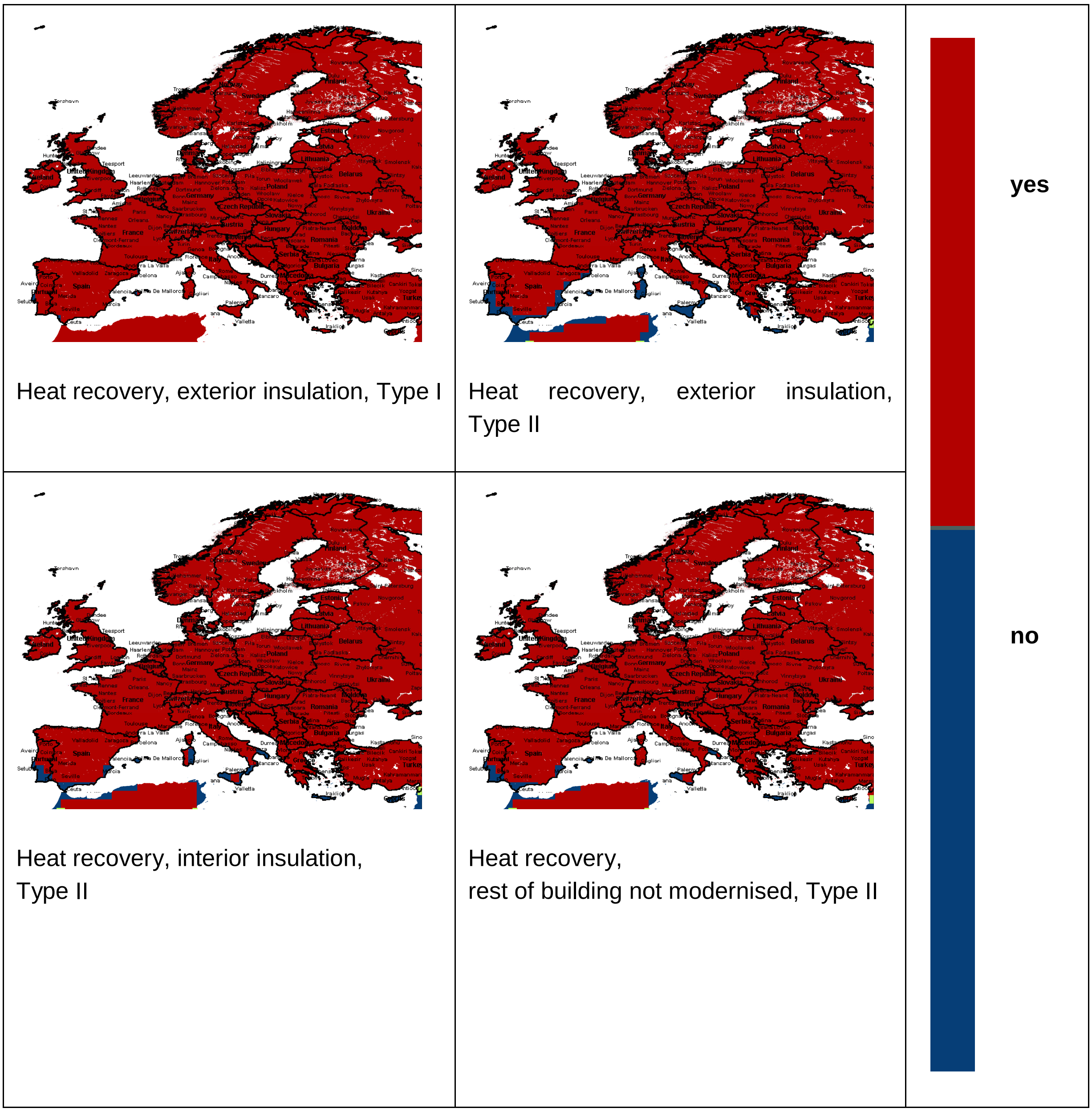
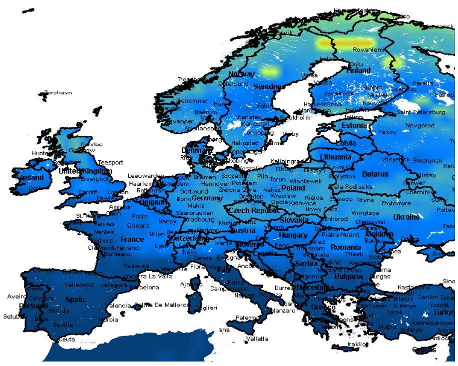


Figure 6: Optimum choice of ventilation heat recovery: yes or no?

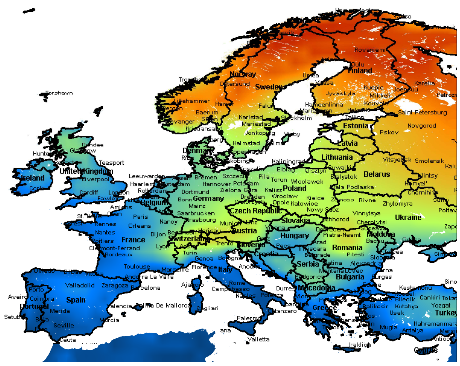
Mechanical ventilation with heat recovery is almost always worthwhile. The mild winter climates in Southern Europe again are an exception. Here, heat recovery on its own is uneconomical; this will become financially interesting only if it allows for omission of a heat and cold distribution system, as assumed for the new construction Type I.

A moisture recovery system for reducing latent cooling loads is economically impractical in European climates; however, for increasing the indoor air humidity in winter, it may be of interest for cold climates in particular.

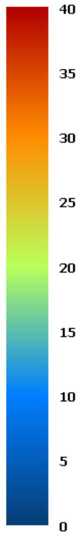
2.2.6 Heating demand

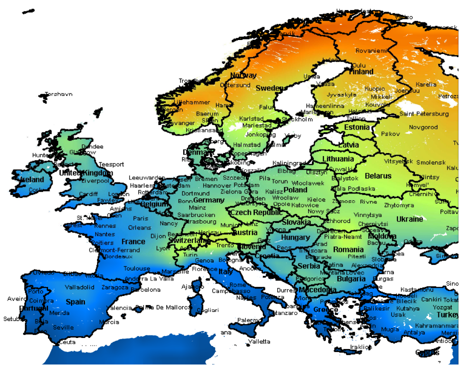


Heating demand, exterior insulation, Type I



Heating demand, exterior insulation, Type II





Heating demand, interior insulation, Type II

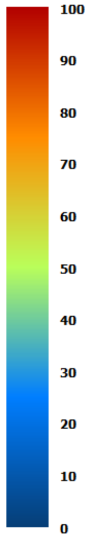


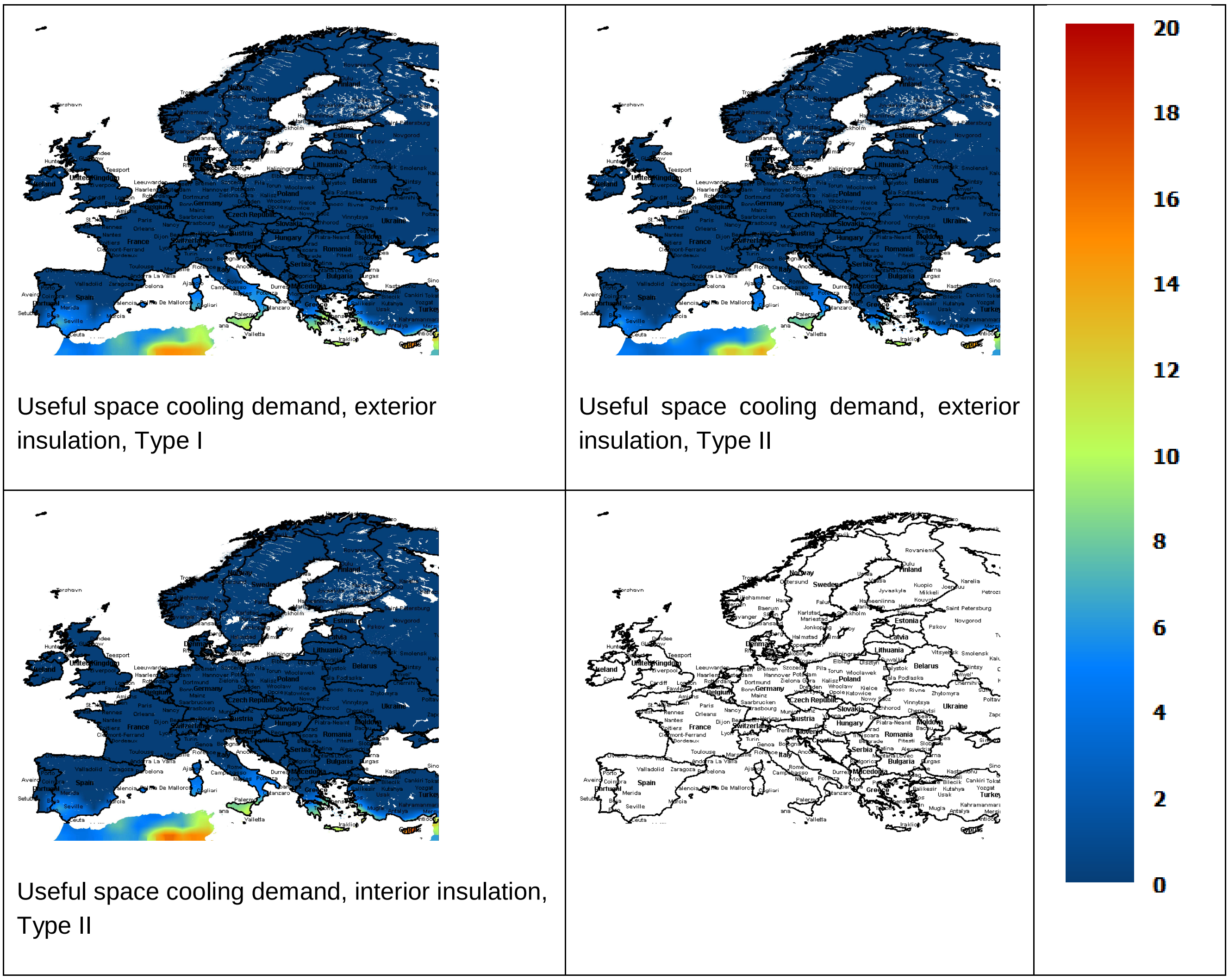
Figure 7: Useful space heating demand of the optimum buildings. On account of the large difference between the interior and exterior insulation, two different scales were used here, up to 40 kWh/(m² yr) for exterior insulation and up to 100 kWh/(m² yr) for interior insulation.
The heating demand can only be specified reasonably for three of the four examined variants, because the case where only an individual component is modernised would lead to many different heating demands depending on the components.

A higher heating demand must be calculated for existing buildings in contrast with new constructions, if only because of the thermal bridges. However, the differences are moderate: in a new construction for Type I, 15 kWh/(m² yr) are seldom exceeded. The heating demand of the cost optimal modernised Type II with exterior insulation is still below 10 in the Mediterranean region. In Germany this is ca. 15 and in Scandinavia this is ca. 30

kWh/(m² yr); it is barely above the result for the new construction in Southern Europe and in Scandinavia between 10 and 15 kWh/(m² yr) above this.

A significantly higher heating demand results with interior insulation on account of the smaller insulation thickness. Near the Mediterranean it is often around 20 kWh/(m² yr); it can even be 40 kWh/(m² yr) in Germany, and in Scandinavia 60 to 80 kWh/(m²a).

2.2.7 Useful space cooling demand



Useful space cooling demand, exterior insulation, Type I

Useful space cooling demand, exterior insulation, Type II

Useful space cooling demand, interior insulation, Type II

Figure 8: Useful space cooling demand of the optimum buildings

A noteworthy energy demand for space cooling in cost optimal houses only arises in the outermost regions of Southern Europe. Here also, this is usually below 10 kWh/(m² yr). The reason for this small value is the shading on the outside and the good level of insulation of the roof. There are no substantial differences apparent between the considered types of buildings and variants.

2.3 Conclusions regarding certification

Using building examples, it was possible to determine economically optimum combinations of thermal insulation and glazing in modernised existing buildings for all regions in Europe. With very few exceptions, usually less than 1 ‰, the cost-optimized components also fulfilled the comfort criterion (cf. section 5.1). Furthermore, the respective heating demand and useful cooling demand were also determined.

From this, requirements were derived for the certification of energy efficient modernisations, at both component and building level.

It is clear that it is necessary to differentiate between interior and exterior insulation in particular. Since interior insulation in existing buildings always decreases the size of the living area – even though its usability and value is increased considerably – only smaller insulation thicknesses are cost-effective.

Is a good level of thermal protection of individual components worthwhile even in buildings which otherwise remain in the old state, e.g. due to building preservation reasons? In relative terms, this is naturally not the case; the poor level of thermal protection of the rest of the building makes for a high heating demand base so that in some circumstances the overall demand can only be reduced by a few percentage points. Nevertheless, this measure may be profitable, even more so than in buildings with a better level of thermal protection; the heating period is longer in a poorly insulated house, therefore the effect of the better level of thermal protection is greater. The quantitative analysis above shows that in practice the influence of the rest of the building on the optimum thermal protection often isn't great; with the exception of buildings with good passive solar energy use in Southern Europe.

3 Component requirements for floor slabs and basement ceilings

3.1 Background

The component-based procedure of the existing EnerPHit criteria contains the following requirements for floor slabs or basement ceilings:

For exterior insulation: $f_t \cdot U \leq 0.15$ W/(m²K)

For interior insulation: $f_t \cdot U \leq 0.35$ W/(m²K)

Where the temperature factor f_t is the "ground reduction factor" from the PHPP "Ground" worksheet.

This approach proved reasonable for heating-dominated climates, but it is not useful in warm or hot climates. Under certain conditions, the reduction factor may have small, negative values. For hot climates, PHPP 8 gave a reduction factor of 1. Both would obviously be inappropriate.

In addition, the ideal insulation level of the floor slab does not only depend on the climate, but also on the building properties. A residential building in Spain, with ground temperatures below 25 °C throughout the year, may r equire primarily heating if good solar control is applied, so that insulation of the floor slab will reduce the heating demand and high insulation levels are advisable. But for a building with high solar gains in the same location cooling may become dominant, and insulation of the floor slab would reduce heat losses to the ground during summer and might even become counterproductive.

This dependency is due to a physical relationship, it should therefore be reflected in the requirements, which will consequently depend not only on the climate, but also on the building properties.

3.2 Requirement

The proposed solution is to use differential heating and cooling degree days as a basis for the required insulation level. Differential degree days serve for calculating the effect of small changes of building properties on the heating or cooling demand:

$$\Delta Q = \Delta H \cdot G_t^*,$$

where

ΔQ additional heating or cooling demand
ΔH (small) change in total conductance of the building envelope
G_t^* differential degree days

There is an optimum insulation thickness where an increase in insulation, i.e. a reduction in the conductance H, does not result in an adequate reduction of the total energy demand any more. From the point of view of economics, what is adequate depends on the cost, lifetime and conductivity of the insulation, the interest rate and the price of useful energy. The optimum U-value of the building component is then inversely proportional to the square root of the (differential) degree days.

A fast procedure for directly estimating the differential degree days from the heat losses and gains and the utilisation factor for free heat, as taken from the monthly energy balances, was derived for the heating and cooling cases.

The monthly heating demand is calculated from

$$Q = L - \eta G$$

with $\eta = \dfrac{1-\gamma^a}{1-\gamma^{a+1}}$ and $\gamma = \dfrac{G}{L}$,

where

Q heating demand
L heat losses
G heat gains
η utilization factor
a exponent depending on the time constant

We substitute L by HG_t, where H is the total conductance of the building envelope and G_t are the heating degree days to the ground. The differential degree days G_t^* are then found from differentiation with respect to H as follows:

$$G_t^* = \frac{dQ}{dH} = G_t \frac{1+(a+1)\gamma^{a+2} - (a+2)\gamma^{a+1}}{\left(1-\gamma^{a+1}\right)^2}$$

For $\gamma \to 1$:

$$G_t^* = G_t \frac{a+2}{2a+2}$$

For cooling, a similar approach is applied. Here,

$$Q_C = G - \eta L$$

with $\eta = \dfrac{1-\gamma^a}{1-\gamma^{a+1}}$ and $\gamma = \dfrac{L}{G}$.

Differentiation with respect to H gives the slightly different expression

$$G_t^* = \frac{dQ}{dH} = G_t \frac{(a+1)\gamma^a - a\gamma^{a+1} - 1}{\left(1-\gamma^{a+1}\right)^2}$$

For $\gamma \rightarrow 1$:

$$G_t^* = G_t \frac{-a}{2a+2}$$

Although the differentiation is exact, the result is approximate because it does not take into account the change in ground temperature under the slab, and thus in G_t, that occurs due to changes in the insulation of the floor slab. The differential degree days calculated according to this procedure are therefore (sometimes considerably) higher than their actual value. However, the great reduction in complexity of the calculation justifies this inaccuracy. By using a higher reference price for insulation, this effect can be counterbalanced.

Based on these differential degree days, the cost-optimum U-value can be determined. The general parameters like real interest rate, lifetime, and energy cost are identical to those used in section 2 above. For the cost of additional insulation, we distinguish between two cases:

- insulation of floor slabs, basement ceilings, exterior insulation of walls adjacent to the ground: The cost of insulation may vary considerably depending on the situation in the individual project. Although cheap insulation materials can often be used under basement ceilings, there are often additional difficulties due to pipes, lamps having to be moved, etc. Often a more expensive insulation material will be used to minimize losses in ceiling height in either the basement or the ground floor. For exterior insulation of walls adjacent to the ground the use of water- and pressure-resistant insulation materials will be required, incurring higher cost. For these reasons the effective cost of insulation in these situations is assumed to be 2 €/cm, higher than above. This also accounts for the effect of thermal bridges, which are usually unavoidable in refurbishment and which will reduce the respective heating degree days.

- interior insulation of walls adjacent to the ground: Similarly to section 2 we assume an effective cost of insulation of 7 €/m², including the loss in living space.

The U-values determined under these boundary conditions form the EnerPHit requirement for floor slabs, basement ceilings, and walls against ground.

4 Requirements for cooling demand, particularly of non-residential buildings

4.1 Background

In many European climates, and particularly in listed buildings, active space cooling is in most cases not required or has not been present in the past. After a deep renovation, however, the comfort requirements may be close to those for new buildings, and for non-residential buildings with higher internal loads in warmer climates the resulting cooling demand may reach a significant level. Apart from requirements for the building components, as they are documented in the criteria, an overall criterion for the sensible space cooling demand of non-residential buildings is desirable which would replace the component procedure, allowing designers to shift between different options as required. The existing EnerPHit criteria [PHI 2014] refer only to buildings in cool, temperature climates and contain no explicit requirements for space cooling at all.

Passive House criteria relating to space cooling of non-residential buildings exist already, but are applicable only for cool, temperate climates like Central Europe and moderate internal heat gains (IHG). Here, as a general rule, the specific useful cooling demand (Note: all figures in this section refer to useful energy, i.e. the amount of heat that needs to be extracted from within the thermal envelope, regardless of the mechanical system) is required not to exceed 15 kWh/(m²a). For many non-residential buildings and for warmer climates it was expected that this requirement cannot always be met. The criteria allow for an individual adjustment according to building use, but no general procedure is given ([PHI 2014a]).

For residential buildings, the criteria for space conditioning in summer are already elaborated in more detail depending on the climate ([PHI 2014b]):

Cooling (including dehumidification)

Total cooling demand ≤ 15 kWh/(m²a) + 0.3 W/(m²aK) · DDH

or alternatively: cooling load ≤ 10 W/m²
AND cooling demand ≤ 4 kWh/(m²aK) · ϑ_e + 2 · 0.3 W/(m²aK) · DDH – 75 kWh/(m²a)
but not greater than: 45 kWh(m²a) + 0.3 W/(m²aK) · DDH

where

ϑ_e: Annual mean outdoor temperature in ℃

DDH: Drying degree hours (time integral of the difference between the dew-point temperature and the reference temperature of 13 ℃ throughout all p eriods during which this difference is positive)

The criteria are summarizing sensible and latent cooling demands. Looking at the sensible part of the cooling demand only, three different cases need to be distinguished:

- A sensible cooling demand below 15 kWh/(m²a) is always considered compliant.
- The sensible cooling demand may never exceed 45 kWh/(m²a)
- For certain climates, depending on temperature and humidity, higher values than 15 kWh/(m²a) are admissible. The influence of humidity can be explained by the missing possibility of night ventilation in humid climates.

These criteria are based on worldwide lifecycle cost analyses for new-built dwellings. These investigations have shown that the annual cooling demand of both cost-optimized buildings and functional Passive Houses (i.e., in this respect, buildings with a peak cooling load below 10 W/m² living area) varies considerably with the climate, between zero for Central Europe or colder climates and up to about 50 kWh/(m²a) for tropical climates. Details about the derivation of the criteria can be found in [Feist 2011].

[PHI 2014b] states that the abovementioned criteria are ‘provisional and may possibly have to be adapted with advances in knowledge’. Apart from their complexity it is dissatisfying that there is no obvious possibility to extend them to different internal heat gains or different temperature setpoints.

This latter subject, the extension to non-residential buildings with higher internal loads, is also important for historical non-residential buildings; it was therefore investigated in greater detail within 3encult. Given that the requirements should ideally fit into the general framework of certification, no distinction between listed buildings and new-built will be made in the following. Many restrictions due to conservation requirements will not affect cooling demand, and if there are severe restrictions that do not allow for the same cooling efficiency as in new-built houses, it will be necessary to consider the building on a component level anyway. As climatic data that cover the whole world were readily available, the investigations were not artificially restricted to Europe.

4.2 Generalized energy balance

Buildings with higher internal heat gains will usually have higher cooling demands because in many cases there will be no other means but active cooling to remove the excess heat from the building envelope, at least during the cooling period. Our experiments indicated that the best way to quantify this increase is to calculate an admissible cooling demand that depends on the magnitude of the IHG. This is done by setting up a monthly energy balance.

For each month we calculate the cooling demand of the Passive House base building (which is, with respect to sensible cooling, highly energy-efficient). This calculation is independent of the properties of the specific building in question, and demonstrates the state of the art approach to Passive Houses. It contains the following heat flows:

- the internal heat gains. For cooling in residential buildings, the PHPP calculates the actual internal heat gains, including losses from the DHW system. If these IHG are greater than the standard value of 2.1 W/m², as efficient appliances and DHW systems should be used in a Passive House, IHG of 2.1 W/m² are always assumed for residential buildings.

- solar loads at a predefined level of 2 W per square meter of treated floor area (TFA). For severe cooling climates (and the criterion will only be valid for these due to the fact that cooling demands below 15 kWh/(m²a) will always be accepted, see below) solar control is a key component of any energy-efficient design. From examples it was found that either solar protective glazing with very low g-values, small windows with fixed shading or windows with a movable shading can be expected to reduce the solar load to the above-mentioned value.

- transmission and ventilation losses calculated from a thermal conductance of 1 $W/K/m^2_{TDA}$ if the monthly average ambient air temperature is below the interior temperature setpoint of e.g. 25 °C, and 0.5 $W/K/m^2_{TDA}$ otherwise. These data are approximately those of a Passive House dwelling in a cool, temperate climate, with or without ventilation heat recovery, respectively. This, or a better, insulation level also turned out to be appropriate for severe cooling climates.

- heat losses due to additional summer ventilation. These losses are calculated from a thermal conductance of 0.4 $W/K/m^2_{TDA}$ and the temperature difference ($T_{setpoint}$ + 7 K - T_a), when positive. Daily temperature variations in climates where night ventilation is possible typically amount to between 6 and 14 K, so that at ambient temperatures of more than 7 K above the setpoint no contribution of night ventilation can be expected. This term only becomes effective if the ambient humidity allows for night ventilation; this is assumed for dew point temperatures below the humidity setpoint (standard value: 17 °C).

It turned out to be appropriate to sum up the positive and negative heat flows without accounting for a utilisation factor. Multiplication with the length of the month results in an admissible sensible cooling demand per month. The sum of all positive cooling demands results in a limit for the annual cooling demand.

As a first application, the cooling demand of cost-optimized buildings for standard residential IHG of 2.1 W/m² from section 2 was compared to the respective Passive House criterion, the same was done for buildings with IHG of 5 W/m² (typical offices or full-time schools will have smaller IHG).

Figure 9 and Figure 10 show the results for the geometries of the Type I and Type II buildings described above. It must be noted that the use of night ventilation was explicitly considered in the calculation of the requirement in the diagram, contrary to the algorithm described above, because the version of the PHPP which was used for the cost optimization could not use different night ventilation strategies for different months.

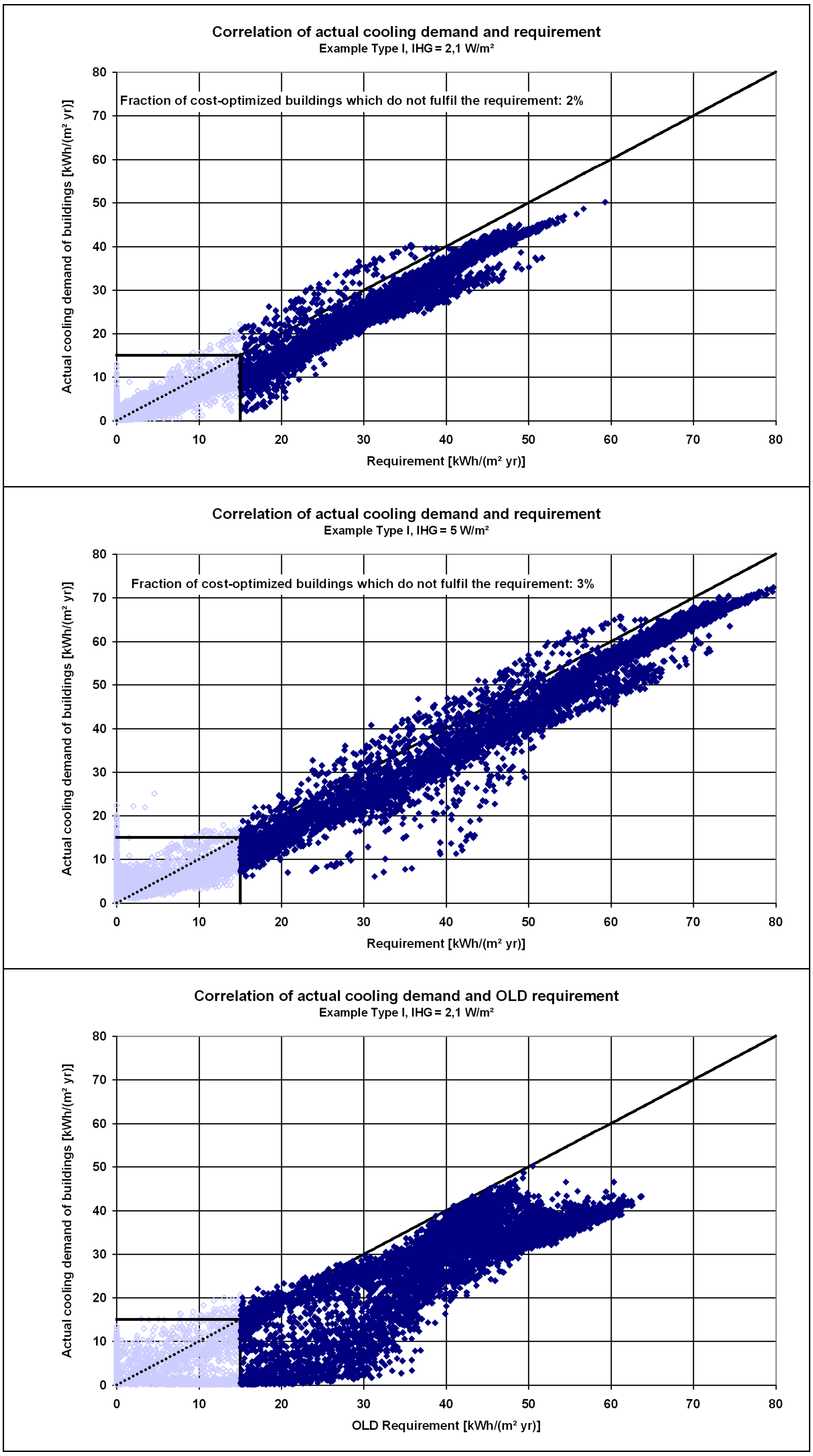


Figure 9: **Type I, comparison of suggested Passive House criterion for sensible cooling demand and actual cooling demand of cost-optimized buildings. The last diagram shows the same comparison for the old criterion.**

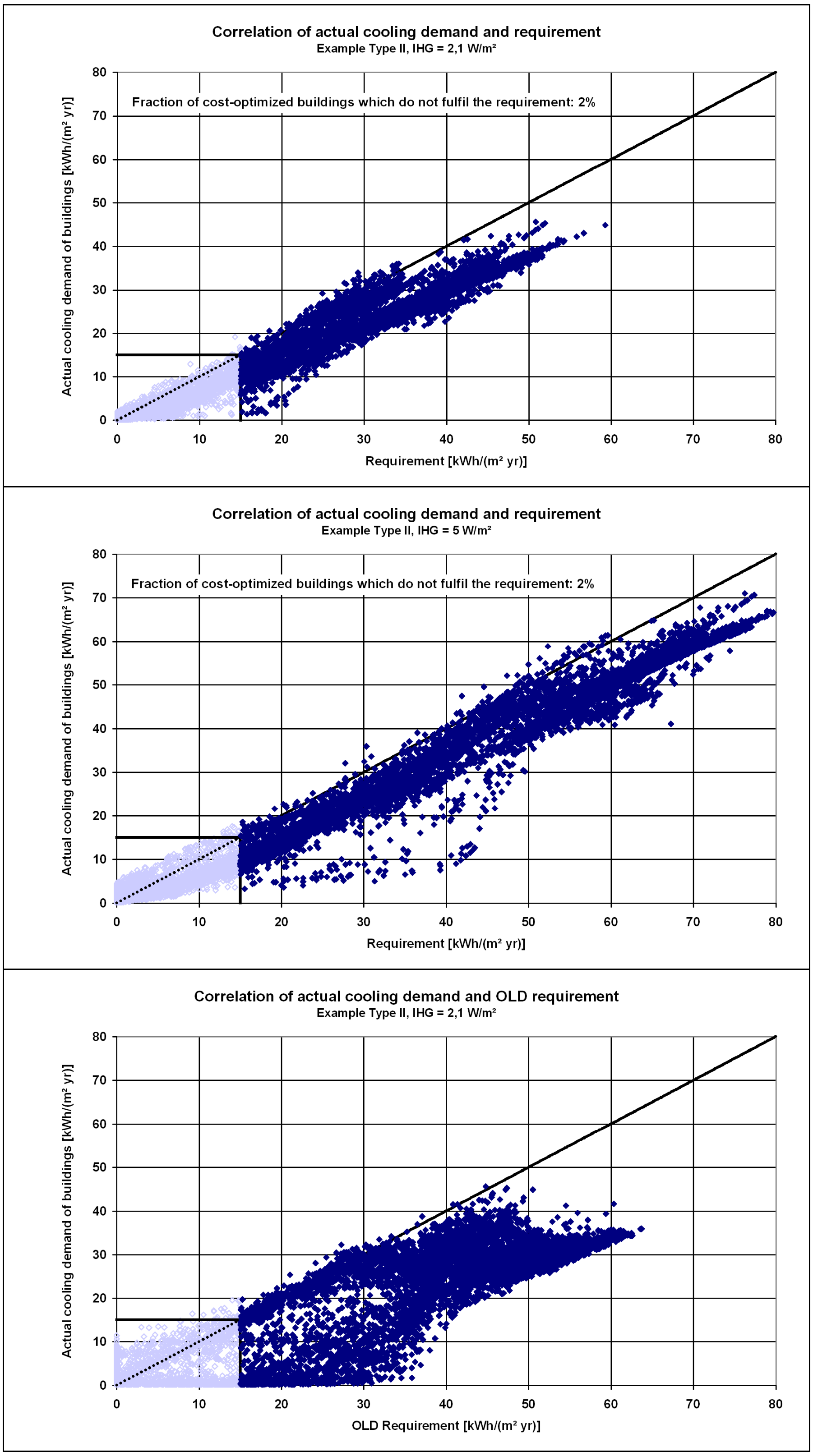


Figure 10: Type II, comparison of suggested Passive House criterion for sensible cooling demand and actual cooling demand of cost-optimized buildings. The last diagram shows the same comparison for the old criterion.

For all cases it turns out that there is a good correlation between the requirement and the properties of the cost-optimized buildings. For increasing IHG, both the requirement and the actual cooling demand increase by a similar value. Only a few percent of the cost-optimized buildings have cooling demands which are higher than the requirement, and only for isolated cases does the difference become greater than 5 kWh/(m²a). It can be concluded that using such a requirement is not too strict.

Nevertheless it can be seen from the last diagrams in Figure 9 and Figure 10 that the old requirement was often much too weak. The new requirement will therefore be more demanding and more precisely adapted to the location at the same time.

The figures also show that the general limit of 15 kWh/(m²a) – whatever is below is acceptable regardless of the climate – should be maintained. There are some cases where the requirement will not allow for cooling demand at all, but the buildings in these climates have a small cooling demand nevertheless. These cases are covered by such a lower limit. The upper limit of 45 kWh/(m²a) is not required anymore because the requirement exceeds this value very rarely anyhow.

4.3 Conclusion

A new Passive House criterion concerning the sensible cooling demand is suggested which is simpler, more precise and more physically motivated than the existing criterion. It allows to derive cooling criteria for listed non-residential buildings with higher internal loads, and it might even replace the existing criterion for cooling altogether.

For residential use in Europe there is no significant change because the permissible cooling demand of residential buildings does not exceed 15 kWh/(m²a) anyway. For non-residential buildings in Southern Europe, an increase of the acceptable cooling demand results. Typical non-residential applications with moderate IHG like schools or offices in Europe are usually not affected either (cf. the upper diagram in Figure 11), the increase becomes relevant only for high internal gains or non-European climates.

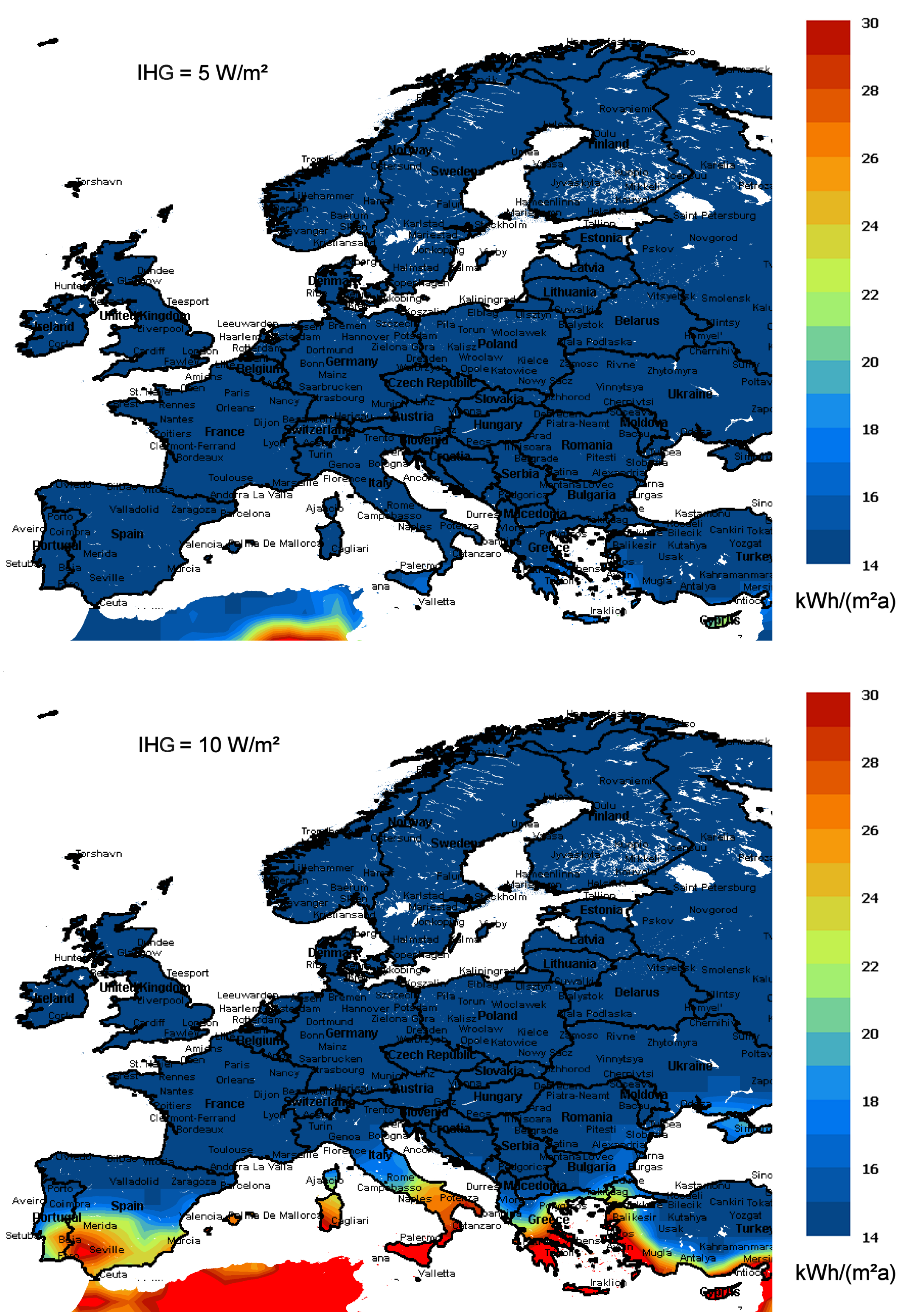


Figure 11: Map of Europe with the sensible cooling requirements at IHG of 5 W/m² (above) and 10 W/m² (below)

5 Climate zones and corresponding sets of component requirements

With respect to the results for the cost-optimized building and its components shown above and under consideration of the thermal comfort of the occupants, the aim was to create a map that is divided into several regions with identical requirements each for all energy-relevant building components like windows, doors, insulation and building services.

5.1 First priority: Meeting the comfort criterion

Any suggestions for requirements for energy efficient building components also have to take the thermal comfort of the users into account at first priority. Optimum thermal comfort can be provided, if the temperature differences between the inner surfaces of the thermal envelope and the operative temperature in the room is not higher than 4.2 K (see e.g.[Feist 1998]. If this temperature criterion is met, unpleasant radiant heat losses as well as cold down droughts and cold air lakes do not occur. Since the temperature of interior surfaces depends on both the thermal quality of the building envelope and the outside temperature, the thermal quality of the envelope has to be the higher, the colder the ambient climate gets. The required U-value which represents the thermal quality of the envelop can be determined by the following equation.

$$U \leq \frac{4.2}{R_{si} \cdot (\theta_{op} - \theta_{ext})}$$

Where is:

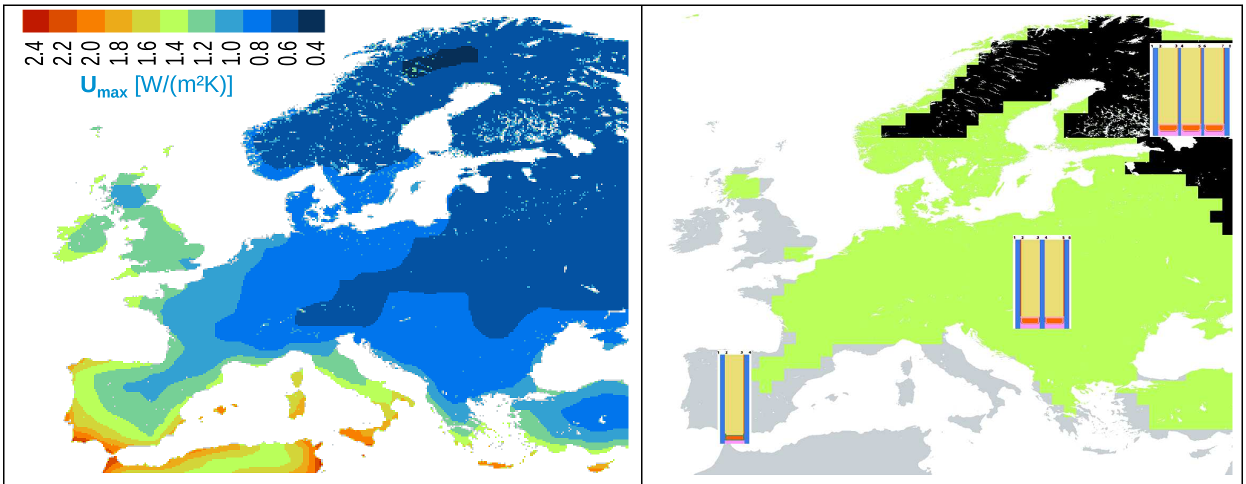
R_{si}: The internal heat transfer resistance (in case of vertical windows 0,13 m²K/W)

θ_{op}: Operative (perceived) room temperature [℃]

θ_{ext}: Design-outside temperature (minimum temperature of the coldest day in a year) [℃]

This climate dependent U-value has to be achieved by any component of the building envelope. In most cases, Windows, as weakest part of the building are the crucial point in this regard, but in special cases, interior insulation, as an example might be critical too.

Figure 12 shows a map of Europe with the required U-values for meeting the comfort criterion (on the left). As mentioned, windows are the critical component in most cases for meeting the comfort criterion. Therefore Figure 12 shows at its right side the type of glazing needed to meet the criterion. For this it was assumed, that an $U_{W,\ installed}$-value (thermal transmittance of an installed window) of 1.20 W/(m²K) might be achieved by a window with double-low-e coated glazing. For triple glazing, this U-value is 0.65 W/(m²K), for quadruple glazing 0,45 W/(m²K.



U-values to be achieved in Europe

Glazing type required for meeting the comfort criterion

Figure 12: Catching the comfort criterion in Europe

It can be seen, that triple glazing is dominating most areas of Europe, if it comes to the comfort criterion. The thermal quality of double glazing is only adequate for mild Mediterranean climates and for parts of the British isles. In the areas of Scandinavia and the north-east of Europe, where triple glazing is not sufficient, quadruple glazing has to be used.

5.2 Second priority: Economic considerations

Figure 2 to Figure 5 and Figure 12 show that the thermal quality of the components at the cost-optimum is much higher than the minimum required to meet the comfort criterion for most European locations. In those regions it is reasonable to set the component requirements according to the cost optimum.

5.3 Defining regions with identical requirements

The creation of a map showing the different requirements for Passive House components was necessary for the international EnerPHit certification criteria. However such a map can also be a great help and give a first orientation to those involved in the design process of new Passive Houses.

The definition of such a map of climatic regions with specific sets of requirements is an important work done at PHI for the 3encult project. Besides the parameters comfort and economy, borders of states and nations were taken into account for better orientation and easier handling. Eventually grouping the world’s climates in seven regions, and thus seven sets of requirements was most suitable:

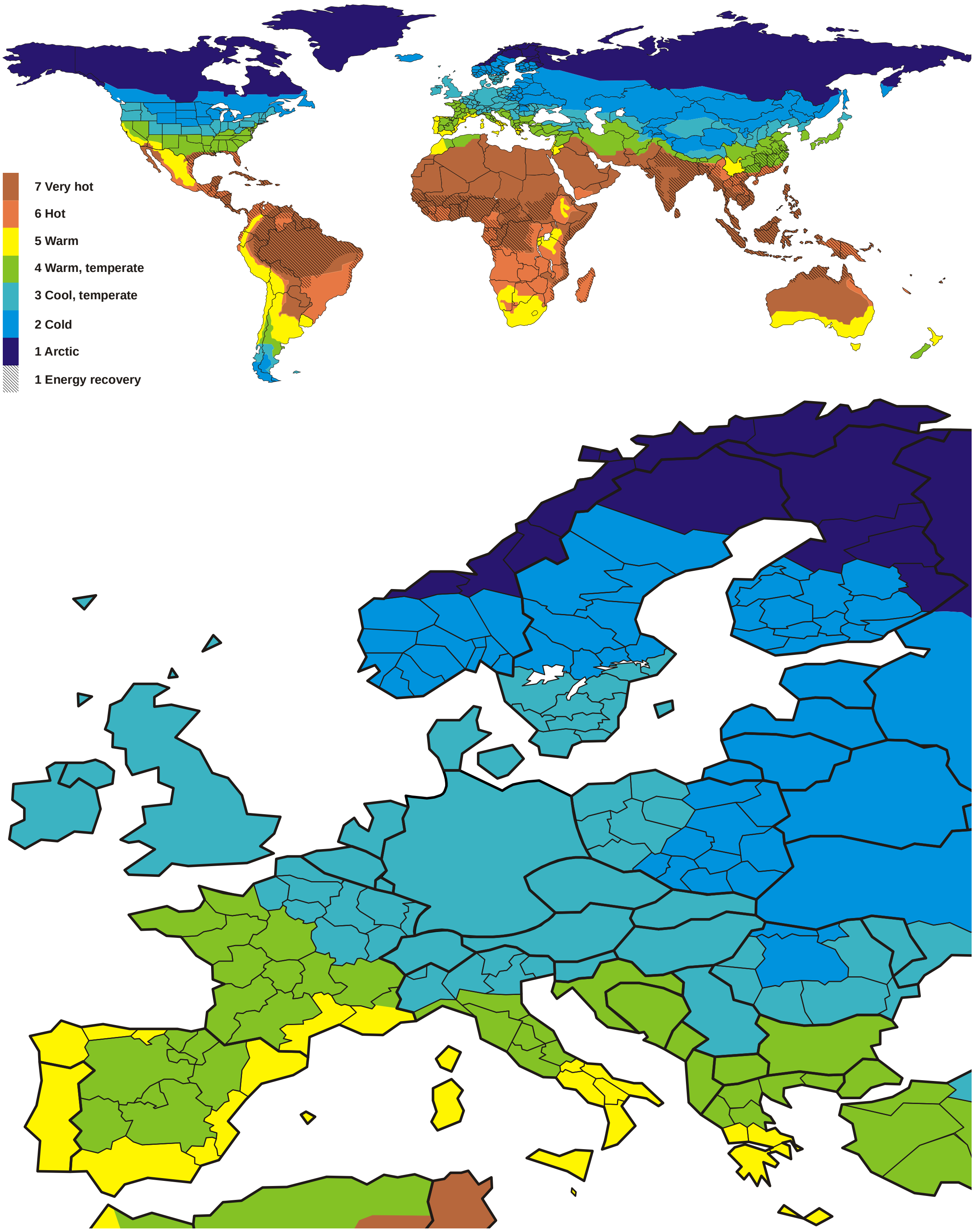


Figure 13: Maps of the world and Europe showing regions with identical requirements

As an example for a region that includes parts of Germany and Italy as well as Austria, the Czech Republic, Slovakia and the Balkan states, the process of designing the map is shown at a simplified level in Figure 14. This procedure was carried out in detail for all of Europe on a detailed, and for the rest of the world on a rough level.

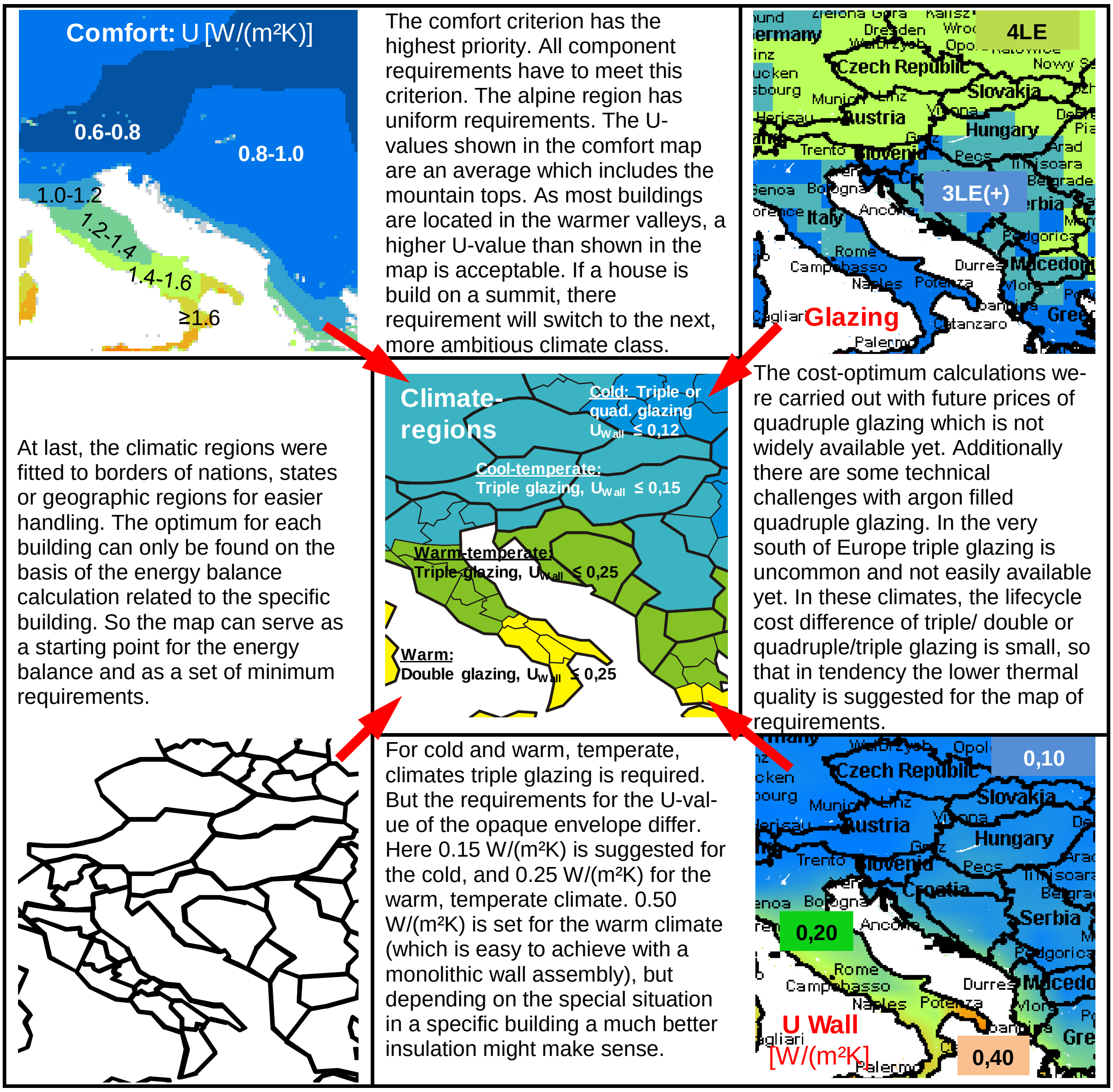


Figure 14: **Defining a map of regions with identical requirements (simplified representation of the process)**

6 Guidelines for evaluation of interior insulation systems during EnerPHit building certification

6.1 Assignment

6.1.1 Refurbishment of existing buildings using Passive House components

The use of Passive House components in the refurbishment of existing buildings results in extensive improvements with reference to thermal comfort, cost-effectiveness, structural integrity and climate protection. A 90 % reduction in the heating demand has now been achieved in a number of projects. Nevertheless, achieving the Passive House Standard in modernisations of existing buildings is not always a realistic goal - among other things due to the fact that after the refurbishment, unavoidable thermal bridges remain for example in the form of basement walls.

The Passive House Institute has developed the certification "EnerPHit - certified modernisation using Passive House components". This specifies either a maximum heating demand of 25 kWh/(m²a) or alternatively the consistent use of Passive House components in accordance with the requirements for building component certification set out by the PHI. The heating demand calculated using the PHPP and the quality of thermal protection of the individual building components are stated on the certificate.

Building refurbishments with interior insulation can be certified with the EnerPHit^{+i} Seal.

Figure 1: EnerPHit^{+i} seal

Energy-efficient refurbishment of historical buildings under preservation orders poses a particular challenge as this requires bringing into accordance the comfort demand of users and maximum possible reduction of energy consumption with the preservation of the original historical building substance. Numerous examples of energy-efficient refurbishments of existing buildings using interior insulation have demonstrated, and continue to demonstrate, that these objectives are not mutually exclusive. Sceptism towards interior insulation discourages or prevents a high quality of urgently needed and desirable energy-efficient refurbishment of existing buildings. This stems from the damage caused in most cases which were all due to incorrect execution.

The energy-relevant refurbishment of existing building stock requires approaches using insulation on the inside, especially in the case of listed historical buildings. The influence of these constructions should be evaluated in terms of building physics within the framework of EnerPHit building certification. The hygrothermal behaviour of the interior insulation systems cannot be considered in isolation as is done for exterior insulation systems; rather, it is closely related to the material characteristics of the existing wall, the local climatic conditions and utilisation. The increased moisture content of the existing wall due to interior insulation involves the risk of damage, which needs to be assessed. The following criteria are intended to provide valuable tips and guidance for assessment.

6.2 Criteria for assessment of interior insulation

Within the framework of building certification, comprehensive planning and documentation should be carried out for the interior insulation measure. This should include information about the existing situation, the system properties of the interior insulation and a concept for airtightness.

6.2.1 Existing structure

6.2.1.1 Structural condition of the construction

The measures required in the context of a refurbishment using interior insulation strongly depend on the quality of the wall structure, therefore the first thing to do is take stock of the situation. Typical impairments or damage such as rising damp and cracks in the masonry must be documented and if necessary, examined by means of technical measurements and remedied within the framework of the refurbishment.

Frequently, basement ceilings and foundation walls are not protected against ground moisture and splashing water. Rising damp can be prevented by installing a horizontal barrier. Measures such as the subsequent installation of bituminous sheeting or injections are necessary for this.

If joints in exposed masonry walls are weathered, these should be repaired or renewed.

The condition of the existing interior plaster will have a influence on the functional reliability of the interior insulation. High moisture levels occur at the transition of the old interior plaster and insulation, which are relevant in respect of the risk of frost damage as well as mould growth. Renewal or removal of the old interior plaster can be dispensed with if it is continuously and firmly joined with the brickwork, and if it is clean and has a homogeneous surface. If there are any wallpaper residues, these will provide an ideal nutrient source for mould spores. Furthermore, glue or adhesive residues as well as paint may significantly reduce vapour transport and thus lead to moisture near the plaster.

6.2.1.2 Characteristic values of materials

Knowledge of the thermal and moisture-relevant characteristics of the existing construction is a major prerequisite for non-destructive implementation of interior insulation measures. Comprehensive information is often unavailable for this class of existing buildings in particular, so that materials are usually determined by means of a visual inspection and estimation of the respective characteristic values. Reference tables, such as the [DIN EN ISO 10456] "Building materials and products - Hygrothermal properties - Tabulated design values", the DIN 4108-4 "Thermal insulation and energy economy in buildings - Part 4: Hygrothermal design values", or the material properties database for energy efficient refurbishment of existing buildings [MASEA] are used as an aid for this purpose.

Reliable statements relating to the hygric behaviour of exterior walls can only be made if the existing elements, i.e. the exterior plaster, wall assembly and interior plaster exhibit specific and clearly assignable characteristic values of the materials. Masonry walls do not provide any useful indications of their hygric behaviour, so that based on current knowledge, a laboratory analysis of the brick constitutes an advisable approach. Statements regarding the suitability of an insulation system for exposed masonry walls can therefore only be made in conjunction with measured results.

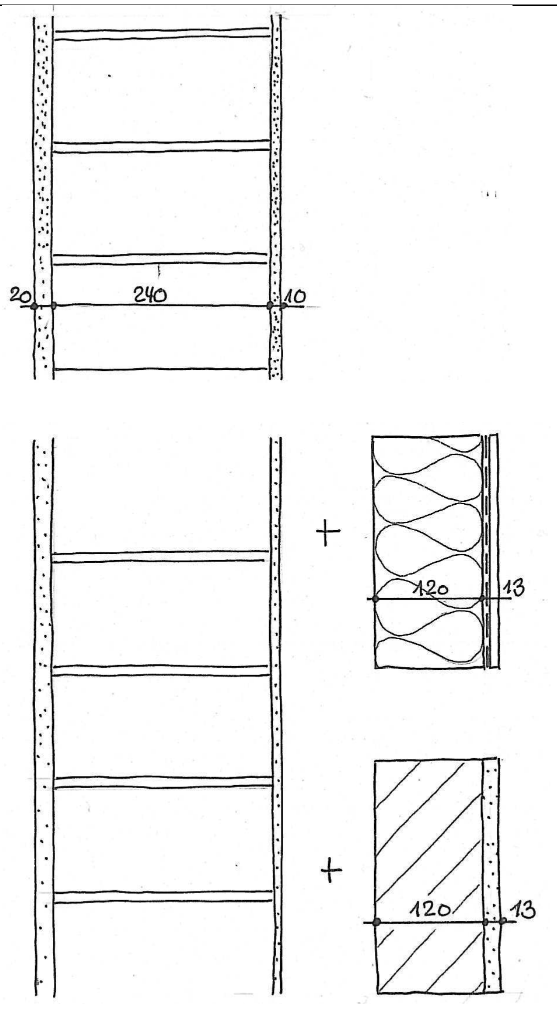
6.2.2 Interior insulation system

Several different interior insulation systems with various components and assemblies are available on the market. Basically, there are three types of systems:

- Diffusion-open, capillary active insulation systems
  This system consists of capillary active insulation material and new interior plaster which is simultaneously the airtight layer. The system is open to vapour diffusion towards the indoor space and can store liquid water, and distribute this by means of capillary suction or transport it back towards the indoor space. Examples of these systems are IQ-Therm from Remmers, calcium silicate or cellulose from various manufacturers.

- Diffusion retardant systems
  This classic interior insulation consists of a non-moisture-absorbent insulation material (e.g. mineral wool) and a vapour retarder on the room side which is usually implemented in the form of a membrane; this layer ensures airtightness.

- Diffusion-tight systems
  Foam glass is a well-known material which prevents vapour diffusion. Water and vapour transport is prevented on account of the closed-cell structure of this material. Even vacuum insulation is an example for a diffusion-tight system.



Existing building

Exterior plaster

Brickwork

Interior plaster

Diffusion retardant interior insulation system

Insulation

Membrane

Planking on the room side

Diffusion-open or diffusion-tight interior insulation system

Insulation

New interior plaster

Figure 15: Typical construction of an existing construction and two different types of interior insulation (dimension in mm)

6.2.3 Climate boundary conditions

Absence of structural damage due to interior insulation systems should be verified by means of appropriate proof. The climatic conditions have a major influence in this respect, therefore these must be as close to reality as possible. This includes the impact on the facade due to driving rain and the effects of moisture on the inside. For climates similar to that of Central Europe, reference can be made to driving rain categories in [DIN EN 4108-3], including the recommendations for the structural condition of the respective exterior plaster.

If installation of a ventilation system is planned in the context of refurbishment, then moisture entry in winter will be reduced. An indoor air humidity of 40% is therefore realistic for cool, temperate climates. Appropriate indoor air humidity values can also be taken from [WTA 2006].

The prevailing outdoor climate (temperature, humidity, rain and wind) should be taken from the appropriate meteorological data.

6.2.4 Planning requirements for interior insulation

Gap-free and meticulous execution of the airtight layer is especially important in refurbishment measures involving interior insulation. Non-airtight connections, faulty execution and systemic weaknesses will lead to moisture accumulation in or behind the insulation layer and considerably increase the risk of structural damage. While the skilled trades are responsible for careful execution of the work, practical solutions which can be implemented for situations specific to existing buildings must be provided by the planners and system suppliers. In the concept for refurbishment, typical penetrations and connections must be taken into account and systemic weaknesses (e.g. the possibility of air currents behind the insulation layer) must be avoided.

In the context of planning for interior insulation systems, constructive solutions should be developed for thermal bridge optimised and airtight connection of the insulation system with intersecting walls and ceilings and at reveals. In doing so, the following general rules for planning must be kept in mind:

- Use of flanking insulation or guide plates for intersecting interior walls increases the surface temperature and reduces the risk of structural damage.
- Insulation of the reveals near the windows is absolutely essential for ensuring a sufficiently high interior surface temperature.

Interior plaster in old buildings is usually uneven. If interior insulation in the form of panels (EPS, foam glass or calcium silicate) is used, hollow spaces may easily result behind the insulation layer. Mould growth will occur if these hollow spaces are connected even minimally with indoor air, e.g. through tiny leaks. This risk can be eliminated either by levelling out any unevenness in advance, or by applying adhesive all over the surface of the insulation panels.

On account of the extra layers on the inside (interior insulation and interior plaster or gypsum plasterboard etc.), the airtight layer must be re-created and joined with the existing building components (interior walls, ceilings and windows). Particular attention must be given to connections with existing wood beam ceilings. In order to ensure that the beam heads which are supported by the cold masonry do not come into contact with the indoor air, opening up the ceilings and continuing the insulation through together with the airtight layer would be a better method. For this, a concept should be developed which ensures permanent sealing of the airtight layer with the wood beam ceiling. This concept should include the following measures:

- Exposing the beam near the exterior wall
- Filling any hollow spaces between the beams and wall area
- Cleaning the beams and filling any cracks
- Preliminary treatment of the beam using a suitable primer
- Creating an airtight seal with the sheeting

Incorrect execution of the airtight layer may not only damage the beam head itself, but structural damage will also be inevitable if indoor air gets behind the insulation through e.g. cracks or intermediate spaces in the ceiling. Solutions must therefore be developed in the context of planning which will enable largely accurate and permanent sealing of the airtight layer with wood beams and adjacent building components such as windows, doors and interior walls.

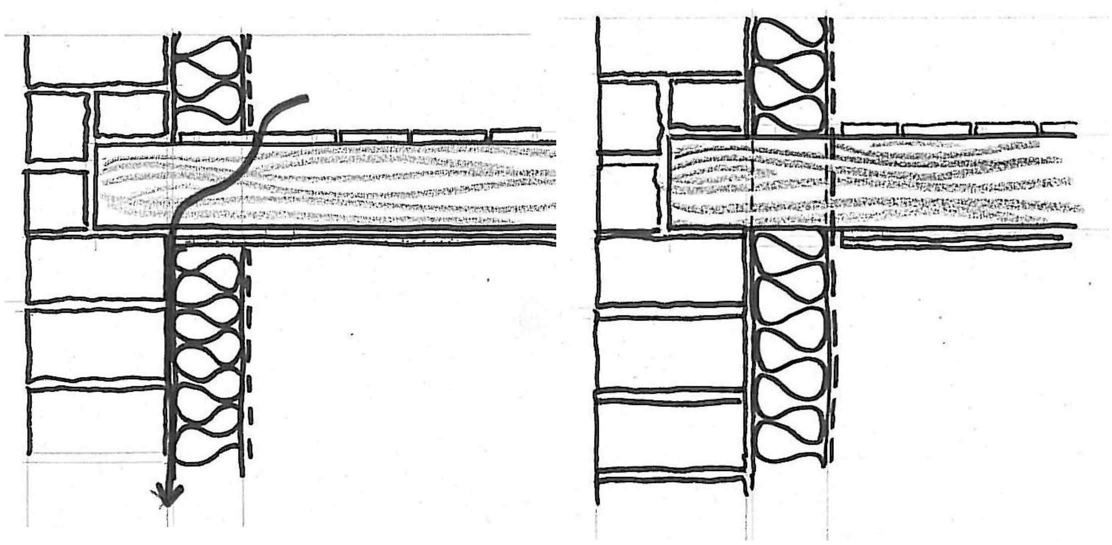


Figure 16: **Installation of interior insulation without opening up of the wood beam ceiling allows indoor air to circulate behind the insulation layer (left). If the insulation and the airtight layer penetrate the ceiling, this leakage will largely be avoided (right).**

The following solutions must be presented:

- Clear, unambiguous identification of the airtight layer e.g. new interior plaster or vapour retarder
- Description of the airtight connection at intersections e.g. adhesive tape
- Sealing of the airtight layer with windows, doors, ceilings (particularly wood beam ceilings) and intersecting walls

6.3 Examination concerning damage due to interior insulation systems

Verification must be provided regarding the absence of damage due to interior insulation based on the heat and moisture-related characteristics of the existing masonry as well as the interior insulation system and the climate boundary conditions prevailing in the location.

Dynamic simulations of the coupled heat and moisture transport are strongly recommended if:

Capillary active insulation materials are used, or if protection from driving rain has not been defined (e.g. in case of brickwork, for determining the hydrophobisation characteristics…)

This dynamic simulation will provide comprehensive information about the hygrothermal processes occurring within a building component and is therefore very suitable for analysing the functional reliability and durability of constructions. A range of criteria which allow assessment of the risk of structural damage have been compiled below. The prerequisite for positive evaluation of a construction are given if:

- durability is not decreased by the insulation measure
- no adverse health effects due to the measure are expected or if interior insulation improves a construction that was previously critical.

The fundamental problem is the evaluation of any decreased durability caused by the interior insulation measure. This applies e.g. in relation to weathering of the existing masonry, the temperature level of which may possibly be reduced and its moisture content increased due to the insulation. Thus it is a matter of evaluating the influence of interior insulation on the construction. This will take place firstly through a comparison of the results with the non-refurbished construction (evaluation of moisture in bricks) and with current methods for assessing the health risks from mould growth.

6.3.1 Durability

6.3.1.1 General notes

Reduced durability can be caused by a whole range of mechanisms which must be assessed differently depending on the material. A significant evaluation parameter is the moisture content. With a relative humidity level ranging between 0 and ca. 95%, hygroscopic building materials store water in the pore walls due to sorption (hygroscopic region or sorption humidity region). Moisture transport takes place through vapour and surface diffusion. With very high relative humidities (above 95%), water is transported by means of capillary suction (overhygroscopic region or capillary water region). Non-hygroscopic building materials cannot store moisture inside their structure.

6.3.1.2 Progression of the moisture content inside the whole building component and in individual layers

The moisture content of a building component is subject to seasonal fluctuations, the intensity of which varies greatly depending on the boundary conditions for the climate. The total moisture mass observed over a period of several years is an important indicator of the moisture characteristics of the building component. A relative humidity of 80 % throughout the cross-section of the building component is a good starting value for the dynamic simulation.

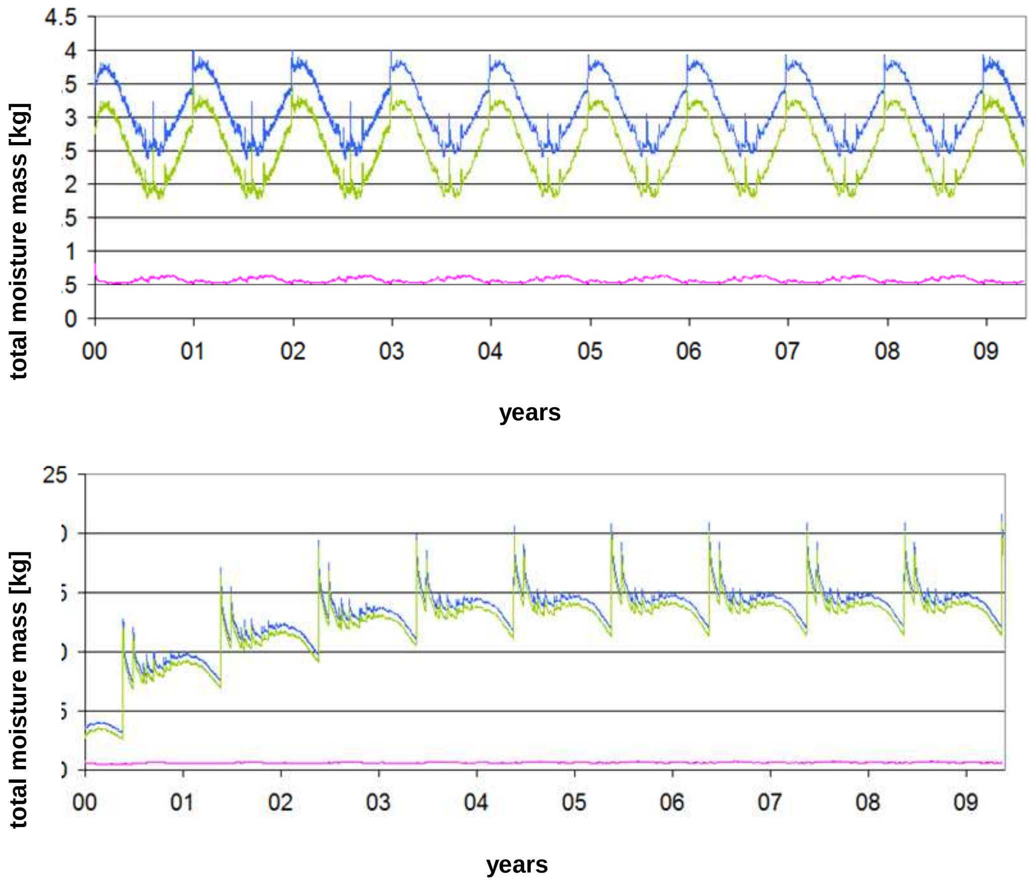


Figure 17: Progression of moisture in two exemplary walls with interior insulation. The wall material (green), interior insulation (pink) and the total moisture mass of all layers (blue) are shown here. The initial value for the simulation was 80 % relative humidity throughout the wall cross-section.

In some locations the moisture gain, for example due to driving rain, is so high that further moisture accumulation occurs. The possibility of drying up in course of one year is important. This also happens with wet application of materials (e.g. plaster). The moisture content in the steady state is significant for assessing the risk of structural damage.

6.3.1.3 Liquid water quantities

For simplified steady-state methods (e.g. according to [Glaser 1958]), the [DIN 4108-3] standard provides evaluation criteria for area-related condensate quantities of roof and wall constructions. Limit values for hygroscopic and non-hygroscopic building materials are given for this. Since this concerns a simplified steady-state method which considers vapour transport due solely to diffusion, a more differentiated analysis of the permissible liquid water quantities seems reasonable. The dynamic simulations carried out in this study additionally take into account liquid water transport and moisture storage mechanisms, enabling more precise depiction of the hygrothermal behaviour of the building component and the actual liquid water quantities. This requires more exact evaluation of the results depending on the respective material.

Basically, porose hygroscopic materials such as plaster or brickwork which come into contact with water absorb this water until free saturation is reached. This liquid water content is not a problem as long as these layers are not located in the area at risk of frost. Due to the application of the interior insulation, the temperature level of the existing wall is reduced so that there is now a risk of frost e.g. for the old interior plaster layer. Here, liquid water inside the pores should only occur to a limited extent in order to ensure unhindered and destruction-free expansion during freezing. This is possible if the moisture level remains within the hygroscopic range (<95% relative humidity in the pore spaces).

In the case of non-hygroscopic materials such as mineral wool, liquid water/condensate which occurs by saturation of air (e.g. in the temperature gradient due to vapour diffusion) can only be retained to a limited extent. For non-absorbent materials the [E DIN EN ISO 13788] standard recommends condensate quantities below 200 $g/m^2_{surface}$ (therefore a threshold of 150 g/m^2 is recommended).

6.3.1.4 Freeze/thaw cycles

If the water inside the pore freezes, its volume increases by ca. 10% , which may lead to irreversible damage to the substance matrix in the case of a high water content near the saturation point and frequent repetition of freeze/thaw cycles. In this connection, the critical degree of filling of the pore largely depends on the structure of the material (porosity and distribution of pores). The values for various wall materials as found in literature have been compiled below.

Table 5: Wall materials and permissible moisture levels based on literature sources (uf= free saturation)

Wall material	Permissible moisture	Source
Concrete	70% u/uf	[Feldrappe 2006]
Sandstone	80% u/uf	[Kotan 2011]
Brick	45% / 85% u/uf	[Sedlbauer 1999]
Lime-sandstone	12 m%	[Holm 2000]
Interior non-resistant to frost	95% RH in pores	[Borsch-Laaks 2010]

The risk functions for various brick types are given in [Sedlbauer 1999]. The critical water saturation with reference to the number of freeze/thaw cycles is given here. With frequent freeze/thaw cycles (≥ 100), no frost damage occurs below 45% u/uf. Bricks which are most resistant to frost remain damage-free up to 85% u/uf.

The moisture content of the masonry before the refurbishment measure is regarded as a criterion for assessing the risk of damage due to freeze/thaw cycles. If the existing masonry is undamaged, a non-critical moisture content can be fixed based on the actual state. At best this can only be an indication, because it is likely that the moisture level in the masonry will increase after the refurbishment and that the temperature level will decrease in winter. These altered boundary conditions must be taken into account in the evaluation.

The lowering of the temperature level inside the wall in winter due to the interior insulation results in shifting of the frost limit further towards the inside. In addition, depending on the thickness and quality of the insulation, this will result in the old interior plaster being situated in the area at risk of frost. As a rule, interior plaster is not frost-resistant, so that the risk of damage inside the pore structure is quite likely in case of free water. Capillary water is present with relative humidities > 95% in building components (overhygroscopic range). The best way to avoid frost damage is to allow moisture levels only within the hygroscopic range (< 95% RH inside the pore spaces) in the old interior plaster.

95 % RH is assumed if there is no exact data available concerning the permissible material moistures in the frost/thaw cycle.

6.3.1.5 Wood-destroying fungi

In contrast, in wood and wood-based materials, free water is present in the substance matrix when the fibre saturation point is reached. This is the prerequisite for germination of wood-destroying fungi spores [Morris 2002], [Viitanen 2009], [Borsch-Laaks 2005]. For the types of wood relevant in central Europe, the fibre saturation point is between 28 and 30 m% [Ruisinger 2009].

The limit values for the permissible moisture content of wood or wood-based materials of 20 and 15 mass percent mentioned in [DIN 68800-2] allow a sufficiently large safety margin for the fibre saturation point range. Damage to the substance due to wood-destroying fungi is not likely if the ascertained wood moisture levels are lower.

Analogous to [DIN 68800-2], in addition to restricting the wood moisture, its annual fluctuation range is also limited to 3 mass percentage points.

6.3.1.6 Corrosion rate

The life duration of building components consisting of reinforced concrete is affected by high material moisture levels. The rate of corrosion of the steel in the concrete increases only slightly in dependence on the relative humidity in the pores of the surrounding concrete up to a relative humidity of 80 %, but then increases significantly [Marquardt 1991].

The construction should be viewed critically if the relative humidity near the construction steel is increased to the extent where the 80 % mark is exceeded frequently or permanently.

6.3.1.7 Health-damaging fungi

The reason for retrofitting a building with an interior insulation system is firstly the significant reduction of the energy demand, and secondly the improvement of thermal comfort and health protection in living areas. In this connection, interior insulation considerably mitigates the problem of moisture on interior surfaces since the temperature is increased compared to the uninsulated state, and the relative surface humidity decreases. Even so, within the context of certification, it is tested whether critical material moisture or surface moisture occurs in the layers on the room side of the airtight layer. An EnerPHit retrofit can only be certified if adverse effects on health due to mould growth under standard usage conditions can be excluded.

An often used assessment of the risk of mould is based on the studies carried out by [Sedlbauer 2001]. The interrelationship between growth rates of mould fungi, the surface climate (temperature and relative humidity) and degree of contamination (substrate classes) were studied here. The result is shown in Figure 18 in the form of curves with identical growth rates (isopleth diagrams) of the mould types commonly found in buildings. Mould germination will not take place if the surface temperature and moisture is below that of the LIM construction isopleth.

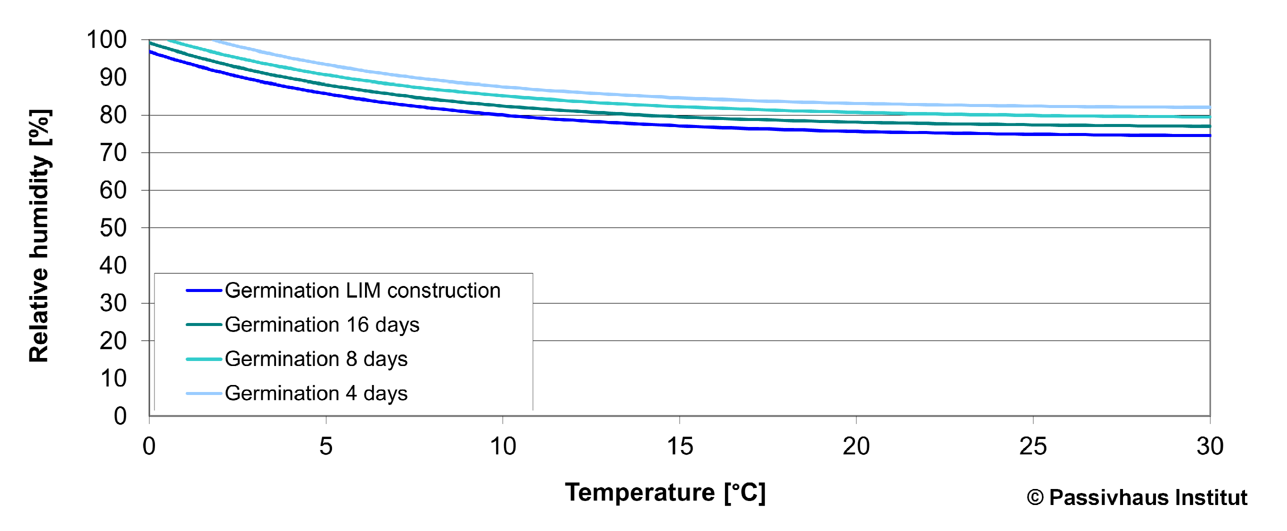


Figure 18: **Lowest Isopleth for Mould (LIM) for mould germination on heavily contaminated surfaces and isopleths for germination with varying exceedance periods.**

If the LIM construction is exceeded, germination does not occur immediately, at least on surfaces which were previously unaffected. Certain exceedance periods are necessary for this. The isopleths for exceedance durations of 4, 8 and 16 days are also shown in Figure 18.

The risk of mould growth is checked using the [Wufi Bio] software. In doing so, the available data pairs for temperature and moisture e.g. at the boundary layer "old interior plaster - interior insulation" (abbreviated as aIP_ID) are converted into their water content using the moisture storage function of a spore. If this moisture content exceeds the LIM, contrary to the explanation given above it will be assumed that growth occurs immediately. If the moisture content of the spore is below the LIM, then growth of the spore will stop but it will not die off. A safety margin is provided by the fact that when the LIM is exceeded, germination occurs first and growth does not take place immediately, while falling short of the LIM again results in some spores dying off.

If the results of the simulation suggest that there is a mould growth risk inside the construction (assessment value: relative humidity > 75% for a longer time), a closer look is necessary e.g. using the [Wufi Bio]. Evaluation of the results is based on the predicted annual growth. Values between 0 and 50 mm/a are within the safety margin and are therefore assessed as unproblematic. The limit value of 50 mm/a is applied as an evaluation criterion. Growth is also influenced by the type of substrate chosen.

[Sedlbauer 2001] differentiates between the substrate classes 0, I and II, where 0 describes an optimal nutrient substrate. Mould types commonly found in buildings do not occur below the LIM. The presence of optimal boundary conditions can be ruled out and is therefore not assessed. The substrate classes I and II form the nutrient base often present in buildings. Class I contains biodegradable materials such as wallpaper residues or heavy contamination, while substrate class II contains materials which are non-biodegradable (e.g. plaster and masonry).

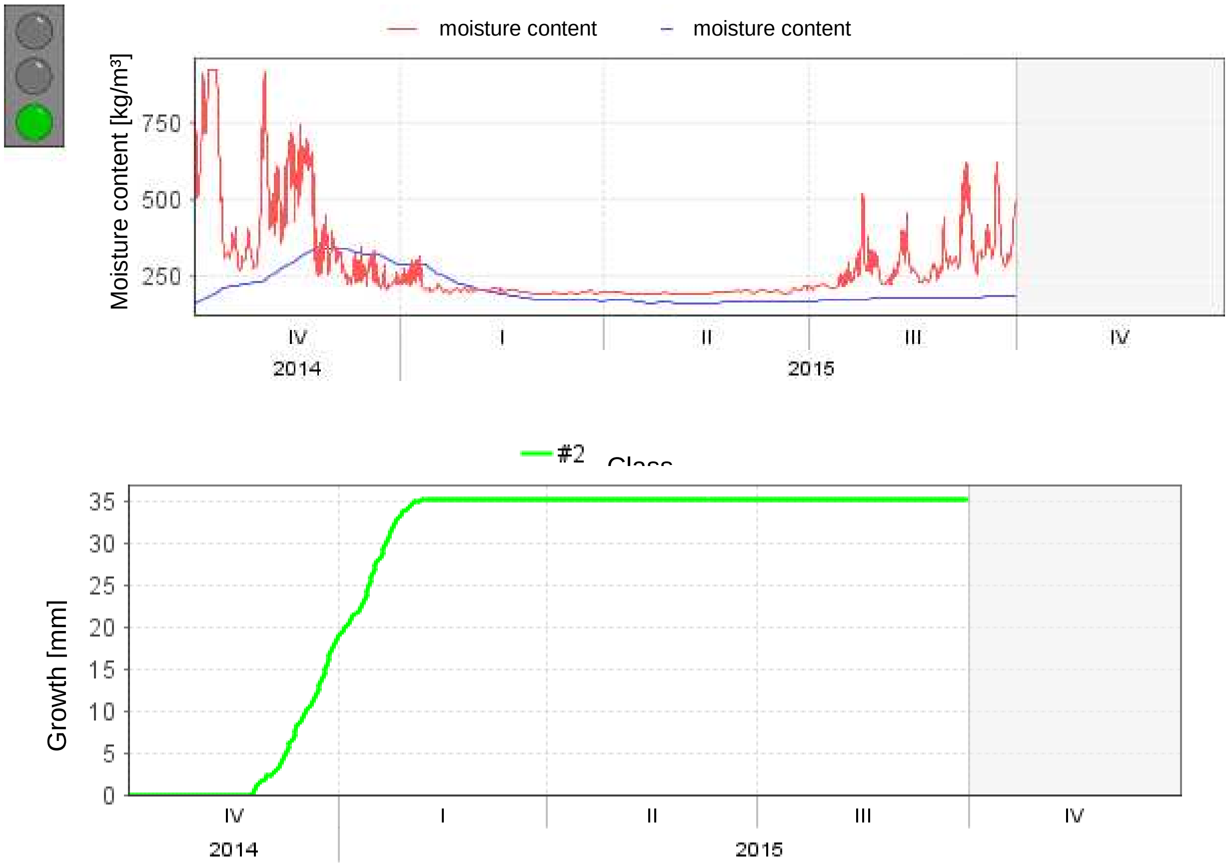


Figure 19: **Qualitative result for the whole year for a wall assembly with interior insulation with comparison of the moisture content threshold (LIM) for a substrate class I material (heavy contamination) with the water content of the spore at the limit layer of "old interior plaster - insulation" (above) and representation of the growth curve (below). In the winter months (IV 2014 and I 2015) the moisture content threshold is exceeded, leading to mould growth of 35mm/a in this case.**

Apart from evaluation of the wall surface in the "uninterrupted" area, surface moisture at thermal bridges such as wall corners is also of interest.

6.3.2 Summarisation of evaluation criteria

On the basis of dynamic simulation of constructions with interior insulation, time-resolved calculation of relative humidity is also carried out for several years. In terms of the annual cycle, the fluctuation range enables evaluation of the construction with reference to the risk of structural damage due to

- Wood-destroying fungi in the case of wood and wood-based materials

- Corrosion of construction steel in building components consisting of reinforced concrete
- Adverse effects on health due to mould growth in component layers on the room side

Observation of the liquid water content in individual building component layers allows assessment of the construction with reference to damage by

- excessively high condensation in case of non-hygroscopic building materials,
- water saturation in hygroscopic building materials and the associated dripping of more liquid water inside the construction,
- weathering due to freeze/thaw cycles in case of critical pore filling levels.

Finally, observation of the total moisture content of the building component and individual layers provides information about moisture saturation occurring over several years.

6.4 Interior insulation in European climate zones

Besides the diffusion and moisture transport properties of the chosen interior insulation system, its reliable functioning also depends largely on the climate boundary conditions on the inside and outside. While the parameters for temperature and moisture on the room side can be optimised to some extent (e.g. use of mechanical ventilation), the opportunities for influencing the external effects are limited (e.g. hydrophobisation). In order to be able to assess better the influence of climate conditions, the hygrothermal behaviour of different wall assemblies in different climatic conditions similar to those in Europe will be examined in this section.

6.4.1 Climate boundary conditions

In order to select the most relevant climatic regions, the behaviour of exposed masonry consisting of clinker and sandstone which are particularly sensitive to the driving rain boundary condition was analysed. 13 locations widely distributed throughout Europe were chosen for this. As shown by the results, particular attention has to be given to the influence of driving rain. Critical levels of moisture appear mostly in the coastal regions with the corresponding unfavourable rain and wind conditions. To obtain an idea of the influence of the external climate, five wall materials (two with brick and three with sandstone) with various types of interior insulation (mineral fibre, cellulose and mineral insulation panels) were tested and evaluated.

Five climate zones resulted from the 13 locations (hot, temperate, coastal, cold, and mountainous). 5 reference locations which provided the most unfavourable results were selected from these. Two locations were considered for the cold climate since the locations for the other wall assemblies provided critical results. Separate consideration was not undertaken for the mountainous regions because moisture behaviour here does not differ much from that in cold climate zones.

It was assessed whether the steady-state can be achieved and whether liquid water occurs in the bricks or the insulation layer. The occurrence of condensation in the insulation layer is assessed as critical, regardless of whether or not the insulation is water-absorbent, or whether the amount of condensate dries out again throughout the year, because mould formation is likely even before condensation occurs. Since the mould growth criterion was not examined in more detail here, conversely it cannot be concluded that lack of condensation simultaneously means that the system is functional!

6.4.2 Boundary conditions for the simulation

The hourly values for the external climatic conditions temperature, relative humidity, amount of rain, wind, and solar radiation were taken from the [Meteonorm2010] database. The respective indoor humidity was determined using dynamic simulations. In doing so, a maximum indoor humidity of 70 % was assumed for the more humid climate regions (e.g. Palermo). The buildings were heated to 20 ℃ in win ter. The duration period used in the simulation was 10 years.

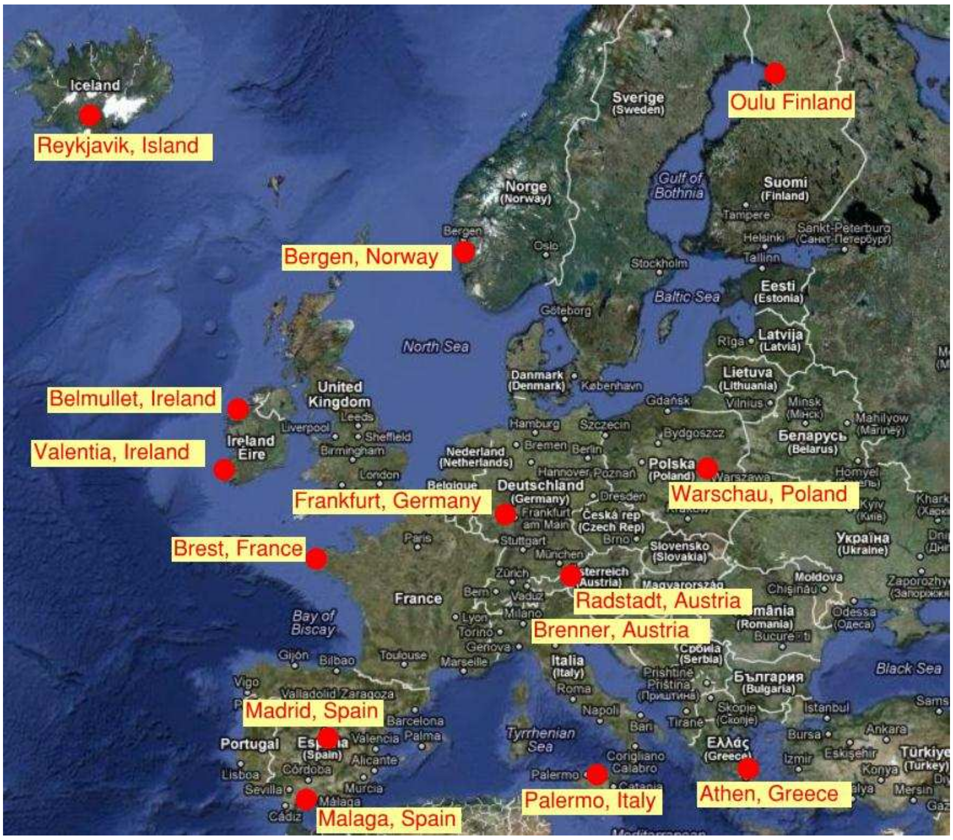


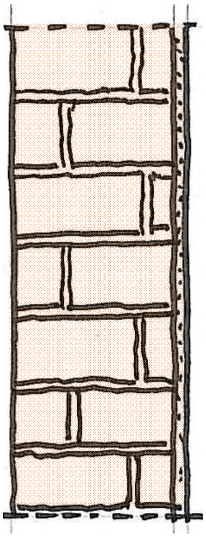
Figure 20: Overview of the studied locations

6.4.3 Examined interior insulation constructions

The hygric behaviour of interior insulation in combination with exposed masonry is more difficult to predict compared with plaster facades on account of the varying transport and storage properties of the wall material and the associated moisture absorption at times with driving rain.

In order to provide assistance in the assessment of interior insulation in combination with exposed masonry, the hygrothermal properties of an exterior wall of sandstone and clinker with two different types of masonry bricks, different interior insulation systems and under different climate boundary conditions will be examined below. The simulations are carried out with the software [Delphin5].

In principle, an existing wall assembly with plaster on the inside is assumed. Typical interior insulation assemblies consist of mineral wool, mineral insulation panels or blown-in cellulose. An airtight layer must be provided on the room side. In the case of mineral wool insulation and cellulose, this is usually ensured by means of a vapour retarder consisting of sheeting or OSBs. Interior plaster forms the airtight layer in the case of mineral insulation panels. Consequently, the following assemblies result for this humidity simulation:

Existing exposed masonry with interior plaster present 	**Clinker (Wienerberger)** Bulk density 1400 kg/m³ Thermal conductivity 0.55 W/(mK) Open/effective porosity 0.35 m³/m³ Moisture content with effective saturation 0.319 m³/m³ Water vapour diffusion resistance factor 18.78 - Water absorption coefficient 0.177 kg/m²s05 **Historic clinker** Bulk density 1700 kg/m³ Thermal conductivity 0.85 W/(mK) Open/effective porosity 0.36 m³/m³ Moisture content with effective saturation 0.32 m³/m³ Water vapour diffusion resistance factor 9 - Water absorption coefficient 0.25 kg/m²s05 **Sandstone (Reinhardsdorf)** Bulk density 1988 kg/m³ Thermal conductivity 2.40 W/(mK) Open/effective porosity 0.25 m³/m³ Moisture content with effective saturation 0.20 m³/m³ Water vapour diffusion resistance factor 16.46 - Water absorption coefficient 0.139 kg/m²s05 **Sandstone (Cotta)** Bulk density 1939 kg/m³ Thermal conductivity 2.43 W/(mK) Open/effective porosity 0.27 m³/m³ Moisture content with effective saturation 0.23 m³/m³ Water vapour diffusion resistance factor 19.29 - Water absorption coefficient 0.070 kg/m²s05 **Sandstone (Posta)** Bulk density 2095 kg/m³ Thermal conductivity 2.46 W/(mK) Open/effective porosity 0.21 m³/m³ Moisture content with effective saturation 0.19 m³/m³ Water vapour diffusion resistance factor 15.83 - Water absorption coefficient 0.368 kg/m²s05 **Existing interior plaster historic lime plaster** Bulk density 1797 kg/m³ Thermal conductivity 0.82 W/(mK) Open/effective porosity 0.30 m³/m³ Moisture content with effective saturation 0.285 m³/m³ Water vapour diffusion resistance factor 12 - Water absorption coefficient 0.127 kg/m²s05

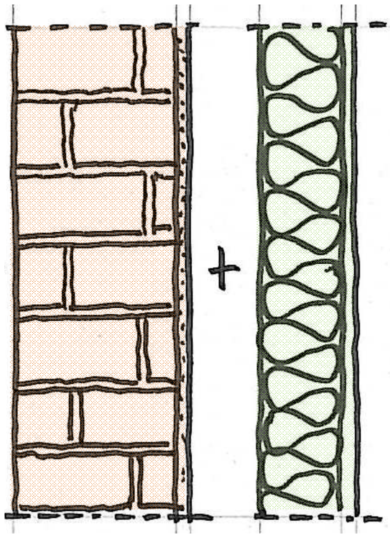
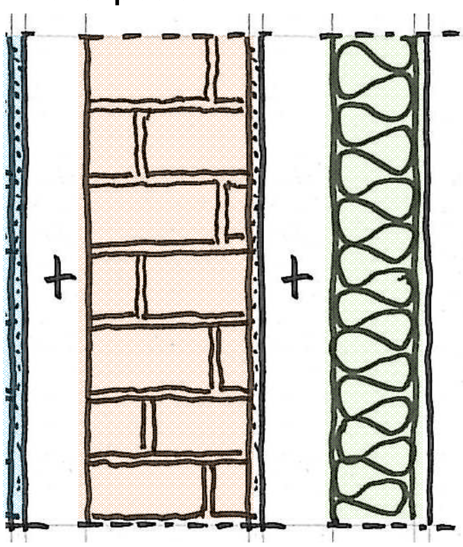
Interior insulation 	**Mineral wool with vapour retarder** Bulk density — 30 kg/m^3 Thermal conductivity — 0.04 W/(mK) Open/effective porosity — 0.92 m^3/m^3 Moisture content with effective saturation — 0.9 m^3/m^3 Water vapour diffusion resistance factor — 1 - Water absorption coefficient — -- kg/m^{2}s05 **Vapour retarder open** sd value — 0.7 m **Vapour retarder vr 19.5** sd value — 19.5 m **Cellulose** Bulk density — 55 kg/m^3 Thermal conductivity — 0.04 W/(mK) Open/effective porosity — 0.926 m^3/m^3 Moisture content with effective saturation — 0.7 m^3/m^3 Water vapour diffusion resistance factor — 2.07 - Water absorption coefficient — 0.563 kg/m^{2}s05 **Mineral insulation panel** Bulk density — 115 kg/m^3 Thermal conductivity — 0.045 W/(mK) Open/effective porosity — 0.96 m^3/m^3 Moisture content with effective saturation — 0.36 m^3/m^3 Water vapour diffusion resistance factor — 4.1 - Water absorption coefficient — 0.008 kg/m^{2}s05
Exterior plaster 	**Cement plaster** Bulk density — 2100 kg/m^3 Thermal conductivity — 1.34 W/(mK) Open/effective porosity — 0.22 m^3/m^3 Moisture content with effective saturation — 0.20 m^3/m^3 Water vapour diffusion resistance factor — 45 - Water absorption coefficient — 0.004 kg/m^{2}s05 **Restoration plaster (lime-cement plaster)** Bulk density — 1266 kg/m^3 Thermal conductivity — 0.55 W/(mK) Open/effective porosity — 0.50 m^3/m^3 Moisture content with effective saturation — 0.45 m^3/m^3 Water vapour diffusion resistance factor — 12 - Water absorption coefficient — 0.0093kg/m^{2}s05

Figure 21: Wall assembly exposed masonry, material data from [Delphin 5.6.8]

6.4.4 Results for climates and brick variants

Figure 21 provides an overview of the studied climates, bricks types and interior insulation systems. As first step, only the humidity in the insulation layer was assessed; the different permissible moisture contents of the insulation materials were taken into account in the process. In the non-hygroscopic mineral wool, a liquid water content of less than 150 g/m² is permissible. Above this limit, water cannot be retained in the substance matrix and starts to drip. In contrast, hygroscopic insulation materials such as cellulose or mineral insulation panels can store water; therefore the available degree of pore filling is stated.

Using the variation in the climatic conditions, different masonry types and interior insulation systems, it was possible to obtain a rough overview of the hygrothermal behaviour of exposed masonry. In hot and temperate climates, the studied constructions prove to be significantly less critical than those in coastal areas or in the cold climate. Basically, this overview also shows that certain brick types or interior insulation systems are particularly suitable in a specific climate, while others are not. The objective of providing statements regarding the suitability of specific systems for exposed masonry cannot be fulfilled.

	HOT				TEMPERATE		COASTAL			COLD				MOUNTAINOUS	
	Athen	Madrid	Malaga	Palermo	Frankfurt	Warschau	Belmullet	Brest	Valentia	Bergen	Jekaterinburg	Oulu	Reykjavik	Brenner	Radstadt
Clinker (Wienerberger)															
+Mineralwool (miwo)	0 g/m²	0 g/m²	0 g/m²	0%	>150 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	< 150g/m²	>150 g/m²
+Miwo + vapour retarder (sd=19.5m)	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	< 150g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	0%	< 150g/m²	>1000g/m²	>1000g/m²	< 150g/m²	0 g/m²
+Cellulose (θ eff=0.7m³/m³)	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
+Min.insulation board (θ eff=0.36m³/m³)	0%	0%	0%	0%	0%	0%	4%	8%	8%	0%	0%	0%	0%	0%	0%
Historical clinker															
+MiWo	0 g/m²	0 g/m²	0 g/m²	0%	>150 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>150 g/m²
+MiWo+ vapour retarder (sd=19.5m)	0 g/m²	0 g/m²	>1000g/m²	>1000g/m²	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	0 g/m²	0 g/m²	>1000g/m²	>1000g/m²	< 150g/m²	0 g/m²
+Cellulose (θ eff=0.7m³/m³)	0%	0%	0%	0%	0%	0%	1%	2%	1%	0%	1%	0%	0%	0%	0%
+Min.insulation board (θ eff=0.36m³/m³)	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%
Sandstone (Cotta)															
+MiWo	0 g/m²	0 g/m²	0 g/m²	0%	>150 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>150 g/m²
+MiWo+ vapour retarder (sd=19.5m)	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	< 150g/m²	0 g/m²
+Zellulose (θ eff=0.7m³/m³)	0%	0%	0%	0%	0%	0%	4%	4%	4%	0%	1%	0%	1%	0%	0%
+Min.insulation panel (θ eff=0.36m³/m³)	0%	0%	0%	0%	0%	0%	4%	7%	8%	0%	0%	0%	0%	0%	0%
Sandstone (Posta)															
+MiWo	0 g/m²	>150 g/m²	>150 g/m²	>150 g/m²	< 150g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	< 150g/m²	>150 g/m²	>150 g/m²	>150 g/m²	>150 g/m²	< 150g/m²
+MiWo+ vapour retarder (sd=19.5m)	0 g/m²	>150 g/m²	>150 g/m²	>150 g/m²	0 g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	0 g/m²	< 150g/m²	>150 g/m²	>150 g/m²	>150 g/m²	< 150g/m²
+Cellulose (θ eff=0.7m³/m³)	0%	1%	2%	2%	0%	0%	5%	5%	6%	0%	0%	2%	0%	1%	0%
+Min.insulation panel (θ eff=0.36m³/m³)	0%	0%	2%	1%	0%	0%	12%	15%	16%	0%	0%	2%	0%	1%	0%
Sandstone (Reinhardsdorf)															
+MiWo	0 g/m²	< 150g/m²	0 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>150 g/m²	>150 g/m²
+MiWo+ vapour retarder (sd=19.5m)	0 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	< 150g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>1000g/m²	0 g/m²	>150 g/m²	>1000g/m²	>1000g/m²	>1000g/m²	>1000g/m²
+Cellulose (θ eff=0.7m³/m³)	0%	0%	0%	1%	0%	0%	3%	4%	4%	0%	1%	1%	2%	0%	0%
+Min.insulation panel (θ eff=0.36m³/m³)	0%	0%	0%	0%	0%	0%	14%	16%	16%	0%	0%	0%	1%	0%	0%

Figure 22: Overview of the results of moisture calculation for the exposed masonry in thirteen different locations in Europe and choice of the reference location for the climate types Hot, Temperate, Cold and Coastal (light grey) and the choice of critical brick types (dark grey). Assessment grid for mineral wool interior insulation: maximum permissible liquid water quantity 150 g/m², black: >1000g/m², red: >150g/m², orange: <150g/m². Assessment grid for capillary active insulation materials: ratio of water content to effective water content (θ/θeff) = degree of pore filling as %.

For further observations, a reference location and a reference masonry type for any climate can be referred to.

Table 6: Five selected locations with unfavourable climatic conditions

Climate region in Europe	Reference location
Coastal	Brest (FR)
Cold	Oulu (SE) and Reykjavik (IS)
Temperate	Warsaw (PL)
Hot	Palermo (IT)

These reference locations can be helpful for future investigations regarding the suitability of interior insulation constructions. The results for one location (here: Warsaw) are shown in the following table. This shows the influence of the wall material, which is particularly apparent in the case of sensitive interior insulation systems such as mineral wool.

	Miwo+vr	Cellulose	Mi.ins.panel
Clinker (Wienerberger)	>150 g/m²	0%	0%
historical clinker	< 150g/m²	0%	0%
Sandstone (Cotta)	< 150g/m²	0%	0%
Sandstone (Posta)	< 150g/m²	0%	0%
Sandstone (Reinhardsdorf)	>1000g/m²	0%	0%

Figure 23: Combination of exposed masonry with three different types of interior insulation in the Warsaw location. Assessment of mineral wool interior insulation takes place in g/m² according to maximum liquid water content. Permissible maximal content here is 150g/m². The liquid water quantities of cellulose and mineral insulation panels is given as a ratio (θ/θeff in %).

As a second step, an examination of the plaster constructions was carried out based on the five reference locations and the two brick types which were unfavourable in terms of their moisture-relevant properties. This showed that it is possible to find a functioning interior insulation system for all locations by choosing a suitable exterior plaster. Mineral wool also proved more demanding because the type of vapour retarder used is crucial. Vapour retarders that are more diffusion open (sd<2m) in cold climates these result in higher humidity levels, therefore more exact consideration of the properties of the sheeting for the respective climate is advised.

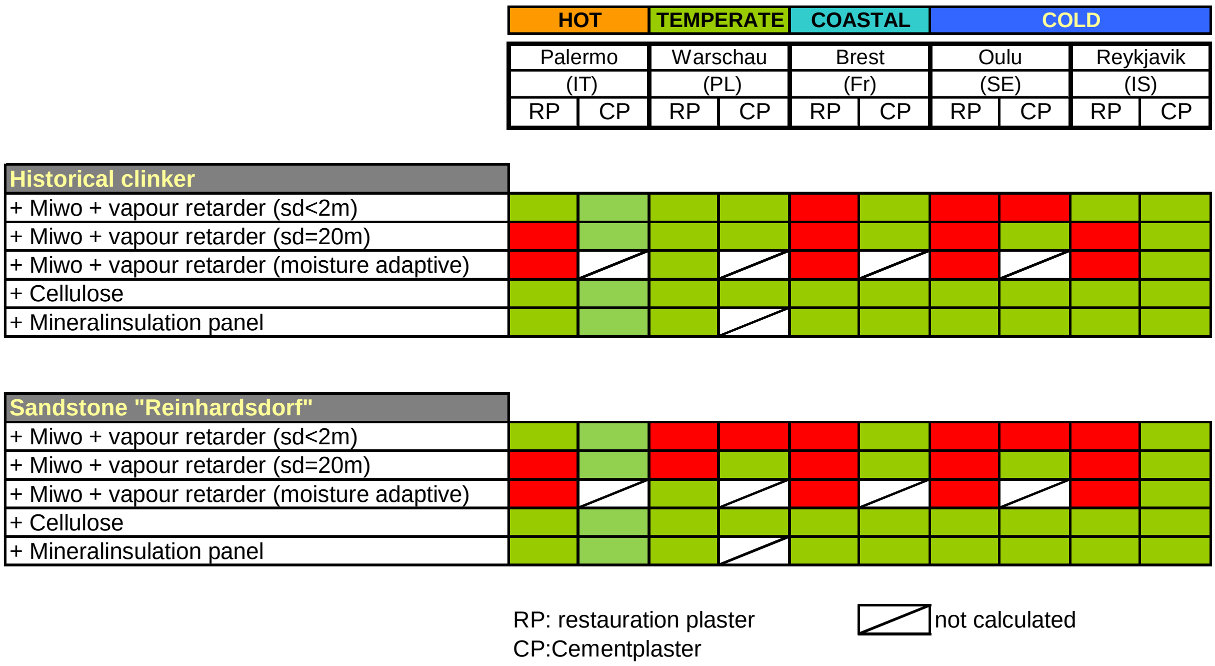
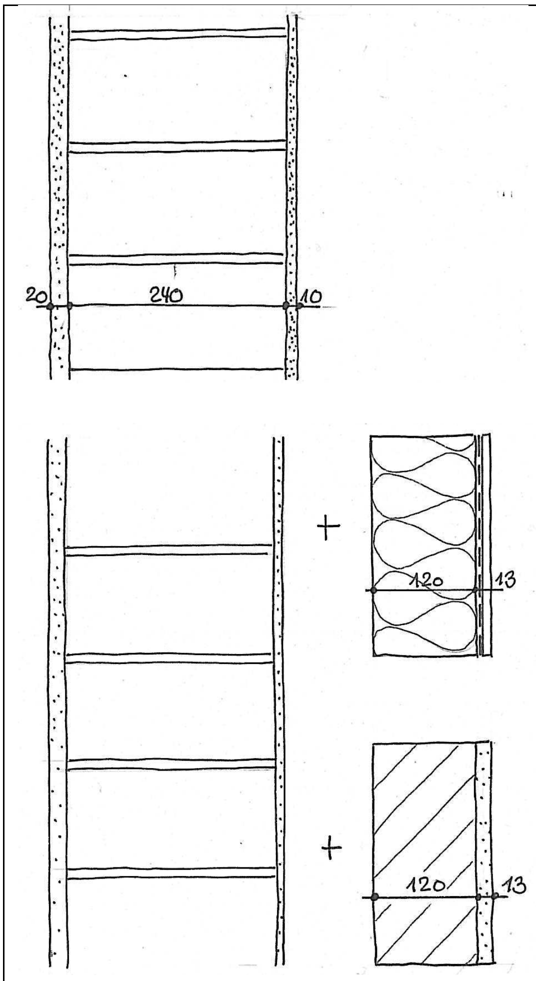


Figure 24: **Combination of plaster constructions with different types of interior insulation in five reference locations. Assessment grid for mineral wool interior insulation: maximum permissible liquid water quantity 150 g/m. red: >150g/m², green: <150g/m². Assessment grid for capillary active insulation materials: green = ratio of water content to effective water content (θ/θeff) <1 %.**

6.5 Examination of interior insulation systems in temperate climates

Interior insulation systems with mineral wool, cellulose and mineral foam for temperate climates and plaster facades are examined more closely below and the influence of masonry bricks, exterior plaster, insulation thickness and properties of vapour retarders are presented in more detail. Based on [DIN EN 4108-3], a distinction is made between rain exposure groups (REG) I, II and III. Accordingly, the climate boundary conditions for three reference locations in REG II (Dresden) and III (Garmisch-Partenkirchen and Bremerhaven in Germany) were chosen.

The following constructions were examined with reference to their structural integrity using dynamic simulations and assessed in respect of durability and health protection.



Exterior plaster (REG III)	**Transputz WD, Hydroment (TP WD)**
Exterior plaster (REG II)	**Transputz SG, Hydroment (TP SG)** **3 mm SHG fibre-reinforced restoration plaster, Tubag and 17 mm lightweight undercoat plaster, Maxit Baustoffwerke,**
Masonry I (MWI)	**Clinker (Innenstein Rote Kaserne Potsdam)**
Masonry II (MWII)	**Natural stone (Sandstone Monte Merlo)**
Interior plaster	**Historic lime plaster**
Variant A	
Build-up of the interior insulation system	
Insulation	**Mineral wool**
Sheeting	**Variation of the sd values**
Planking on room side	**Gypsum plasterboard**
Variant B	
Build-up of the interior insulation system	
Insulation	**Cellulose** **Mineral insulation panel**
New interior plaster	**Gypsum plaster**

Figure 25: Wall assembly. Masonry, external plaster and different insulation types.

The results show that in all cases, consideration of the risk of mould at the boundary layer of the old interior plaster is a decisive evaluation criterion. Furthermore, it was possible to find structurally sound constructions for all three insulation materials. With systems with an airtight layer on the room side consisting of sheeting, attention must be given to the vapour retardant characteristics.

In the context of refurbishment using interior insulation, a question that is frequently asked concerns the renewal of the old interior plaster. Old coatings can hinder vapour transport and lead to moisture accumulation. For this reason, a system with purposely increased resistance in the interior plaster area was examined. The result showed that there is only a slight influence on the risk of mould. Furthermore, old plaster coats may still contain residual organic matter even after meticulous cleaning. In order to assess this risk accordingly, reference was made to Substrate Class I in accordance with [Sedlbauer 2001].

	U-Value W/(m²K)	ex. rendering/ final coat 3 mm	ex. rendering/ 17 mm	masonry 240 mm	old plaster 10 mm	insulation 120 mm	foil 1 mm	rendering/ gypsum board 10 mm	final coat/ gypsum board 3 mm	build up of humidity	liquid water insulation	liquid water stone average [kg/m³]	liquid water stone 2cm out [kg/m³]	liquid water stone Pore fill level [%]	old plaster freeze risk	old plaster max. rel H [%]	boundary layer old plaster/ insulation substrat I	boundary layer old plaster/ insulation substrat II	note
		structure ant thickness of layers								assessment criteria									
1	1.537	TP-WD		OB	LP	--	--	--	--	no	--	4.16	4.69	4	n.t.	67	n.t.	n.t.	Brick without insulation appropriate external rendering
2	1.537	TP-SG		OB	LP	--	--	--	--	no	--	21.48	125.62	105	n.t.	n.B.	n.t.	n.t.	Brick without insulation inappropriate external rendering
3	1.605	TP-WD		MM	LP	--	--	--	--	no	--	17.96	26.87	8	n.t.	69	n.t.	n.t.	Sandstone without insulation appropriate external rendering
4	0.271	TP-WD		OB	LP	MW	VR sd 0.7 fix	GB	LR	no	no	4.72	6.25	5	yes	93%	150mm/a	75 mm/a	Brick and mineralwool insulation with differnt foils
5	0.271	TP-WD		OB	LP	MW	VR sd 0.2-20	GB	LR	no	no	4.57	6.17	5	yes	85%	0.75mm/a	0 mm/a	
6	0.271	TP-WD		OB	LP	MW	VR sd 10 fix	GB	LR	no	no	4.57	6.16	5	yes	85%	2mm/a	0 mm/a	
7	0.313	TP-WD		OB	LP	MW 10cm	VR sd 0.2-20	GB	LR	no	no	4.55	6.02	5	yes	84%	0.07mm/a	0 mm/a	Influence thickness of insulation
8	0.273	TP-WD		MM	LP	MW	VR sd 0.7 fix	GB	LR	no	no	22.12	29.16	9	yes	89%	50mm/a	12mm/a	Influence of stone
9	0.282	RP	UL	OB	LP	MW	VR sd 0.7 fix	GB	LR	no	no	6.09	21.61	18	yes	95%	200mm/a	100mm/a	Influence external rendering
10	0.282	RP	UL	OB	LP	MW	VR sd 0.2-20	GB	LR	no	no	5.97	21.54	18	yes	88%	35mm/a	5mm/a	inprovement by vapour retarder
11	0.317	TP-WD		MM	LP	CE	VR sd 0.7 fix	GB	LR	no	no	21.66	29.10	9	yes	87%	32mm/a	6mm/a	
12	0.317	TP-WD		MM	LP+OP	CE	VR sd 0.7 fix	GB	LR	no	no	21.65	29.10	9	yes	87%	35mm/a	6mm/a	Influence of oil paint

TP-WD	Transputz WD Hydroment	MW	Mineralwool
TP-SG	Transputz SG Hydroment	CE	Cellulose
RP	Renovating Plaster	VR	Vapour retarder
UL	Undercoat light	GB	Gypsum board
OB	Old Brick	LR	Leveling render
MM	Sandstone Monte Merlo	n.t.	not testet

green	mould growth below 50 mm/a: OK
yellow	mould growth between 50 and 200 mm/a
red	mould growth more than 200 mm/a: not acceptable
	[Wufi Bio]

Figure 26: Overview of moisture calculation for clima type Temperate and rain exposure group III (Bremer-haven). Assessment grid: liquid water in insulation and stone and mould growth risk. Material data [Delphin 5.8]

		structure ant thickness of layers								assessment criteria									
		ex. rendering/ final coat	ex. rendering/	masonry	old plaster	insulation	foil	rendering/ gypsum board	final coat/ gypsum board			liquid water stone			old plaster		boundary layer old plaster/ insulation		
	U-Value W/(m²K)	3 mm	17 mm	240 mm	10 mm	120 mm	1 mm	10 mm	3 mm	build up of humidity	liquid water insulation	average [kg/m³]	2cm out [kg/m³]	Pore fill level [%]	freeze risk	max. rel H [%]	substrat I	substrat II	note
1	0.271	LR	TP-WD	OB	LP	MW	VR sd 0.7 fix	GB	LR	no	yes (<150g/m²)	4.47	4.39	4	ja	96%	180mm/a	110mm/a	Influence of foil characteristics for old brick and mineralwoolinsulation
2	0.271	LR	TP-WD	OB	LP	MW	VR sd 10 fix	GB	LR	no	no	4.27	4.36	4	ja	83%	0	0	
3	0.273	LR	TP-WD	MM	LP	MW	VR sd 0.7 fix	GB	LR	no	no	18.89	18.29	5	ja	89%	175mm/a	110mm/a	Influence of foil characteristics for sandstone and mineralwoolinsulation
4	0.273	LR	TP-WD	MM	LP	MW	VR sd 0.18-3.6	GB	LR	no	no	18.15	18.16	5	ja	84%	0	0	
5	0.273	LR	TP-WD	MM	LP	MW	VR sd 0.2-20	GB	LR	no	no	17.50	18.11	5	ja	69%	0	0	
6	0.273	LR	TP-WD	MM	LP	MW	VR sd 10 fix	GB	LR	no	no	17.73	18.17	5	ja	73%	0	0	
7	0.317	LR	TP-WD	MM	LP	CE	VR sd 0.7 fix	GB	LR	no	no	18.54	18.19	5	ja	88%	25mm/a	5mm/a	Influence of foil characteristics for sandstone and celluloseinsulation
8	0.317	LR	TP-WD	MM	LP	CE	VR sd 0.18-3.6	GB	LR	no	no	18.06	18.11	5	ja	80%	0	0	

TP-WD	Transputz WD Hydroment	MW	Mineralwool
LR	Leveling render	CE	Cellulose
OB	Old Brick	VR	Vapour retarder
MM	Sandstone Monte Merlo	GB	Gypsum board

- (green) mould growth below 50 mm/a: OK
- (yellow) mould growth between 50 and 200 mm/a
- (red) mould growth more than 200 mm/a: not acceptable

[Wufi Bio]

Figure 27: Overview of moisture calculation for climate type Temperate and rain exposure group III (Garmisch-Partenkirchen). Assessment grid: liquid water in insulation and stone and mould growth risk. Material data [Delphin 5.8]

Non-hygroscopic insulation materials such as mineral wool are particularly sensitive because liquid water can be retained in the material structure only to a limited extent, therefore in order to derive generally applicable recommendations, several different types of vapour retarder were examined here. For the climate in Bremerhaven (REG III) it was apparent that a very small risk of mould is achievable with a sd value of 10 m. Although a higher sd value of 20 m gives better results in the simulation, this is difficult to achieve in practice due to the lower fault-tolerance. Seen from this perspective, the excellent result with the moisture-adaptive vapour retarder is also assessed with a sd value ranging between 0.2 and 20 m.

The influence of exterior plaster is worth emphasising. Calculations with an unsuitable plaster coat demonstrate an unacceptably high risk of mould. Here, the moisture-adaptive vapour retarder contributes quite substantially to mitigation (of this risk) provided that the stated value range can be fully exploited.

The influence of insulation thickness is identifiable in the results. Here, the risk of mould decreases from the already non-critical 0.75 mm/a to 0.07mm/a.

6.6 Examination of the risk of structural damage

6.6.1 Assessment of airtightness

Assessment of an uninterrupted, i.e. airtight and thermal bridge free wall element using dynamic simulations provides information about the fundamental suitability of the system in combination with different wall materials. Careful implementation of the airtight layer is of special importance. Potential leakage paths and their effects on a wall with interior insulation are examined and assessed below.

6.6.2 Leakage paths

With interior insulation, moisture damage is often caused by leakages. These are especially critical in the case of exterior walls with interior insulation because the masonry or timber framework cools down to almost the same temperature as the outside. If the warm, humid indoor air travels through a leak towards the outside, condensation accumulates in the insulation or exterior masonry when the temperature falls below dewpoint. Leaks directly connecting with the inside and the outside are often unproblematic. The leakage path is short and even at low air speeds the air cools down only slightly, so that the moisture only condenses on the outside of the wall (Figure 28). The risk of moisture accumulation inside the construction increases considerably if the leakage paths are longer. Even with leaks not in contact with the outdoor air, e.g. air flow behind the insulation layer, indoor air cools down so much that condensation occurs in the old plaster layer.

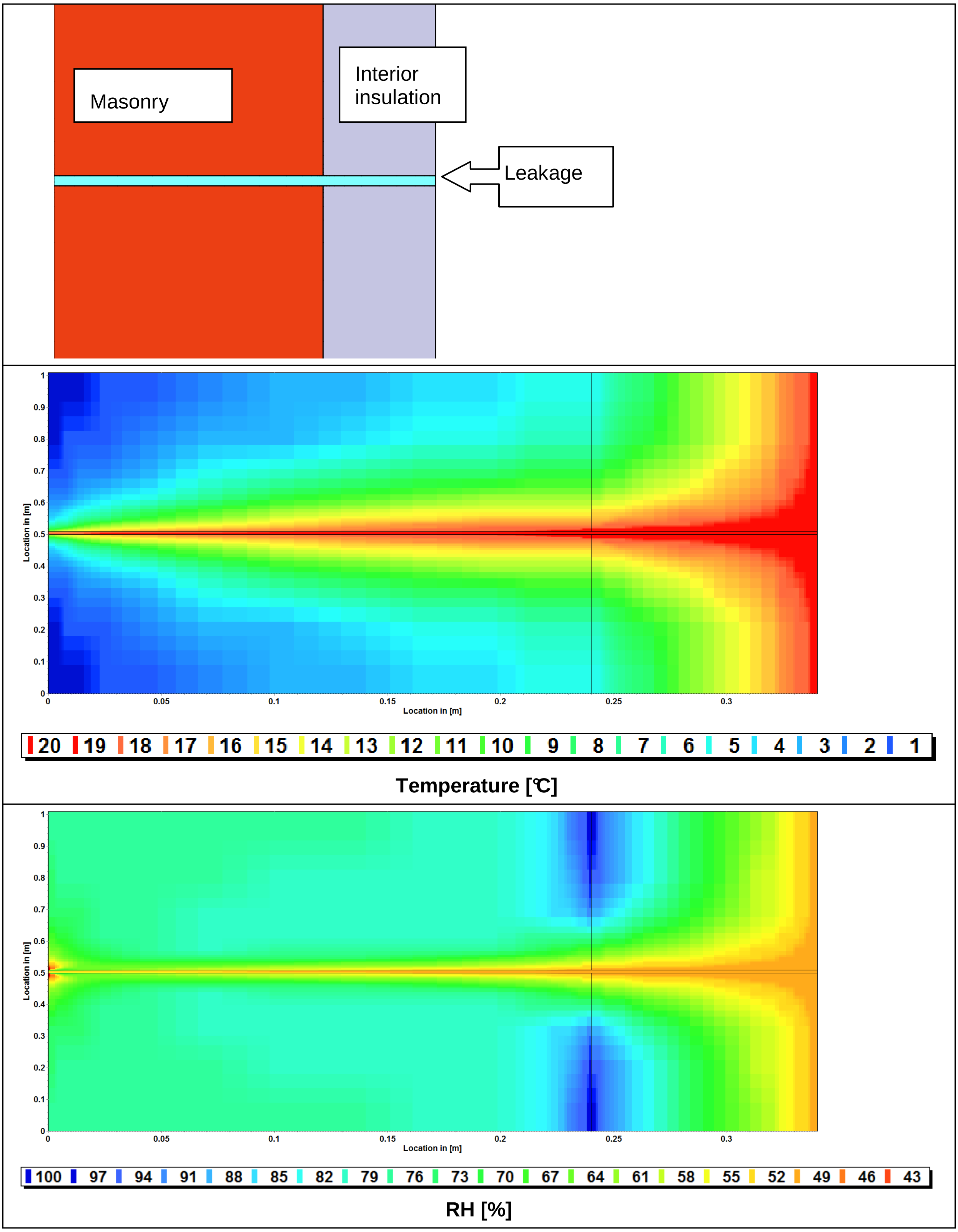


Figure 28: **Short leakage path directly connecting with outside air. Inside 20°C/ 50% RH and outside 0°C/ 80%. Pressure drop from inside towards outside 5 Pa.**

Intersecting ceilings represent an interruption of the airtight layer. In case of defective connection with the interior insulation, indoor air passes into or behind the insulation layer. If there is a leak elsewhere in the masonry, e.g. due to an eroded joint, then air flow will take place in the direction of the pressure drop. With greater pressure gradients, larger amounts of condensate will also accumulate here. However, the pressure gradient depends mainly on the factors wind, distribution of leakage in the building, and the difference in density due to different conditions inside and outside. In order to allow a realistic estimate of the air flow through leakages, a climate boundary condition was defined for the simulation model which obtains hourly values for indoor and outdoor pressure in dependence on the wind direction and wind speed as well as the inside and outside temperatures. If these pressure differences are assumed for a model affected by leakages, this will result in volume flow rates which vary with time. The examined assembly shows distinct phases of humidification and drying, corresponding much better with the reality compared with examination using average annual values.

Figure 29 shows the wind speed of the prevailing wind direction for the Frankfurt location. For an unfavourably exposed building, wind suction (Figure 30) is calculated from these wind speeds in accordance with the equation:

$w = cp * q$ [Pa] where

w= wind suction [Pa], cp= pressure coefficient (-0.7 for unfavourable exposure)

q = back pressure= $\frac{1}{2} * \rho * v^2$

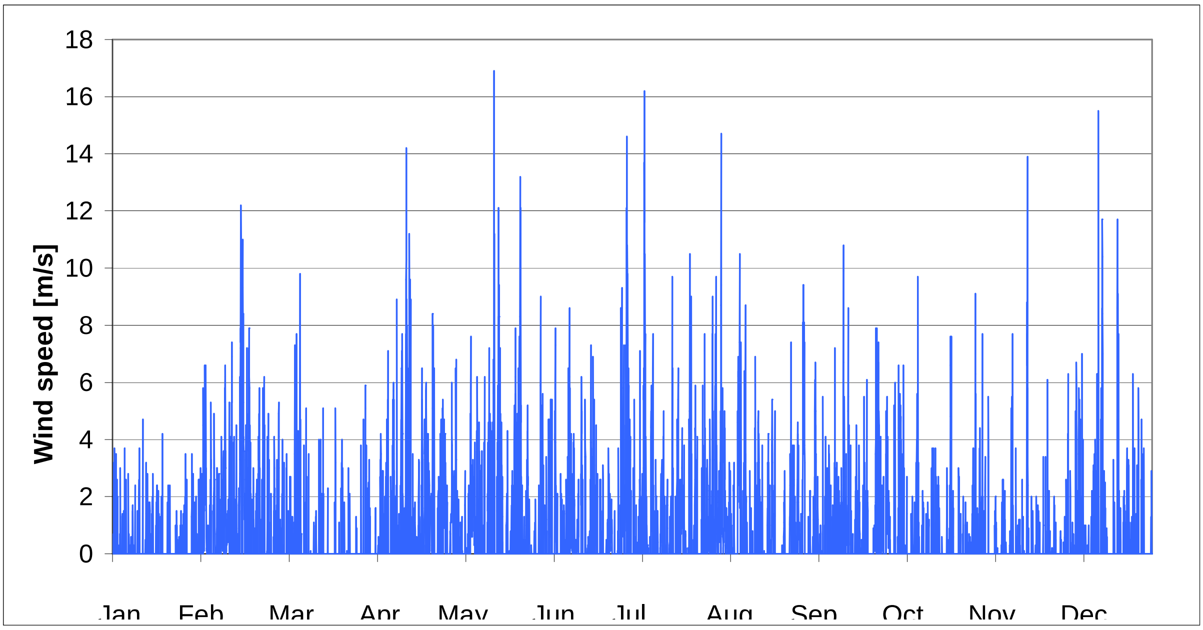


Figure 29: Hourly values for wind speed for the Frankfurt location [Meteonorm]

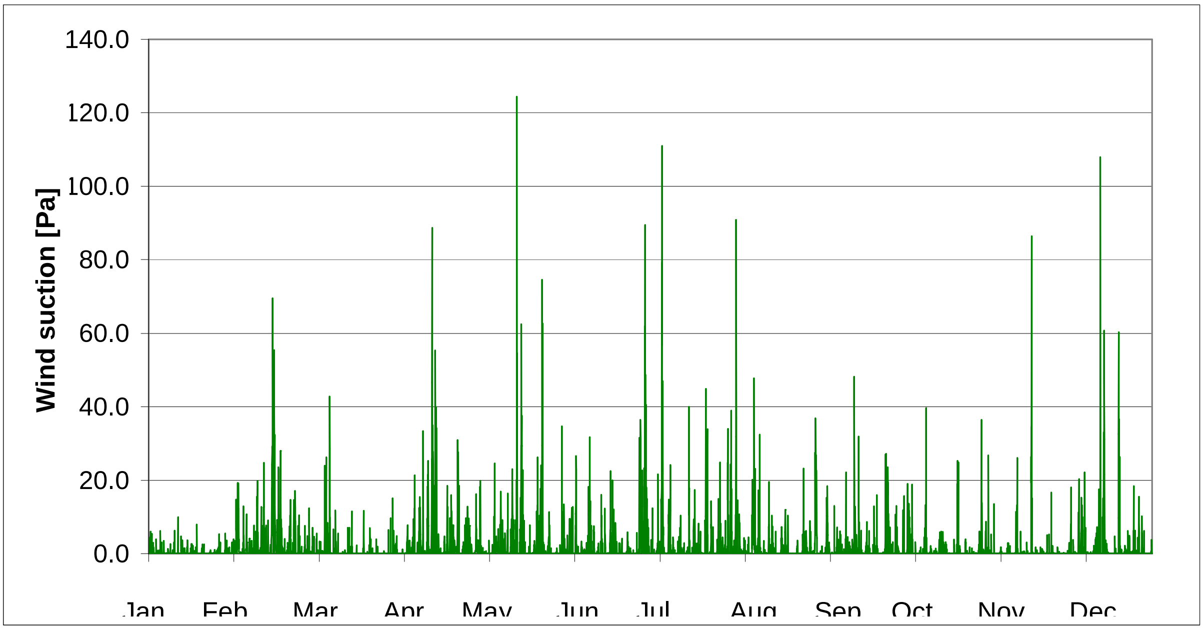


Figure 30: **Wind suction calculated from the wind speed and exposure for an unfavourable area of the exterior wall.**

In addition, there is the difference in density due to the temperature differences between the inside and the outside. The difference in air pressure between the inside and outside is shown in Figure 31.

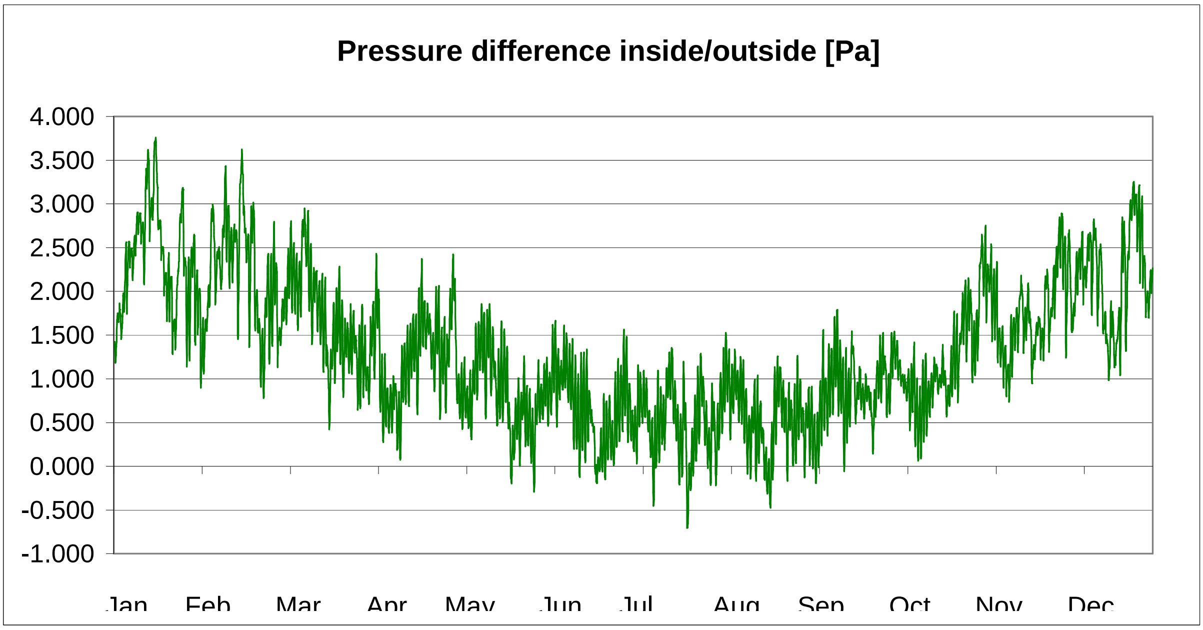


Figure 31: **Difference in air pressure due to temperature differences between the inside and the outside**

Wind and density differences are subject to constant changes so that hourly values for pressure differences have to be used for a realistic estimate of the resulting moisture gain.

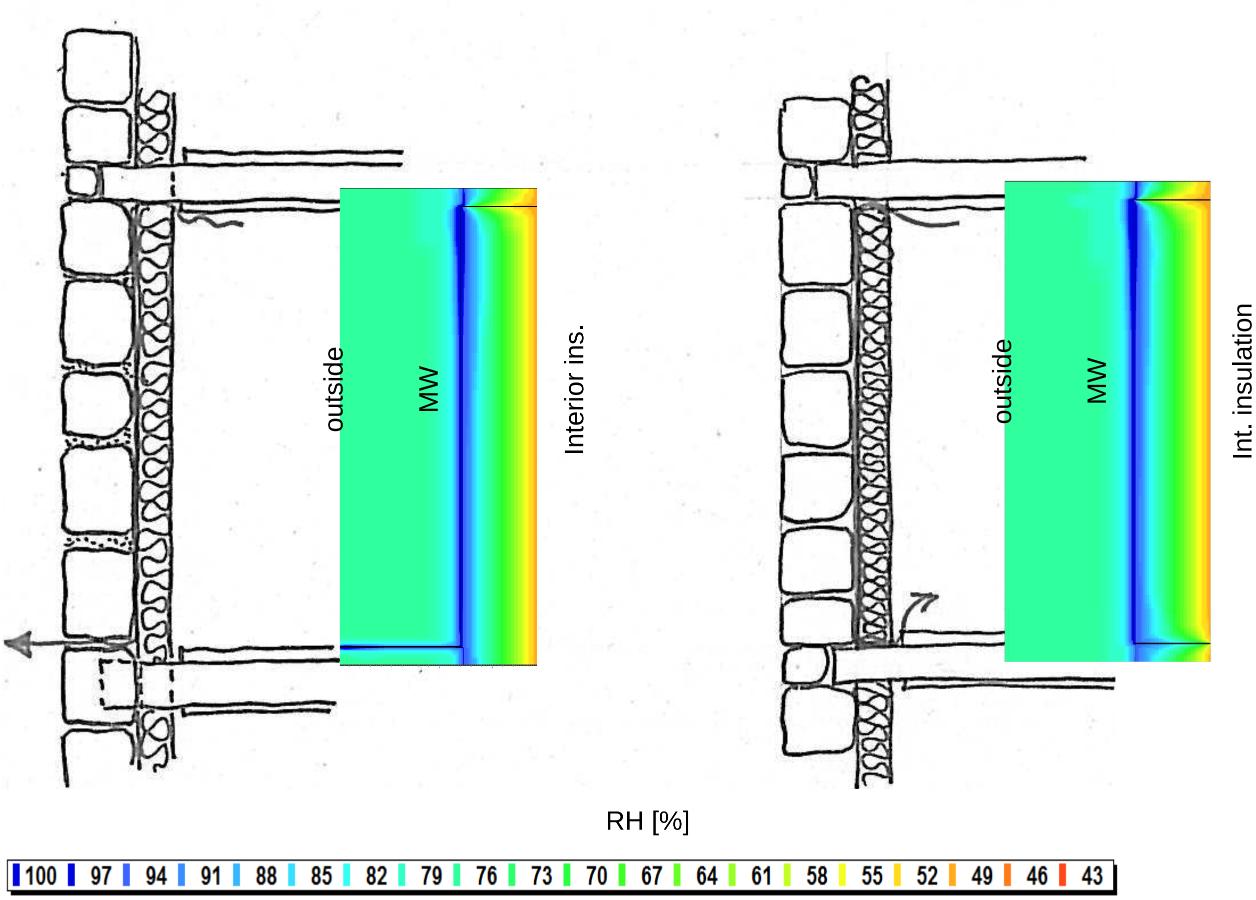


Figure 32: Extended leakage path in contact with the outside air (left) and air flow behind the insulation in contact only with indoor air (right)

The results of the simulation show clearly that with air flow behind the insulation layer, high quantities of condensate form between the existing wall and the interior insulation, even though the leakage is not in contact with the outdoor air. Interior insulation systems which preclude construction-related air flow behind insulation are advantageous for avoiding such damage.

6.6.3 Incorrect connection to the airtight layer

Flaws can hardly be avoided even with careful execution of the airtight layer on the inside. On the room side of the interior insulation consisting of mineral wool or cellulose there is usually a vapour retarder consisting of sheeting or wood-based material. The edges should be sealed airtightly using suitable adhesive tape. If these are incorrectly joined, water vapour will escape into the building component due to diffusion. This effect was depicted in the model by decreasing the vapour diffusion resistance factor of the vapour retarder. A faulty wall assembly was modelled in order to allow better estimation of the effect of a leakage. The sd value was decreased in order to obtain the same outcome with fault-free implementation of the vapour retarder.

Table 7: Vapour flow through a wall with 0,5m leak per m² and a sd value of sheeting of 100m in comparison to a sheeting without leakage and sd value of 25m. The vapour flow is almost equal.

Variant with leakage	Variant without leakage
Sd value of sheeting = 100 m	**Equivalent sd value = 25 m**
Constant vapour pressure gradient 20/50 0/80: 680 Pa	**Constant vapour pressure gradient 20/50 0/80: 680 Pa**
Vapour flow with 0.5m length of leak:	**Vapour flow through 1 m²**
0.00090 kg/h	**0.00087 kg/h**

The interior insulation is interrupted by the partition walls and ceiling. Long joints arise here which may be subject to leakage. Based on the assumption that joints in the uninterrupted area are fault-free if implemented carefully, only the joint length of the room limits is assumed here. With ordinary living space dimensions and assuming one window for each room, the joint length is between 2.5 m and 3 m for each square metre of wall area. Assuming that 15 to 20% of these joints are non-airtight, this result in a leakage of 0.5 m to 1.0 m per square metre of wall.

Implementation of interior insulation with a vapour retarder on the room side which has a sd value of 100 m will reduce this to 25 m due to non-airtight joining of the sheeting (see Table 8). The more vapour diffusion open the sheeting is, the lower the influence of the leakage will be. An equivalent sd value of 12 m will still result with a leakage of 0.5 m/m² for sheeting sd values of 20 m. The leakage effect will become negligibly small only with sheeting with sd values below 10 m, so that no further reduction in the sd value will result. However, it must be borne in mind that this study only considers the additional vapour flow due to diffusion. Convective moisture transports significantly more water vapour into the construction. This occurs especially if there are hollow spaces in the interior insulation area, e.g. at the joints of sheetings.

Table 8: Sheeting sd value and respective equivalent sd value with leakage at 1 m and 0.5m for each square metre of wall area.

Sheeting sd value	equivalent sd value	
Without leak	with 0.5 m/m²	with 1.0 m/m²
[m]	[m]	[m]
100	25	10
20	12	7
10	7	5
2	2	2
0.2	0.2	0.2

Interior insulation systems with more vapour diffusion open sheeting ensure that a certain amount of leakage does not lead to failure.

6.7 Summary

Based on the variations in climate boundary conditions, wall materials and interior insulation systems, the moisture content of the interior insulation was assessed as a first step. An impression was provided showing the parameters which were relevant for the behaviour of the system as a whole. Exposed masonry is especially sensitive to varying driving rain exposure. This raises questions regarding the assessment of functional reliability, which are difficult to answer. The suitability of an interior insulation system accordingly depends not so much on the insulation system but rather on the climate-relevant and building physical properties of the existing wall. Functional solutions can be generated for many combinations (climate - wall material - interior insulation), but these always require an exact knowledge of the local boundary conditions as well as the quality of the wall. Based on current knowledge, a general demand for hydrophobisation of the facade without exact knowledge of the specific values of the materials is not recommended. A targeted analysis specific to the location and type of brick has proved to be the safest way of ensuring a wall assembly that is permanently damage-free, and for coordinating any hydrophobisation measures that may be necessary. Consideration of the moisture content in the interior insulation system provides information about particularly demanding climate regions and initial indications regarding interior insulation systems which usually lead to critical outcomes.

It is apparent that in the hot climate regions studied (Athens, Madrid, Malaga and Palermo), it is possible to produce interior insulation systems using different materials. Diffusion-open vapour retarders (sd<2 m) are necessary if mineral wool is used. Capillary active interior insulation systems prove more advantageous than non-capillary active systems, particularly in the cold and the coastal climate regions. However, it is not possible to derive general recommendations from this since further investigation in this regard can also result in functional systems.

In the case of plastered masonry, the influence of the location is much less provided that exterior plasters exist which are adapted for the respective rain exposure. The characteristics of the insulation system will dominate in this case. Satisfactory results were achieved for the reference models considered here.

In a further step, models were developed which allow testing of the system with reference to its susceptibility to structural damage. Leakages result in considerably higher moisture inside the building component and they are a frequent cause of structural damage. Air flow passing through a leak from the inside towards the outside depends firstly on the wind suction which affects the facade, and secondly on the pressure difference which exists due to the differences between the inside and the outside climate. The results showed that individual leakages which passed directly from the inside towards the outside did not cause moisture accumulation inside the construction, and that air flow behind the interior insulation leads to structural damage regardless of whether or not the leakage path leads towards the outside. Fault-tolerant interior insulation systems should therefore include solutions which constructively prevent air flow behind insulation (e.g. full surface application of adhesive etc.).

6.8 Outlook

Refurbishment of historic listed buildings using interior insulation is an important measure for preserving historical assets and at the same time it is an essential measure for reducing their energy demand and improving thermal comfort. Uncertainties and reservations still exist to a large extent with regard to assessment of interior insulation systems. As a first step, the criteria for assessing planning were prepared and compiled in the form of a checklist. As a further step, functioning systems will be determined for climates similar to Europe. This parameter study will provide an overview of the hygrothermal behaviour of interior insulation systems in climatic regions similar to Europe and with various wall materials. Furthermore, it will provide an initial impression of the reliable system components which are possible. However, assessment of structural integrity cannot be made based on the moisture content of the interior insulation alone. Simulations of interior insulation systems for the climate in Germany have shown that to some extent, even interior insulation systems which are free of condensation exhibit a considerable risk of mould at the old interior plaster layer; further investigations regarding this would be appropriate.

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8 Certification criteria (annex)

EnerPHit

Certification criteria for energy retrofits with Passive House components

If an energy retrofit of an existing building meets Passive House criteria (for new builds), it, too, can be certified as a Certified Passive House.

It is, however, often difficult to feasibly achieve the Passive House Standard in older buildings for a variety of reasons. Passive House technology for relevant building components in such buildings does, nevertheless, lead to considerable improvements with respect to thermal comfort, structural longevity, cost-effectiveness over the building lifecycle and energy use.

Buildings that have been retrofitted with Passive House components can achieve EnerPHit certification as evidence of both building quality and fulfilment of specific energy values. The EnerPHit^{+i} designation (with superscript "+i") is applied if more than 25 % of the opaque exterior wall surface has interior insulation[4].

9 EnerPHit requirements according to climate zones

The building's location is allocated to a climate zone according to the map in the annex (Section 13.4). With the following table the applicable requirements can be derived for each climate zone. Additional explanations for the requirements tables can be found in section 10.

[4] Not applicable in warm, hot and very hot climate zones.

			Arctic	Cold	Cool-temperate	Warm-temperate	Warm	Hot	Very hot
		Climate zone	Arctic	Cold	Cool-temperate	Warm-temperate	Warm	Hot	Very hot
		Building component inclination							
Always compulsory	Minimum insu-lation	Hygiene, $f_{Rsi=0.25\ m^2K/W}$	≥ 0.8	≥ 0.75	≥ 0.7	≥ 0.6	≥ 0.55	-	-
		Comfort, U [W/(m²K)] ≤	0,45 | 0,50 | 0,60 | 0,35	0,65 | 0,70 | 0,80 | 0,50	0,85 | 0,90 | 1,00 | 0,65	1,10 | 1,15 | 1,25 | 0,85	1,35 | 1,40 | 1,50 | 1,00	1,60 | 1,65 | 1,75 | -	1,35 | 1,40 | 1,50 | 1,00
	Air-tight-ness	n_{50} [1/h]				≤ 1.0			
	Pass. cool-ing	Frequency of overheating (>25°C)				≤ 10 %			
	PE	Primary energy demand [kWh/(m²a)]		$Q_P \le 120$ kWh/(m²a) + [(Q_H - 15 kWh/(m²a)) • 1.2]*+ [Q_C - $Q_{C,\ Passive\ House\ requirement}$]**					
Certification by component quality	Window	$U_{W,\ installed}$ [W/(m²K)] ≤	0,45 | 0,50 | 0,60 | -	0,65 | 0,70 | 0,80 | -	0,85 | 0,90 | 1,00 | -	0,85 | 0,90 | 1,00 | -	1,30 | 1,35 | 1,45 | -	1,30 | 1,35 | 1,45 | -	0,85 | 0,90 | 1,00 | -
		If active heating present	$U_g - g*0.7 \le 0$	$U_g - g*1.0 \le 0$	$U_g - g*1.6 \le 0$	$U_g - g*2.8 \le -1$	$U_g - g*5.2 \le -2.3$	-	-
		If active cooling present: Solar load [kWh/m²$_{window}$a]				≤ 100			
	Door	U_D [W/(m²K)] (without installation thermal bridge)	≤ 0.35	≤ 0.55	≤ 0.75	≤ 0.75	≤ 1.20	≤ 1.20	≤ 0.75
	Opaque envelope against ambient air	Exterior insulation [W/(m²K)]	≤ 0.09	≤ 0.12	≤ 0.15	≤ 0.25	≤ 0.50	≤ 0.50	≤ 0.25
		Interior insulation [W/(m²K)]	≤ 0.25	≤ 0.30	≤ 0.35	≤ 0.45	≤ 0.75	≤ 0.75	≤ 0.45
		Exterior paint	-	-	-	-	-	Cool colours	Cool colours
	Opaque envelope against ground			Determined in PHPP from project specific heating and cooling degree days against ground.					
	Ventilation	Heat recovery	≥ 80%	≥ 80%	≥ 75%	≥ 75%	-	≥ 70%	≥ 70%
		Humidity recovery	Yes	Yes	-	-	-	≥ 60 % (in humid climate)	≥ 60 % (in humid climate)
Alter-natively		Space heating demand [kWh/(m²a)]	≤ 35	≤ 30	≤ 25	≤ 20	≤ 15	-	-
		Space cooling demand [kWh/(m²a)]			Determined in PHPP from project specific climate and building use.				

*only to be added if Q_H - 15 kWh/(m²a) > 0 kWh/(m²a) ** only to be added if $Q_C - Q_{C,\ Passive\ House\ requirement}$ > 0 kWh/(m²a)

10 Additional explanations for the requirements table

The following sections contain additional explanations for the table columns with the respective identical heading, as necessary.

10.1 “Always compulsory”

These minimum requirements apply always, independently of the certification method. They still have to be fulfilled when any exemptions according to Section 10.2.4 are applicable.

10.1.1 “Minimum insulation”

The requirements for hygiene (mould prevention) and thermal comfort are applicable for each individual component separately (e.g. wall assembly, window, connection detail). Contrary to the requirements from Section 10.2 it is not allowed to use a mean value for various different components in order to fulfil the requirements.

10.1.1.1 “Hygiene” (Protection against moisture)

Apart from the interior surfaces temperature requirements named in the table ($f_{Rsi=0.25\ m^2K/W}$), all standard cross-sections and connection details, without exception, must be planned and executed so that excessive moisture on the interior surface or in the building component build-up can be ruled out.

Should there be any uncertainty, evidence of protection against moisture must be provided in accordance with accepted technical standards.

For building components with interior insulation, evidence of careful planning that would prevent indoor air currents behind the insulation layer must be provided. For interior insulation, components with proven suitability with regard to moisture protection must be used for the specific application. In case of doubt, proof of suitability with regard to moisture protection which is based on accepted methods must be provided by means of a corresponding expert's report (with legally effective acceptance of responsibility). This usually takes place through a hygrothermal simulation.

10.1.1.2 “Comfort”

Alternatively, comfort requirements are met if a verification of comfort conditions according to EN ISO 7730 is presented.

Exceeding the limiting value for windows and doors is permitted if, in case of thermal comfort concerns, low temperatures occurring on the interior surface are compensated by heating surfaces (verification with ISO 7730).

For components towards ground the U-value requirement can be divided by the reduction factor f_T („ground reduction factor“ from the PHPP “Ground” worksheet).

For inclined components the required value for the respective inclination closest to the real inclination is applicable (according to drawing „building component inclination“ in the requirements table). There is no interpolation between two requirements.

10.1.2 “Airtightness”

If the air tightness test yields values from 0.6 h^{-1} to 1.0 h^{-1}, comprehensive leak detection must be carried out within the framework of a pressure test during which individual leaks that can cause building damage or impair comfort are sealed. This must be confirmed in writing and signed by the person in charge in accordance with Section 13.3.

10.1.3 “Primary energy demand”

The primary energy demand includes all necessary energy applications for heating, cooling, domestic hot water, auxiliary electricity, lighting, and other electricity uses. The limit value applies for residential buildings, office buildings, schools and other similar uses and further as a preliminary criterion which must be checked for specific uses. In individual cases where a very high energy demand is necessary, this limit value can be exceeded after agreement with the Passive House Institute. For this, evidence of efficient use of electrical energy is necessary, with the exception of existing electricity uses for which an improvement of the electrical efficiency by means of upgrading or renewal would prove uneconomical over the lifecycle (see 13.1.3).

10.2 "Certification by component quality"

Certification can take place based on the requirement for individual building components (this Section) or on the requirements for the space heating and space cooling demand (Section 10.3). Compliance with only one of the two methods is required.

Required limit values must not be exceeded on average[5] for the entire building. A higher value is permissible in some areas if this is compensated for by lower values in other areas.

The requirements named in the table typically correspond to the criteria for certified Passive House components. For products not certified by the PHI, the applicant is responsible for providing evidence that the specific component criteria have been met. Evidence of compliance must be recorded in writing and confirmed with a legally binding signature It is the responsibility of the certifier to ensure that this has been done.

10.2.1 "Windows"

10.2.1.1 "$U_{w,installed}$" (window U value including the installation thermal bridge)

For inclined components the required value for the respective inclination closest to the real inclination is applicable. There is no interpolation between two requirements. For the component itself the glazing U value U_g has to be used which corresponds to the real inclination.

10.2.1.2 "If active cooling present: Solar load"

The limiting value refers to the solar irradiation entering the building after consideration of all reduction factors for shading, etc.. The mean value of all windows per orientation, for example all south-facing windows, has to be lower than the limiting value. If the limiting value has been exceeded, suitable measures have to be taken to reduce the solar load until compliance is achieved. Suitable measures include moveable shading elements, shading overhangs and sun protective glazings (last ones only in pure cooling climates)

10.2.2 "Opaque envelope against"

[5] Note: When calculating average values for insulated building component assemblies, the area weighted mean of the U-value, not the average insulation thickness, applies. Thermal bridges must only be taken into account during the calculation of the average value if they are part of the standard structure of the building component. For multiple ventilation systems, the average value weighted by volumetric flow applies.

If the heat transfer resistance (R-value) of existing building components is taken into account for the improvement of the heat transfer coefficients (U-value) of modernised building components, this must be demonstrated in accordance with the accepted technical standards. It is sufficient to adopt a conservative approximation of the thermal conductivity of the present building materials from suitable reference charts. If building component assemblies of existing buildings are not clearly identifiable, standardised estimates according to the year of construction as taken from appropriate component catalogues[6] can be used as long as these are comparable with the component at hand.

In refurbishments of existing buildings, it is not always possible to largely eliminate thermal bridge effects ($\Psi_{ext} \leq +0.01$ W/(mK)) with justifiable effort as is necessary for Passive House new builds. Nevertheless, thermal bridge effects must always be avoided or minimised as much as possible while ensuring cost-effectiveness (see 11.3) Thermal bridges that are part of the standard structure of a building component are taken into account in the evaluation of the heat transfer coefficient.

10.2.2.1 “Opaque envelope against ground”

Please note:The requirement for “opaque envelope against ground” depends on the building geometry and the properties of other components. Thus the requirement may change, if one of these is changed.

10.2.2.2 “Exterior paint”

Cool Colours: Colours, which have a low absorption coefficient in the infrared part of the solar spectrum.

The requirement to use *Cool Colours* does not apply for areas which cannot be painted or which should not be painted (for example facing brickwork) or for areas which are not exposed to strong solar irradiation (shaded or non-sunny areas).

10.2.3 “Ventilation”

All rooms within the heated building volume must be served by a mechanical ventilation system.

10.2.3.1 “Heat recovery”

The requirements for heat recovery must be complied with by the entire ventilation system going over and above the criteria for Certified Passive House components, i.e. the heat

[6] E.g. "EnerPHit -Planerhandbuch", PHI 2012 (available in German only)

losses from warm ventilation ducts in cold areas or cold ducts in the warm areas should also be included. In cooling climates, the excess heat from fans reduces the efficiency of the heat recovery as it is an additional heat load. This has to be considered when determining the heat recovery efficiency.

10.2.3.2 „Humidity recovery“

In the arctic and cold climate zone, humidity recovery from extract air is required in order to avoid very low relative humidity in the rooms. By using humidity recovery, it can be assured that the relative humidity inside the building continuously remains above 30% most of the time. Alternative measures are permissible if they lead to the same goal.

10.2.4 Exemptions

The limit values for the heat transfer coefficients of the exterior envelope building components may be exceeded if absolutely necessary for one or more of the following compelling reasons:

- If required by the historical building preservation authorities
- If the cost-effectiveness (see 13.1.3) of a required measure is no longer assured due to exceptional circumstances or additional requirements
- In the presence of specific legal requirements
- If implementation of the required standard of thermal insulation would result in unacceptable restriction of the use of the building or adjacent outer areas
- If special, additional requirements (e.g. fire safety) exist and there are no components available on the market that comply both with these additional requirements and the EnerPHit criteria
- Should other essential reasons relating to construction exist

For heat transfer coefficients > 0.35 W/(m²K), the maximum possible insulation thickness must be implemented using insulating materials having a thermal conductivity of $\lambda \leq 0.025$ W/(mK). In the case of floor slabs and basement ceilings, the additional use of a surrounding insulation skirt should be considered and implemented if applicable.

If a standard requirement is exceeded on the basis of an exception, clear evidence that the conditions for this exception have been fulfilled must be provided in the form of suitable documents that have been signed by the person in charge.

If a significant reduction in heating demand or cooling demand is not achievable due to extensive use of exceptional rules, a written confirmation regarding the values achieved may be issued in place of an EnerPHit certificate at the discretion of the certifier.

10.3 "Alternatively" (Certification according to space heating and space cooling demand)

Certification can take place based on the requirement for individual building components (see Section 10.2) or on the requirements for the space heating and space cooling demand (this Section). Compliance with only one of the two methods is required.

10.3.1 "Space cooling demand"

The space cooling demand requirement is calculated in the PHPP depending on the local climate and the building use according to the following specifications:

Cooling[7] (including dehumidification[8])

Total cooling demand			≤ 15 kWh/(m²a) + 0.3 W/(m²aK) · DDH
or alternatively:		cooling load	≤ 10 W/m²
	AND	cooling demand	≤ Q_{sens} + 0.3 W/(m²aK) · DDH

[7] DDH: Drying degree hours (time integral of the difference between the dew-point temperature and the reference temperature of 13 ℃ throughout all perio ds during which this difference is positive)

Q_{sens}: Permissible sensible cooling demand, calculated from a generalized monthly energy balance including the internal heat gains, standard values for the solar load and the thermal conductance, and heat losses for summer ventilation. Q_sens is calculated from the IHG and the climatic data in the PHPP.

[8] The partial requirement for dehumidification is described by the term '0.3 W/(m²aK) · DDH'.

11 Other general requirements

For certification, the valid Certification Criteria (available at www.passivehouse.com) apply and take precedence over the calculation methodology described in the PHPP User Guide and the PHPP application software, which shall apply subordinately.

Due to the large number of requirements for retrofits of existing buildings, it is possible that absolutely precise requirements for some individual energy-related measures are not included in the certification criteria. In this case, the measure should be implemented in such a way that energy efficiency is improved as much as possible, provided that the measure is cost-effective over its lifecycle (see 13.1.3). The standard of thermal protection necessary for the building component will then be determined by the certifier on a case by case basis (in cooperation with the PHI for highly relevant, exemplary cases).

11.1 Energy balance

The energy balance of the retrofit must be verified using the latest version of the Passive House Planning Package (PHPP). However, transfer of data to a newer PHPP version published when the project is already under way is not necessary. The monthly method is used for the specific heating demand. The reference value is the treated floor area (TFA) calculated in accordance with the current PHPP User Guide.

The entire building envelope, e.g. a row of terraced houses or an apartment block, can be taken into account for calculation of the specific values. An overall calculation can be used to verify this. If all zones have the same set temperature, then a TFA weighted average value from single PHPP calculations of several partial zones can also be used. Combining thermally separated buildings is not permissible. Buildings that adjoin other buildings (e.g. in high-density urban areas) must have at least one exterior wall, one roof surface and a floor slab or basement ceiling in order for them to be certified individually.

11.2 Time of certification

All requirements for the building must be met upon issuance of the certificate. Currently, certificates cannot be issued in advance for retrofits that are being carried out in several steps.

11.3 Restriction to existing buildings

Only buildings for which modernisation to the Passive House Standard would be uneconomical (see 13.1.3) or not practically implementable due to the existing building characteristics or building substance will be certified. In principle, an EnerPHit certificate cannot be issued for new builds.

12 Evaluation procedure

An informal application for the certificate can be made with the chosen Passive House Institute accredited Building Certifier. The required documents must be filled in completely and submitted to the certifier. The certification documents must be checked at least once. Depending on the procedure, further checks may also be arranged.

Note: If possible, checking of the EnerPHit Standard relevant documents should be carried out during the planning stage so that any necessary corrections or suggestions for improvement can be taken into account at an early stage.

After the assessment the client will receive the results, with corrected calculations and suggestions for improvement, if applicable. Inspection of the construction work is not automatically covered by the certification. However, evidence of the building's airtightness, the HRV commissioning report, the construction manager's declaration and at least one photograph must be provided. If the technical accuracy of the documentation necessary is confirmed and the aforementioned criteria are fulfilled, the following seal will be issued:

EnerPHit
Certified Retrofit
Passive House Institute

The awarding of the EnerPHit certificate verifies the correctness of the documents submitted only in accordance with the EnerPHit Standard as defined at the time of certification. The assessment relates neither to the monitoring of the work, nor to the supervision of the user behaviour. The liability for the planning remains with the responsible technical planners, and the liability for the implementation lies with the appropriate construction management. The EnerPHit seal may only be used in connection with the associated certificate as issued.

Additional quality assurance of the construction work by the certifying body is particularly useful if the construction management has no previous experience with the retrofits using Passive House components.

Passive House Institute reserve the right to adapt criteria and calculation procedures to reflect technical advances and developments.

13 Annex

13.1 Documents necessary for certification

13.1.1 Signed PHPP with at least the following calculations:

(Please also attach the Excel file) **PHPP worksheet:**

- ☐ Property data, summary of results .... **Verification**
- ☐ Selection of the climatic region or specification of individual climate data, ... **Climate**
- ☐ Calculation of U-values of regular building elements .... **U-values**
- ☐ Summary of areas with allocation of radiation balance data, thermal bridges .... **Areas**
- ☐ Calculation of reduction factors against ground, if used .... **Ground**
- ☐ Building component database .... **Components**
- ☐ Determination of the U_W-values .... **Windows**
- ☐ Determination of shading coefficients .... **Shading**
- ☐ Air flow rates, heat recovery efficiency, input of pressurisation test results .... **Ventilation**
- ☐ Dimensioning and planning of ventilation systems with several ventilation units (if used) ... **Additional vent**
- ☐ Calculation of the heating demand using monthly method based on EN 13790 .... **Heating**
- ☐ Calculation of the heating load of the building[9] .... **Heating Load**
- ☐ Determination of summer ventilation .... **SummVent**
- ☐ Assessment of summer climate[5] .... **Summer**
- ☐ Specific value of useful cooling (if active cooling is used) [5] .... **Cooling**
- ☐ Latent cooling energy (if active cooling is used) [5] .... **Cooling Units**
- ☐ Heating distribution losses; DHW demand and distribution losses .... **DHW+Distribution**
- ☐ Solar DHW provision (if solar heating system is present) .... **SolarDHW**
- ☐ Utilisation profiles (only for non-residential buildings) .... **Use non-res**
- ☐ Calculation of shared and domestic electricity demand (only for residential buildings) .... **Electricity**
- ☐ Calculation of electricity demand (only for non-residential buildings) .... **Electricity non-res**
- ☐ Calculation of the auxiliary electricity demand .... **Aux Electricity**
- ☐ Calculation of internal heat gains (only for residential buildings) .... **IHG**
- ☐ Calculation of internal heat gains (only for non-residential buildings) .... **IHG non-res**
- ☐ Calculation of the primary energy value .... **PE Value**
- ☐ Annual utilisation factor for heat generators .... **Compact, HP, HP Ground, Boiler or District Heating**

[9]The PHPP calculations for the heating load, summer ventilation and cooling load have been developed for buildings with homogeneous utilisation. More in-depth studies/other methods should be referred to for buildings with intermittent ventilation or heating operation and greatly fluctuating internal loads.

13.1.2 Planning documents for design, construction, building services

- ☐ Site plan including the building orientation, neighbouring structures (position and height), prominent trees or similar vegetation and possible horizontal shading from ground level elevations along with photographs of the plot and surroundings. The shading situation must be made clear.
- ☐ Design plans (floor plans, sections, elevations) with comprehensible dimensioning for all area calculations (room dimensions, envelope areas, unfinished window opening sizes).
- ☐ Location plans of envelope areas and windows as well as thermal bridges if present, for clear allocation of the areas or thermal bridges calculated in the PHPP.
- ☐ Detailed drawings of all building envelope connections, e.g. the exterior and interior walls at the basement ceiling or floor slab, exterior wall at the roof and ceiling, roof ridge, verge, installation of windows (laterally, above and below), attachment of balconies etc. The details should be given with dimensions and information about materials used and their conductivities. The airtight layer should be indicated along with details as to how it is to be maintained at junctures during construction.
- ☐ Proof of protection against moisture (should their be uncertainty)
- ☐ Building services plans for ventilation: representation and dimensioning of ventilation units, volumetric flows (Final Protocol Worksheet for Ventilation Systems: 'Design', see PHPP CD), sound protection, filters, supply and extract air valves, openings for transferred air, outdoor air intake and exhaust air outlet, dimensioning and insulation of ducts, sub-soil heat exchanger (if present), regulation, etc..
- ☐ Building services plans for heating, cooling (if present), plumbing: representation of heat generators, heat storage, heat distribution (pipes, heating coils, heating surfaces, pumps, regulation), hot water distribution (circulation, single pipes, pumps, regulation), cold water pipes, aerated drain pipes including their diameters and insulation thicknesses.
- ☐ Building services plans for electrical fittings (if used): representation and dimensioning of lighting (concepts or simulations for the use of daylight also, if applicable), elevators, kitchen equipment, computers, telecommunication systems and other specific uses of electricity (e.g. furnaces).
- ☐ Building services plans for air conditioning (if used): representation and dimensioning of cooling and dehumidification systems

13.1.3 Supporting documents and technical information, with product data sheets if applicable

- ☐ Details of the project-specific conditions mentioned under point 5.
- ☐ If applicable, required evidence for exemptions: e.g. economic feasibility analysis[10], written confirmations by the historical building preservation authority, copy of the legal requirements/ordinances, sections from plans.
- ☐ Manufacturer, type and technical data sheets, especially of insulation materials with very low conductivity (λ_R < 0.032 W/(mK)).
- ☐ Comprehensible specification of the treated floor area calculation.
- ☐ Information about the window and door frames to be installed: manufacturer, type, U_w value, $\Psi_{Install}$, $\Psi_{Glazing\ Edge}$ and graphical representations of all planned installations in the exterior wall. The calculation values should be mathematically computed in accordance with EN 10077-2. These verifications are available for products that have been certified[11] by the Passive House Institute.
- ☐ Information about the glazing to be fitted: manufacturer, type, build-up, U_g value according to EN 673 (to two decimal places) g-value according to EN 410, type of edge spacer.
- ☐ Evidence regarding the thermal bridge loss coefficients used in the PHPP based on EN ISO 10211. Alternatively, reference can be made to comparable documented thermal bridges (e.g. in certified Passive House construction systems, PHI publications, Passive House thermal bridge catalogues).
- ☐ Short description of the planned building services supply systems, with schematic drawings if applicable.
- ☐ Manufacturer, type, technical data sheets and verification of the electricity demand of all building services components: ventilation system, heat generator for heating and hot water, heat storage, insulation of ductwork and pipes, heating coils, freeze protection, pumps, elevator, lighting etc.
- ☐ Heat recovery efficiency and electricity demand of the ventilation system in accordance with the Passive House method. Exhaust air systems with heat recovery (e.g. fume hoods and fume cabinets etc.) should be included. Different operating settings and operation times should be taken into account.
- ☐ Information about the sub-soil heat exchanger (if present): length, depth and type of installation, soil quality, size and tube material and verification of the heat recovery efficiency (e.g. with PHLuft[12]). For sub-soil brine heat exchangers: regulation, temperature limits for winter/summer, verification of the heat recovery efficiency
- ☐ Information about the length, dimensioning and insulation level of the supply pipelines (hot water and heating as well as cooling, if present) as well as the ventilation ducts between the heat exchanger and thermal building envelope.
- ☐ Concept for efficient use of electricity (e.g. specific devices, instructions and incentives for the building owner). If efficient electricity utilisation is not verified, average values for devices available on the market will be used (standard PHPP values).
- ☐ Summer comfort must be provided for the buildings to be certified. The PHPP method for determination of summer overheating initially only depicts an average value for the entire building; individual parts can still

[10] Economic feasibility calculation (dynamic valuation method, e.g. net present value method) in accordance with PHI recommended methodology and in coordination with the certifier – must be carried out over the lifecycle of the building component and include all relevant costs minus costs that would have anyway been incurred); see more detailed description in " Wirtschaftlichkeit von Wärmedämm-Maßnahmen im Gebäudebestand 2005" (in German), available for download from www.passivehouse.com.

[11] Data sheets for certified components can be found on www.passivehouse.com.

[12] PHLuft: Programme facilitating planning of Passive House ventilation systems. Free download from www.passivehouse.com.

become overheated. If this is suspected, a more in-depth examination must be carried out (e.g. by means of a transient simulation).

13.1.4 Verification of the airtight building envelope

The airtightness measurement is carried out in accordance with EN 13829 or ISO 9972. In case of differences or uncertainty, the EN 13829 standard is to be used. A series of measurements is required for positive pressure and negative pressure, in deviation from the standard. The pressure test should only be carried out for the heated building volume (basement, porches, conservatories etc. that are not integrated into the thermal envelope of the building should not be included in the pressure test). It is recommended that the test be carried out when the airtight layer is still accessible so that needed repairs can be more easily carried out. The pressure test report should also document the calculation of the indoor air volume.

In principle, the pressure test should be carried out by an institution or person independent of the client or contractor. A pressure test that has been carried out by the client will only be accepted if the test result is signed by someone taking personal responsibility for the accuracy of the information provided.

13.1.5 HRV commissioning report

The report must at least include the following: description of the property, location/address of the building, name and address of the tester, time of adjustment, ventilation system manufacturer and type of device, adjusted volume flow rates per valve for normal operation, mass flow/volumetric flow balance for outdoor air and exhaust air (maximum unbalance of 10%). Recommended: “Final Protocol Worksheet for Ventilation Systems”, source PHPP CD or www.passivehouse.com.

13.1.6 Construction manager's declaration

Execution according to the reviewed PHPP project planning must be documented and confirmed with the construction manager's declaration. Any variation in construction should be mentioned; if any of the products used deviate from those included in the project planning, evidence of compliance with criteria must be provided.

13.1.7 Photographs

Photographs documenting construction progress should be provided; digital images are preferable.

It may be necessary to provide additional test reports or data sheets for the components used in the building. If values that are more favourable than those in the standard PHPP procedure are to be used, these should be supported by evidence.

13.2 Calculation methods, conditions, standard references

The following boundary conditions or calculation rules should be used in the PHPP:

- ☐ Climate data: regional data set (suitable for location, for deviating altitudes with temperature correction of – 0.6 ℃ per 100 m increase in altitude).
- ☐ Individual climate data: applicability is to be agreed previously with the relevant certifier. If climate data are already available in the PHPP, these should be used.
- ☐ Design indoor temperature:
  Residential buildings: 20 ℃ without night set-back.
  Non-residential buildings: the standard indoor temperatures based on EN 12831 apply. For unspecified uses or deviating requirements the indoor temperature is to be determined for the specific project. For intermittent heating (night setback), the indoor design temperature may be lowered upon verification.
- ☐ Internal heat gains: the PHPP contains standard values for internal heat gains in a range of utilisation types: apartments (2.1 W/m²), offices (3.5 W/m²), schools/kindergartens/gymnasiums (2.8 W/m²) and nursing homes (4.1 W/m²). These are to be used unless the PHI has specified other national values. The use of the individually calculated internal heat gains is only permitted if it can be shown that actual utilisation will and must differ considerably from the utilisation on which the standard values are based.
- ☐ Occupancy rates:
  Residential buildings: 35 m²/person, deviating values are permitted if the reason is given (actual occupancy or design parameters) within the 20-50 m²/person range
  Non-residential buildings: occupancy rates and periods of occupancy must be determined on a project-specific basis and coordinated with the utilisation profile.
- ☐ Domestic hot water demand:
  Residential buildings: 25 litres per person per day at 60 ℃, provided t hat no other national values have been set by the PHI.
  Non-residential buildings: Domestic hot water demand in litres of 60 ℃ wate r per person and day must be determined for each specific project.
- ☐ Average ventilation volumetric flow:
  Residential buildings: 20-30 m³/h per person in the household, but at least a 0.30-fold air change with reference to the treated floor area multiplied by 2.5 m room height.
  Non-residential buildings: Average ventilation volumetric flow must be determined for the specific project based on a fresh air demand of 15-30 m³/h per person (or according to the applicable legal requirements, if present). The different operation settings and times of the ventilation system must be considered. Operating times for pre-ventilation and post-ventilation should be taken into account when switching off the ventilation system. The mass flows used must correspond with the actual adjusted values.
- ☐ Electricity demand:
  Residential buildings: standard values according to the PHPP, deviating values only if individually verified by the client or domestic electricity concept.
  Non-residential buildings: the electricity demand is to be determined on a project-specific basis according to the PHPP. A building utilisation profile with occupancies and occupancy times should be prepared. Without a plan of the lighting to be installed or details as to other electricity uses, standard values as per the PHPP are to be used.
- ☐ Thermal envelope surface: exterior dimension reference without exception.
- ☐ U-value of opaque building components: PHPP procedure on the basis of EN 6946 with conductivity values according to national standards or building authority regulations.
- ☐ U-values of windows and doors: PHPP procedure with computed values in accordance with EN 10077 for the frame U-value (U_f), the glazing edge thermal bridge (Ψ_g), and the installation thermal bridge ($\Psi_{Install}$).

- □ Glazing: computed U-value (U_g; to two decimal places) in accordance with EN 673 and g-value in accordance with EN 410.
- □ Heat recovery efficiency: testing method in accordance with the PHI (see www.passivehouse.com); if applicable, auxiliary test result according to the DIBt method (or equivalent) with a deduction of 12 % after consultation with the certifier.
- □ Energy performance indicator of the heat generator: PHPP method or separate verification.
- □ Primary energy factors: PHPP dataset.

13.3 Confirmation of detection and sealing of leaks during the pressurisation test

(Only necessary if $0.6\ h^{-1} < n_{50} \leq 1.0\ h^{-1}$)

Standard text:

It is hereby confirmed that a search for leaks was carried out during the pressurisation test. All rooms within the airtight building envelope were accessed for this purpose. All potential weak points were checked for leaks. This also applies in the case of areas which were difficult to access (e.g. large room heights). Any larger leaks that were found having a relevant share of the total leakage volumetric flow were sealed.

The following information is necessary:

- Name, address, company of the person signing
- Date and signature
- Description and address of the construction project
- Pressurisation test: date and name of the person carrying this out

13.4 Climate zone map