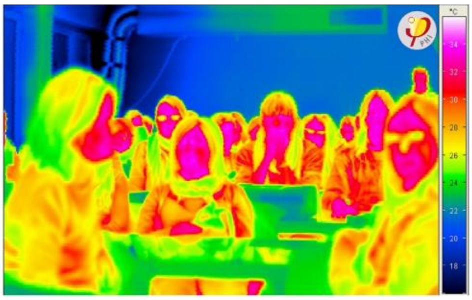
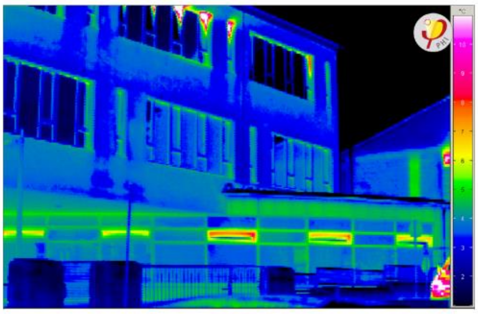
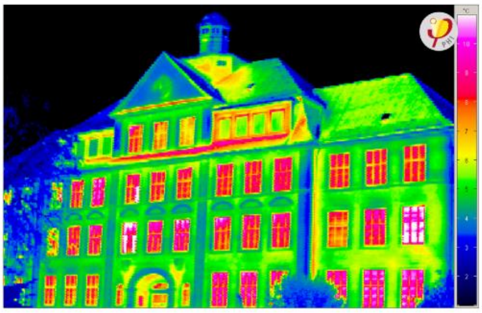
Passive House Institute

Handbook for energy-efficient educational-use buildings







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Scope of content / Disclaimer

This publication deals mainly with the sub-topic of energy aspects of educational buildings, therefore it does not claim to cover all other aspects that are essential for the planning and implementation of schools, sports halls for schools and day care centres.

The content of this publication has been compiled with the greatest care and to the best of our knowledge and belief. Nevertheless, with regard to the use of the information provided here each user must independently check the legal requirements and standards or ordinances. Any liability for accuracy and completeness of the contents and data, and in particular for any damage arising from the use of the presented material or consequences thereof, is excluded.

1 Contents

2 Introduction

In the next few years, children's day care is to be expanded significantly; for example, by the year 2013 a day care place must be created for every third child under the age of three (compared with 2007 this would mean around 500,000 nursery places). At the same time, more full day-care places will be offered.

In Germany there are more than 40,000 schools, many of which are in need of renovation. Expansion of all-day schooling with meals also necessitates the provision of suitable facilities.

There is an acute need for construction and modernisation in the area of educational buildings. The energy demand for space heating and hot water for the next 30 to 40 years is determined today by a construction measure. Energy efficiency and improved comfort can be experienced directly in schools, day-care centres and sports halls, and is becoming more and more widespread through replication in the region. Municipalities should therefore set an example specifically in this area.

With topics relating to energy efficiency and comfort in educational buildings, this handbook addresses construction authorities, planners and those involved in construction. The planning and construction process should be supported through arguments for more energy efficiency, examples and practical know-how.

This handbook will deal with the special features of energy efficient schools, day-care centres and school sports halls. High occupancy rates in recreation rooms and shorter usage times in general (e.g. compared to office buildings) are typical for schools and day-care centres. With their large room heights and usually low occupancy rates, sports halls differ from the above-mentioned building types.

What are energy efficient educational buildings?

The European Commission requires each member state to introduce a national early zero emery standard by the year 2020 for new constructions and for buildings that are to be extensively modernised (revised "EU Directive for overall energy efficiency of buildings"). This requirement will already be applicable for public buildings in 2018. Another revision of the German energy savings ordinance has already been announced for 2012. The signs are all pointing towards energy efficiency!

Educational-use buildings act as exemplary models and are built for the future. Accordingly, the efficiency measures described below exceed the usual norm. The large number of educational-use buildings that have now been constructed proves that the Passive House Standard for new constructions brings together energy savings and improved comfort for the uses being considered here. The following recommendations for new energy efficient educational-use buildings are therefore based on the Passive House Standard.

"Seizing the opportunity" is a good approach in the case of modernisations. As far as possible, extensive use should be made of renewal or repair measures for improving the thermal situation of the building at the same time (see [AkkP 39]), because carrying out an energy-relevant improvement later on will no longer be worthwhile in the case of a building component that is renovated only to a moderate extent; building components that are only moderately modernised today constitute the problem areas of the future. The time point of the modernisation plays a less significant role provided that improved efficiency is achieved to a large extent. As profitability calculations on the basis of life cycle assessment have shown, the economically optimum measures have shifted significantly towards improved efficiency (see [Kah et al 2008]). Even without public subsidies, Passive House suitable insulation thicknesses and windows with triple low-e glazing are within the economic range today.

Main topic: indoor air quality

Numerous studies have proved that the air quality inside schools and day-care centres is poor. Often, adequate ventilation via windows is hardly realisable due to the high occupancy rates. Added to this is the fact that the large air quantities that are necessary quickly lead to draughts. Air quality in educational-use buildings should matter to us; there is evidence that children are more sensitive to indoor air pollution as they breathe in larger amounts of air in relation to weight, and their organs are still developing (see [Faustman et al. 2000], [Landrigan 1998]).

Insights were gained from these experiences which showed that a good quality of air in schools and day care centres is implementable only with a controlled ventilation system.

As a key component of the Passive House Standard, an efficient ventilation system with heat recovery also saves a significant amount of energy in addition to improving the air quality. This handbook will therefore also deal in detail with the subject matter of air quality and concepts for efficient controlled ventilation.

Win-win situation for municipalities

The advantages of measures for improving energy efficiency in buildings are compelling and aren't just restricted to the resultant energy savings. The following aspects are important when making decisions relating to investments:

- Comfort: controlled ventilation with heat recovery sustainably improves air quality in schools and day-care centres. In addition, a good level of thermal protection particularly in existing buildings provides for more comfortable and healthy conditions.

- Preservation of building substance: an improved standard of thermal protection preserves the building substance and results in increased value of the property. A specific problem in existing buildings is mould growth. Studies have shown that fungus growth can occur even before the formation of condensation (see e.g. [Sedlbauer 2002]). The conditions are particularly critical if there is furniture placed next to exterior walls or near exterior wall corners. A good level of thermal protection and controlled air flow and ventilation also help prevent fungus growth in the long term.
- Contribution to climate protection: a significant share of the energy consumption in Germany is used for low temperature heat, in particular for heating purposes. A reduced heating demand and thus lower CO_2 emissions constitutes an active contribution to climate protection.
- Planning security with reference to operating cost trends: a reduced energy demand reduces dependence on future energy price trends and also means more planning security with reference to future running costs. A potential switch to sustainable energy sources is only possible if the demand is greatly reduced.
- Support for the regional economy: investment in energy efficiency is an alternative to the service provision of energy consumption, which mainly leads to imports of raw materials. With thermal protection measures, value creation takes place almost exclusively at the domestic level in medium-sized businesses; the firms operating here employ a very large number of people so that measures for energy efficiency have a significant employment effect.
- Profitability of economic efficiency measures: Passive House suitable insulation thicknesses with low-e triple glazing are economically viable even without government incentives (see [Kah et al. 2008]). With appropriate planning, the additional investment resources for a controlled ventilation system remain within limits and are economically feasible as an overall concept on account of the saved energy (see [Bretzke 2009], [Baumgärtner 2009]). Based on the verified operating cost savings for a Passive House school, [Baumgärtner 2009] calculated that extra investment to the amount of 6 to 9 % of the construction costs can be refinanced over the lifecycle.

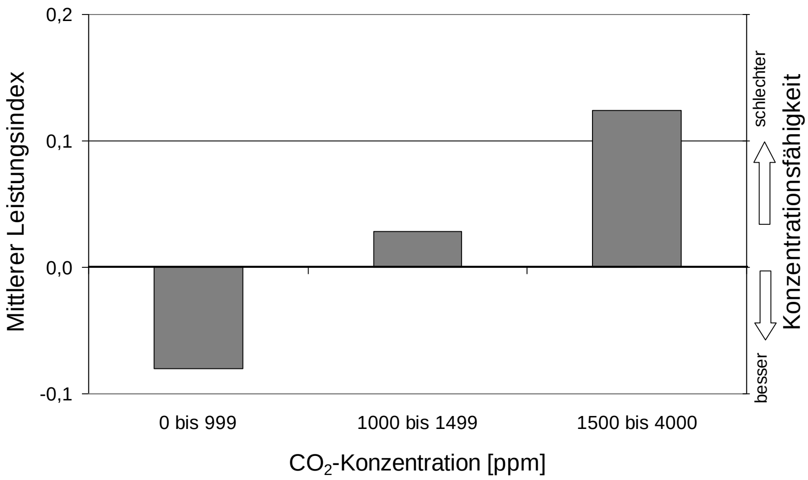
3 Frequently asked questions relating to energy efficient schools, children's day-care centres and school sports halls in brief

<u>Why is the ventilation system of key importance in schools and children's day-care centres?</u>

Compared to residential and office buildings, schools and children's day-care centres have a different characteristic utilisation with high occupancy rates and shorter usage times. A basic issue with high occupancy rates is the adequate supply of outdoor air. Numerous studies have demonstrated that the quality of air is poor especially in schools, although as already explained above, the quality of indoor air in schools and children's day-care centres should be a matter of special concern. This problem is well-known, not only in Germany; initial studies relating to this problem have also been carried out in the USA.

The influence of inadequate air quality on health and performance was examined. [Myhrvold et al. 1996] was able to show a relationship between the ability to concentrate and the air quality (based on carbon dioxide as the leading indicator).

Fig. 1: Performance index and CO_2 concentration. Positive values correspond with poorer performance and negative values correspond with good performance (N=548, diagram according to [Myhrvold et al.1996]).



Mittlerer Leistungsindex=average performance index, CO2-Concentration, besser=better, schlechter=poorer, Konzentrationsfähigkeit= ability to concentrate

As further tests show, the problem of poor air quality arises especially in winter because bad air is easier to bear than a draught. With solely ventilation via windows, this must take place often enough so that a good air quality is achieved. For this, ventilation via windows according to a plan is necessary, which was also tested in research projects under the keyword "motivated ventilation via windows".

An attempt was made to improve the indoor air quality in educational-use buildings using different approaches. "Motivated ventilation via windows" relies on adequate replacement with outdoor air through targeted ventilation by the users in accordance with a time schedule or through a warning message in case of poor air quality with so-called "ventilation indicators".

Furthermore, there are concepts in which natural ventilation takes place via motorised valves, and experiments where controlled mechanical ventilation systems are supplemented with natural ventilation, known as hybrid ventilation concepts.

In concepts with natural ventilation, controlling the air quantities also poses a challenge due to the fluctuating motive forces (wind, temperature differences). In general, heat recovery is barely possible on account of flow resistance.

An additional challenge is the draught-free introduction of outdoor air. In the winter this is mainly a question of the supply air temperature. One possibility for natural ventilation concepts is preheating via suitably positioned heating surfaces. In addition, maximum flow velocities should not be exceeded as this is critical on account of the fluctuating natural motive forces.

In contrast, controlled ventilation with heat recovery as a central building services component of the Passive House Standard is an ideal solution for schools and children's day-care centres. Controlled ventilation constantly provides adequate outdoor air and the heat recovery system prevents excessively low supply air temperatures. These findings are supported by extensive experiences gained from realised projects with controlled ventilation.

The necessity for controlled ventilation and its significance for the indoor air quality in schools was also recognised in Denmark. From 1995, building regulations (see [BR 1995]) stipulate a supply air and extract air system for classrooms.

<u>With the customarily high occupancy rates, is a highly efficient heat recovery system appropriate?</u>

The question whether high heat recovery efficiencies are necessary at all in schools and children's day-care centres is the subject of debate; after all, the schoolchildren cause high internal heat gains, therefore an "excellent" heat recovery efficiency might lead to a need for cooling. Isn't 60 % sufficient?

Large numbers of people require correspondingly high air quantities which must be introduced into the building without draughts in the winter as well. As the results for ventilation via windows show, in winter poor air quality is more easily tolerated than draughts down the back. Supply air with temperatures around 17 °C can still be introduced with an acceptable risk of draughts (see [EN ISO 7730], [DIN 13799]);

with lower supply air temperatures the expected level of dissatisfaction rises significantly.

Which supply air temperatures can one reckon with in the case of only moderate heat recovery? With a typical daytime temperature of 5 °C during the heating period, a moderate heat recovery efficiency of 60 % would heat the supply air to just 14.6 °C (assumed extract air temperature 21 °C). A reasonable supply air temperature of around 17 °C which allows draught-free introduction of air would only be achieved with an outdoor air temperature of 11 °C. More efficient heat recovery therefore makes sense in the winters typical for Germany for reasons of comfort alone.

But doesn't efficient heat recovery increase the cooling demand in rooms with high occupancy rates? In principle this is the case if ventilation only takes place via the ventilation system with heat recovery during the transitional periods when no heating is needed. This is exactly what would happen in naturally ventilated rooms if the windows remained shut. Usually the windows are then opened and the "cooling potential" of the outdoor air is utilised. The heating period thus simply becomes a little shorter with heat recovery.

With controlled ventilation with efficient heat recovery, two requirements for rooms with high occupancy rates can be met at the same time; a good quality of air and thermal comfort can be provided simultaneously.

Controlled ventilation improves the air quality in sports halls. Even in conventional sports halls the secondary areas such as showers and changing rooms usually have controlled ventilation. With the simple concept of directional airflow (see Section 6.4.4), a ventilation unit of comparable size can be used to ventilate the entire sports hall with only little additional effort.

Does controlled ventilation have an influence on potential pollution by particulate matter?

For some time, pollution by particulate matter has increasingly been in the focus of public interest. One reason for this was the implementation of the EU Directive 96/62/EG on pollution by particulate matter in outdoor air, which led to more measurements being carried out in indoor spaces and particularly in schools. The effect of particulate matter inside and outside is not directly comparable due to the different sources. Specific risks due to particulate matter in indoor spaces are still being debated, according to the indoor space air hygiene commission of the Federal Environment Agency UBA (see [IRK 2007]), "increased concentrations of particulates in indoor spaces are undesirable in terms of health (...). A reduction in the concentration of dust in the air therefore protects against avoidable pollution". As shown by measurements in two primary school buildings in the context of this handbook, controlled ventilation also significantly reduces pollution by particulate matter by means of adequate continuous air exchange (see Section 6.2).

Is a good level of thermal protection appropriate for schools and children's day-care centres as well?

A simplified steady-state calculation of gains and losses in a school or a children's day-care centre may lead to the assumption that these types of buildings will remain warm due to the presence of the occupants alone and therefore a good standard of thermal protection and a ventilation system with heat recovery will not be necessary.

However, steady-state consideration is not expedient for clarifying this question because the school building is constantly in the heating-up or cooling-down phase due to the intermittent operation. The "cold" building structure must be brought up to temperature in the morning; some of the heating output and internal heat gains is used for "charging" the heat-accumulating construction. Added to this is the fact that in the evening and at the weekend, and in schools also during specific lessons (when pupils are not in the classroom and are instead in the special subject rooms or sports halls) there are no internal gains and the warm construction is discharged again at these times.

For this reason, dynamic simulations were carried out for a school building in the context of this handbook. The gains (body heat of persons, lighting, solar radiation) and ventilation or transmission heat losses were taken into account in the process. If too much free heat (solar and internal gains) is available then the decrease in the space heating demand is no longer proportionate to the reduction in the heat losses. The utilisation factor of the free heat decreases and the reduction in the heat losses does not have an effect to the full extent in the form of heating energy savings. Fig. 2 shows the resulting heating demand as a function of the reduction in the heat losses.

As the dynamic simulation calculations for a school building show, the reduction in the heat losses that is associated with the Passive House construction method are still utilisable as heating energy savings to the full extent, the specific heating energy declines almost proportionately to the reduction in the heat losses (note: the saved heating energy is just 2 % less than the total reduction in heat losses).

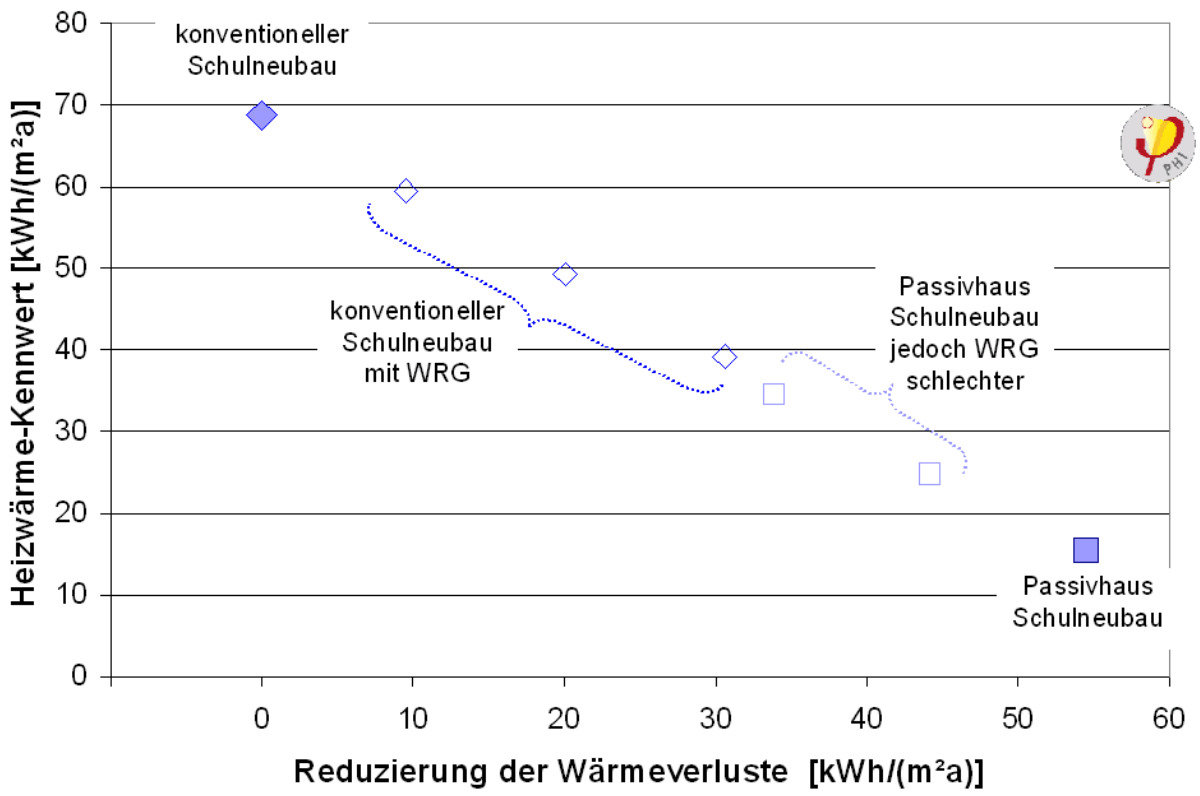


Fig. 2: **Heating demand calculated using dynamic simulations for a school building. The heating energy value decreases almost proportionately to the reduction in the heat losses. The better standard of thermal protection and the ventilation system with heat recovery (for the Passive House Standard) have the effect of heating energy savings to the full extent.** ***(Source: PHI)***
konventioneller Schulneubau mit WRG=Conventional new school building with HRV, Passivhaus Schulneubau jedoch…=new Passive House school building but with poorer level of HRV, Passivhaus Schulneubau…=new Passive House school building, Heizwärme-Kennwert…=Heating energy value, Reduzierung der Wärmeverluste=reduction in heat losses

What happens in the summer?

To some extent it is presumed that the good level of thermal protection in conjunction with the high internal heat gains will lead to problems in the summer. Systematic simulation calculations were performed investigate this more precisely. In doing so, the temperature behaviour of a conventional new construction for a school was compared with a Passive House school building.

This revealed that three factors are decisive in the summer:

- For good daylight conditions, classrooms as well as group rooms require large window areas. Good sun protection is essential for the summer situation. The internal loads can be more than twice as high without sun protection due to solar insolation.

- In summer, it is essential to ventilate as much as possible. The outdoor air has enough cooling potential for most school buildings. During a typical summer, outdoor temperatures over 25°C occur during only about 30 school hours (morning school, climate data set for Frankfurt), and during 90 hours for all-day school operation (school operation till 17 p.m.). During the remaining summer hours the low outdoor temperature can be maintained almost solely through adequate airing.
- For buffering peak temperatures, educational-use buildings should have an adequate thermal storage capacity. During the hot period, the heat loads stored throughout the day must be removed through sufficient ventilation at night.

The results of the simulation reflect these findings (see Section 8.1). If good sun protection is present and if adequate ventilation takes place, then the indoor temperatures in schools and children's day-care centres will remain comfortable even in the summer. Almost identical indoor temperature profiles will result if these strategies are applied for both standards of thermal protection. Measurements in a Passive House primary school (see [Peper et al 2007]) confirm these excellent results.

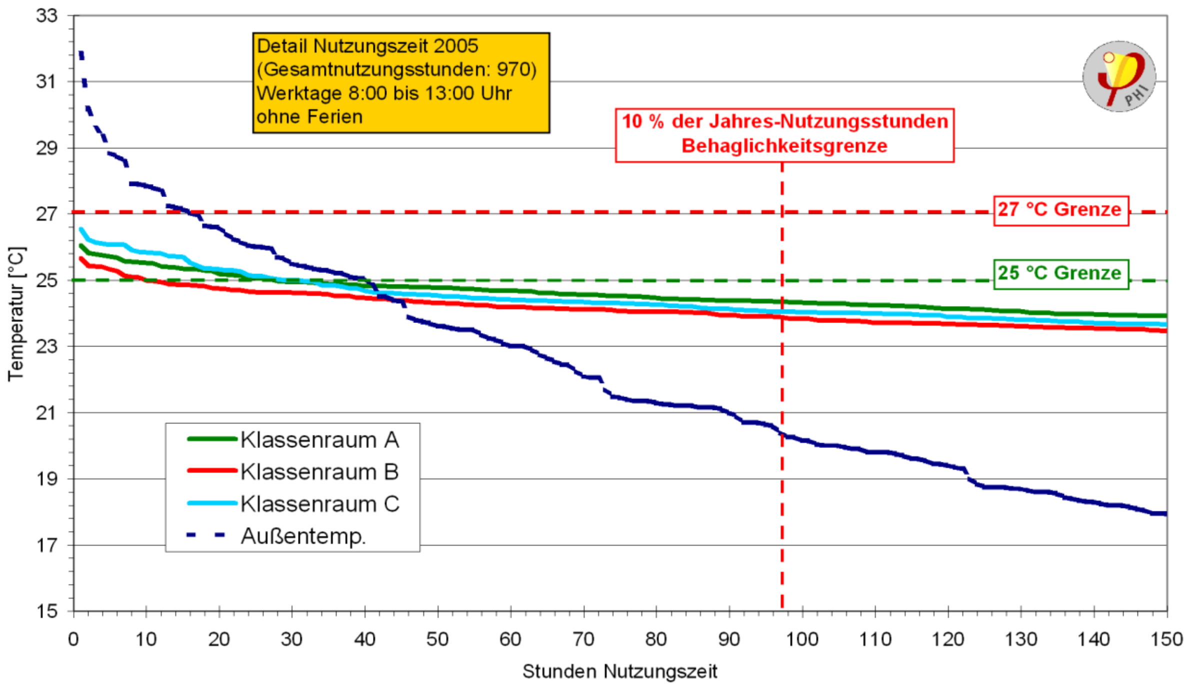


Fig. 3: **Load duration curve of the measured indoor temperature in a Passive House primary school. The indoor temperatures remain comfortable even in the summer. *(Source: [Peper et al 2007])***
Klassenraum=classroom, Außentemp=outdoor temperature, Detail Nutzungszeit…=details of usage period in 2005 (Total hours of utilisation: 970)

Workdays 8 am till 13 pm, without holidays, 10% der …=10 % of the annual hours of utilisation comfort limit, Grenze=limit, Stunden Nutzungszeit=hours of utilisation

Are heat losses from entrance areas relevant?

Entrance areas of public buildings such as schools and children's day-care centres are used intensively. The frequent opening cycles are associated with additional air exchange which may increase heat losses significantly during the heating period. The energy-relevant influence of door opening cycles was assessed in a survey carried out in a school (see [Peper et al. 2007]). Based on an entire building, the additional ventilation heat losses were generally low, for the examined school building the additional heat loss was estimated to be 0.5 kWh/(m²a). Group rooms in children's day-care centres in particular additionally have doors towards the outside area. As experience has shown, these doors are hardly used during the main winter period, simply because excessive entry of dirt can be avoided in this way (in winter the entrance with the walk-dry/dirt-trapping zone is used). Excessive heat losses through open group room doors can normally be disregarded for this reason (see Section 0).

Should ventilation via windows continue to be possible in the case of controlled ventilation?

It is always essential to foresee a sufficient number of windows for natural ventilation, even in Passive House buildings for educational use. In the summer natural ventilation should be given priority and as experience has shown, this is also desired by the users. In addition, this type of summer operation saves significant amounts of operating energy that would otherwise be necessary.

In contrast, during the heating period, air supply and ventilation takes place in a controlled manner. The users *do not have to* ventilate via windows (but may do so if required). Otherwise, denying users the possibility of ventilation via windows will generally lead to dissatisfaction. In contrast with conventional schools or children's day-care centres, the heating outputs available in Passive House buildings are considerably lower. Moreover, heaters under the windows are not necessary, so when the windows are opened the inflowing outdoor air quickly leads to perceptible cooling down. Experience gained with Passive House schools indicates that as a rule, ventilation via windows is only practised to a small extent in the main winter period and that neither the function nor energy consumption is unreasonably influenced by this.

Do special requirements apply for heating in Passive House sports halls?

Large room heights are a special feature of sports halls. In the reference literature special measures are recommended for halls which counteract pronounced temperature stratification. However, these conditions change with excellent thermal protection – this is a key finding of the investigations carried out in the context of this handbook:

Measurements and CFD simulations show that very uniform temperature distribution is achieved even with heating via supply air and similarly to Passive House residential buildings, the type of heating does not play any significant role in sports halls with large volumes (see Section 7.2).

What energy saving potentials can be expected?

As a central building services component of Passive House buildings, controlled ventilation with heat recovery significantly improves the air quality and offers an ideal solution for the comfortable introduction of supply air with the occupancy rates commonly occurring in schools and children's day-care centres. At the same time, the heat losses are noticeably reduced through heat recovery and the Passive House Standard is just a small step away.

With existing buildings the Passive House Standard cannot always be achieved with reasonable measures. However, modernisation using highly-efficient Passive House components offers a very large savings potential. Heating energy savings of around 90 % are possible with energy-efficient retrofits. For modernisations, artificial lighting usually also offers considerable savings potentials depending on the starting quality (up to 80 %; see [VDI 3807-4]).

With the Passive House Standard, new constructions have a heating energy savings potential of more than 70 % compared to the requirements of the EnEV (see Fig. 4). The measured heating energy consumption values of three example Passive House buildings for educational use range between 9 and 22 kWh/(m²a), proving that large saving potentials are achievable.

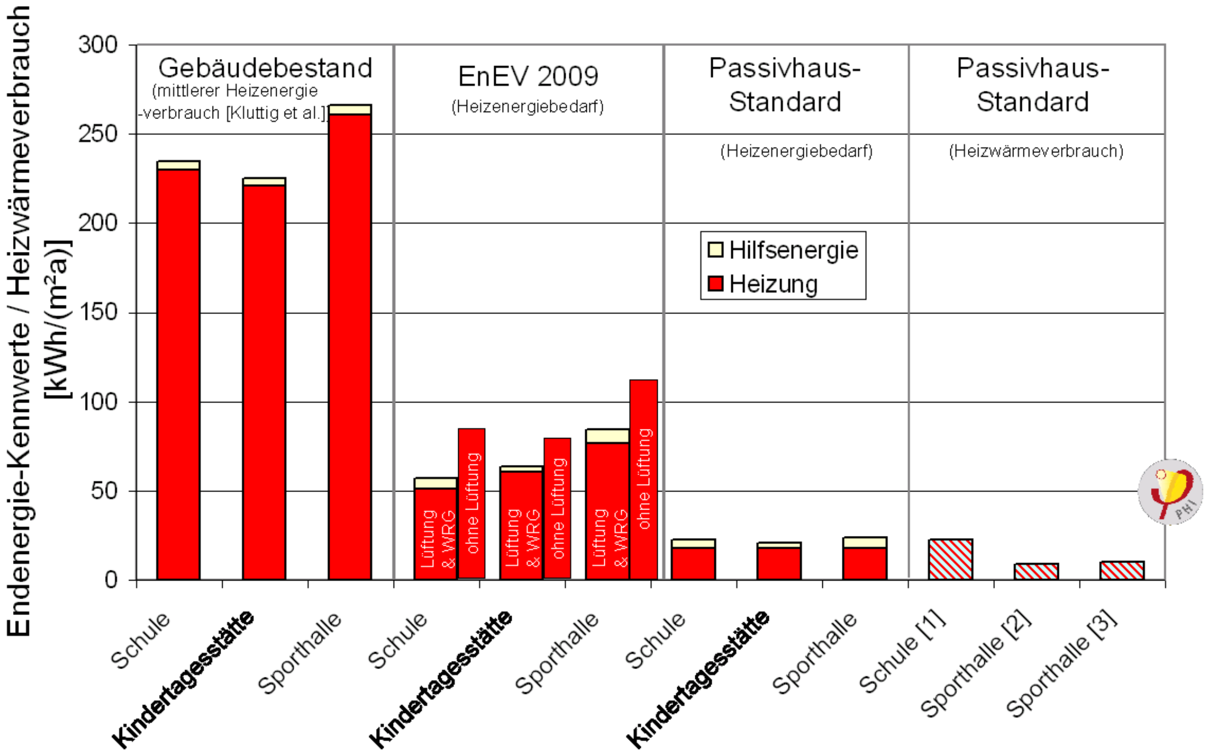


Fig. 4: **Comparison of heating energy values of educational buildings. While the heating energy consumption of the studied building types is between 260 and 220 kWh/(m²a) in existing buildings (see [Klutig et al 2001]), with the revised EnEV standard (EnEV2009) the heating energy demand values decrease to between 50 and 100 kWh/(m²a). Another significant reduction in the heating energy demand is possible with the Passive House Standard for educational buildings. As an example, published measured data for the heating energy consumption of three Passive House buildings for educational use have also been given. The measured value between 9.0 and 22.8 kWh/(m²a) proves the large savings potential of energy efficiency measures (the heating energy consumption (final energy) is about 15 % higher).** ***(Source: PHI)***

Kindertagestätte=children's day-care centre, Schule=school, sports hall=sports hall, Endenergiekennwerte…=final energy values /heating energy consumption, Gebäudebestand=existing building stock (average heating energy consumption), Heizenergiebedarf=heating energy demand, Heizwärmeverbrauch=heating energy consumption, Passsivhaus-Standard=Passive House Standard, Hilfsenergie=auxiliary energy, Heizung=heating, Lüftung&WRG=ventilation and HRV, ohne Lüftung=without ventilation,

The energy demand values in accordance with EnEV2009 and the Passive House Standard are calculated with the energy balance tool [PHPP 2007] based on actual projects. For the energy standard according to EnEV2009 the energy values are given with and without controlled ventilation.

[1]: Passive House primary school in Frankfurt Riedberg [Peper et al. 2007]

[2]: Passive House sports hall in Laatzen [Kis/Grobe 2006]

[3]: Passive House sports hall in Neuberend [Vollert et al. 2006], [Vollert et al. 2008]

4 Building design

4.1 The Passive House Standard

Due to the excellent thermal protection of Passive House buildings, the heat losses are so low that they can largely be compensated through solar and internal heat gains (people, electrical appliances, see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). The residual heating demand that is left can easily be covered in a cost-effective way by means of additional heating of the supply air flow that is required anyway for a good quality of air. Radiators are no longer absolutely essential.

The world's first Passive House building that was completed in 1991 in Darmstadt-Kranichstein (Germany) was a row of 4 terraced houses (see [HMUE 1993], [Feist/Werner 1994]). The ever-increasing numbers of Passive House buildings that followed in the course of the 1990s were initially exclusively residential buildings. The first Passive House administrative building was built in the year 1998 and the first factory building in 2000; it was only in 2001 that the first Passive House school building was completed in Bremen-Sebaldsbrück.

Accordingly, the Passive House criteria and also the requirements for Passive House buildings were originally developed primarily for residential buildings. When schools and children's day-care centres were built to the Passive House Standard for the first time at the beginning of the new century, the question that arose was whether the same principles and criteria which had already proved successful in housing construction for some years could be applied here. It soon turned out that the maximum heating demand value of 15 kWh/(m²a) also made sense in educational buildings. The basic principles for this were worked out on the basis of systematic building simulation calculations during the Research Group on Passive House Schools (see [AkkP 33]). Specific issues with large-volume sports halls were clarified in parameter studies carried out within the framework of this handbook (see Section 11.2). That the resulting heating demand value is identical to the requirements for housing construction is by no means self-evident. Despite the different uses, the comparable requirements for thermal protection stem from the fact that among other things, the average values of the boundary conditions (temporally and spatially averaged internal heat gains and average outdoor air exchange) correlate quite well.

In addition, as more Passive House buildings were built, it became clearer that this type of building use was actually especially suitable for the application of the Passive House Standard. On account of the high occupancy rates and the high fresh air demand associated with these, a ventilation system with heat recovery is absolutely necessary in every case in order to avoid impairing comfort and air quality. With their usually large size, educational-use buildings also have a quite favourable surface area to volume ratio, due to which the Passive House Standard can be achieved even with lower requirements for thermal protection of individual building components in comparison with single-family houses.

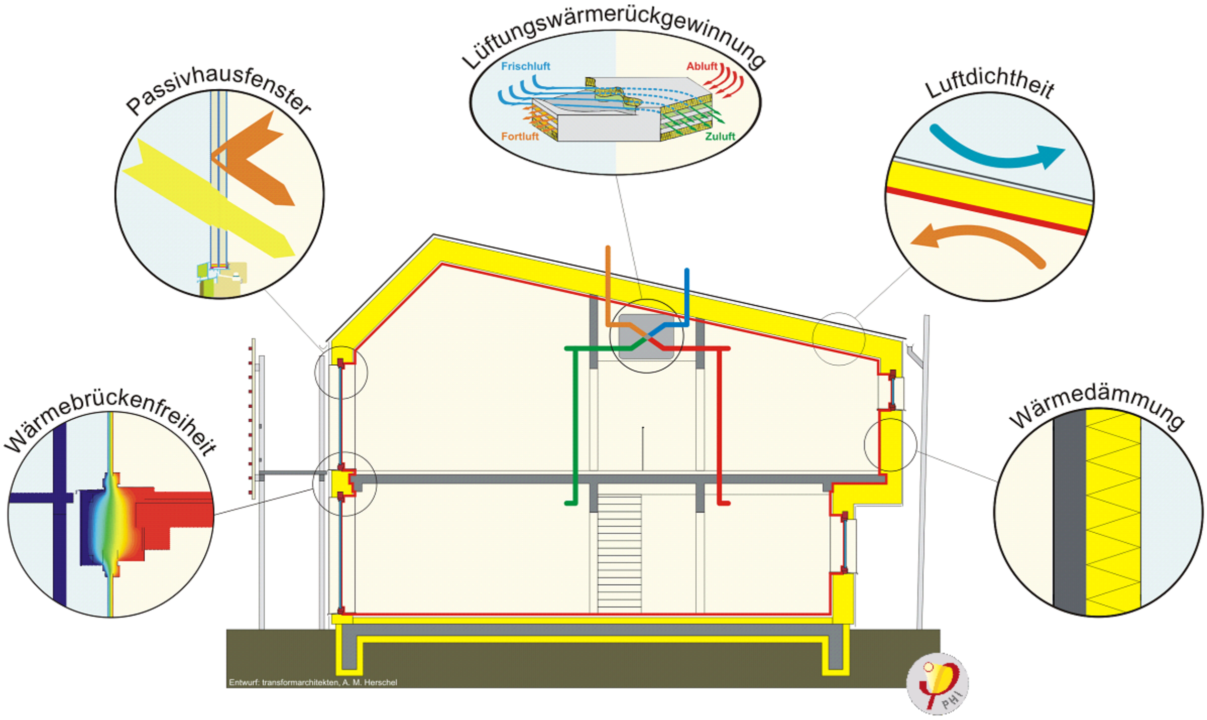


Fig. 5: **The five basic Passive House principles *(Source: PHI)***
Wärmebrückenfreiheit=absence of thermal bridges, Passivhausfenster=Passive House windows, Lüftugnswärmerückgewinnung= ventilation heat recovery, Luftdichheit=airtightness, Wärmedämmung=thermal insulation

At first glance, Passive House buildings are no different from other buildings. Components and building parts for Passive House buildings can also be found in conventional buildings. However, all relevant components are of a significantly better quality in terms of the avoidance of heat losses. Each of the five principles given below is essential for achieving the Passive House Standard.

4.1.1 Thermal insulation

A continuous layer of insulation completely encloses the heated building volume and minimises the transmission heat losses. It should have a maximum heat transfer coefficient (U-value) of 0.15 W/(m²K). A substantially better level of thermal protection especially in the roof may be appropriate and can be realised cost-effectively.

4.1.2 Absence of thermal bridges

Gaps or offsets in the insulation layer constitute thermal bridges and should therefore be avoided. The same is true for penetrations of the insulation layer; these should be executed using materials with a lower thermal conductivity whenever possible.

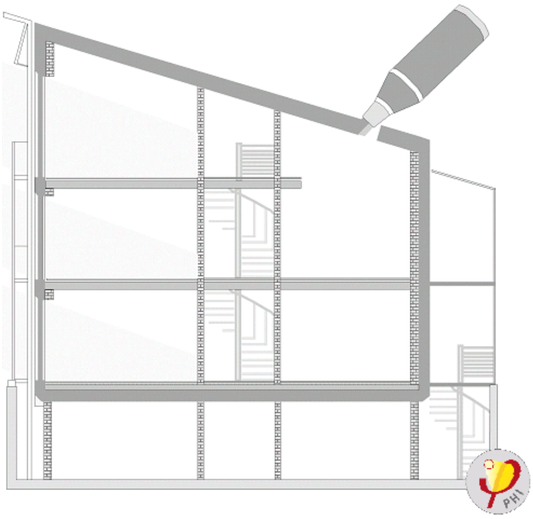


Fig. 6: Pencil rule:
It should be possible to outline the thermally insulating layer and the airtight building envelope in a cross-section of the building without needing to take the pencil off the paper. (Source: PHI)

4.1.3 Airtightness

An airtight envelope encloses the heated building volume. This is usually situated on the room side of the thermal insulation, and prevents ventilation heat losses due to infiltration and exfiltration.

4.1.4 Passive House windows

Passive house windows are also referred to as "energy gain windows", because with a predominantly south-facing orientation during the heating period they let more heat into the house in the form of solar radiation than they lose to the outside due to heat losses. In this way they contribute to heating of the building. This is achieved by means of low-e triple glazing and thermally insulated window frames.

4.1.5 Ventilation system with heat recovery

Through the removal of air contaminants, odours and moisture the ventilation system reliably provides fresh air. The heat recovery system transfers the heat in the "used" extract air to the fresh supply air. In this way the ventilation heat losses are reduced by up to 90 %. With the aid of a simple post-heating coil in the supply air duct, the ventilation system can also be used for heating the building.

Important parameters for Passive House buildings
(see also Section Fehler! Verweisquelle konnte nicht gefunden werden.**, www.passivehouse.com)**

Heating demand:	**maximum 15 kWh/(m²a)**	(criterion)
Primary energy demand:	**maximum 120 kWh/(m²a)**	(criterion)
Airtightness (n_{50}):	**maximum 0.6 h^{-1}**	(criterion)
Thermal insulation (U-value):	**maximum 0.15 W/(m²K)**	(reference value)
Windows ($U_{w,installed}$)	**maximum 0.85 W/(m²K) with simultaneous high solar transmittance of the glazing**	(reference value)
Heat recovery (η_{HRV})	**minimum 75 %**	(reference value)

4.2 Design, zoning and orientation

4.2.1 Design

Not only is integrated planning essential for Passive House buildings, it is also indispensable to a great extent for achieving an energy-efficient and cost-effective building. Because fundamental decisions relating to the building design are made during the preliminary planning phase, engineering professionals (for building physics, energy concept, structural and construction engineering, building services engineering and fire protection) should already be involved in the planning process at this stage. Close interdisciplinary cooperation of the planning team should continue throughout all phases of planning and implementation until the completion of the building.

An optimised building design holds the greatest potential for cost savings. Evaluation of 12 competition designs for an office building yielded an investment cost spectrum ranging from €1550 to €2280 per square metre of gross floor space. In contrast, the additional investment costs for implementation to the Passive House Standard were a marginal €13 in comparison [Kahlert et al. 2004]. However, the additional investment costs for the Passive House Standard depend greatly on how well the building design has been optimised towards the achievement of the Passive House Standard. The following approaches contain some optimisation tips.

Fig. 7: **Smaller, single-storey buildings also achieve the Passive House Standard - with slightly more effort**
Day nursery in Lengdorf, architect: Gernot Vallentin (picture: Gernot Vallentin)

Compared to residential buildings, educational-use buildings are quite large and have a better surface area to volume ratio (SA/V ratio). This "natural" advantage can be enhanced by a compact building shape with as few projections and recesses as possible. Multiple storeys as well as a large building depth with the main utilisation (classrooms, group rooms etc.) arranged on both sides of the central access area also improve the SA/V ratio. If these optimisation opportunities are used, it is possible to achieve the Passive House Standard with accordingly less stringent requirements for thermal protection of the exterior envelope and the ventilation system.

The high requirements for a good level of airtightness and absence of thermal bridges in Passive House buildings necessitate particularly careful planning and execution. Experience has shown that both the planning effort and the frequency of defects in the execution can be significantly reduced if attention is paid to simple details, which in addition are repeated as far as possible at all comparable points in the building.

Sufficient space should be provided for the ventilation system at an early stage. The relatively large volumetric flows necessary in educational-use buildings during the usage period require sufficiently large duct cross-sections which must be taken into account in the planning, e.g. for suspended ceilings. For multi-storey buildings, shafts will be required for the vertical routing of ducts. An optimised location of the plant room with the ventilation unit will result in smaller duct cross-sections, shorter ductwork and improved electrical efficiency of the ventilation system.

The entrances of the building necessitate a certain amount of effort for vestibules and for serviceable, airtight and insulated doors. A design with as few entrances as possible is therefore more economical. On the other hand, doors in group rooms or classrooms that open directly towards the outside do not need a vestibule because as shown by experience, these are hardly used during the heating period anyway. During this period the main entrance with the walk-dry/dirt-trapping zone (door mats) is generally used to prevent the entry of excessive dirt.

Measurements in a Passive House school building showed that the additional ventilation heat losses caused by door opening cycles of the main entrance with a maximum of 0.5 kWh/(m²a) are rather low. If larger groups of people pass through the entrance area, as is the case in schools before the start of lessons and during the breaks, then hardly any energy savings are achieved with vestibules. In contrast, if people enter the building singly, then the additional ventilation heat losses can be reduced by a half with a vestibule. [Peper et al. 2007].

Nevertheless, thermal comfort can be improved significantly with a vestibule, particularly if recreational areas are located near the doors, because otherwise pools of cold air can form due to opening of the doors. This applies to e.g. children's day-care centres in which the access areas are often used as additional play areas. With reference to thermal comfort and reduction of the ventilation heat losses, mechanical door closers should be preferred over automatically opening door panels as the latter result in significantly longer opening times. This makes a vestibule almost useless. If an automatically opening door is necessary for barrier free access then it can be considered whether it might be possible to use this only for an additional side entrance.

Fig. 8: **Entrance area of a Passive House school with a vestibule (Frankfurt Riedberg).**
Architecture: 4a, Stuttgart

The rule that there should only be one airtight (and insulating) layer also applies for the vestibule area. This means that only one of the two door levels must be implemented with an airtight Passive House door; a simpler standard will suffice for the second level. In order to avoid unnecessarily increasing the thermal envelope area due to the vestibule, it will be advantageous to position this Passive House door in alignment with the surrounding building envelope, as shown in Fig. 8.

4.2.2 Zoning

Clear functional structuring of the building facilitates supply and regulation with reference to heating and ventilation in particular. First and foremost this requires a spatial concentration of the installation zones (sanitary rooms). This will allow for short extract air ductwork which will lead to savings in construction costs and to lower pressure losses of the ventilation system with accordingly lower electricity consumption during operation.

Unnecessary costs for construction and maintenance may arise due to a lack of coordination between fire protection and ventilation planning. Complex fire protection measures will become necessary if ventilation ducts pass through walls or ceilings into an adjacent fire compartment (e.g. fire dampers, see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

4.2.3 Orientation

Because educational-use buildings are usually large and compact structures, the orientation of the building plays a less important role for the heating energy demand than smaller residential buildings. However, a north-west alignment is more favourable with regard to thermal protection in summer because the solar gains in the summer are considerably higher with windows facing East or West. Nevertheless, in order to utilise the solar radiation for reducing the heating energy demand, attention should be given to as little shading of the windows as possible. This applies both to self-shading by window reveal and lintel as well as other building wings and to external shading by other buildings, trees and topography. Protection from excessive solar heat gains in summer should not take place through permanent shading elements or solar control glazing; instead, temporary shading elements such as external Venetian blinds should be used.

In order to avoid a concentration of internal heat gains (especially body heat of people) and solar heat loads on the inside in the summer, it may be appropriate to have the recreational rooms and access areas facing south, instead of the classrooms or group rooms. In general, a temporary increase in temperature in these areas is more easily tolerated, so that they can serve as a kind of "buffer zone". Conversely, rooms with high internal loads, such as server rooms or kitchens should preferably be located on the northern side.

4.3 Construction method

In the case of residential and office buildings, the construction method (solid or lightweight construction) only has a small influence on the thermal behaviour of a building [AkkP 15]. However, in educational-use buildings the higher occupancy rate in group rooms or classrooms during the periods of use leads to high temporal and spatial concentrations of internal heat gains. In the summer and during the transitional period, this leads to a continuous increase in the temperature in the affected rooms during the daily duration of use [AkkP 33]. Incidentally, Passive House buildings and buildings with a lower standard of thermal protection (Low-Energy Building) are barely different in this regard. Ceilings and walls with a higher thermal storage capacity (solid constructions) attenuate this daily temperature amplitude. In addition, they mitigate continuous heating up over several successive days of use.

Good thermal coupling of the storage mass to the space is essential. Suspended (acoustic) ceilings, built-in cabinets etc. may therefore be problematic. Thermal coupling of the rooms with each other is also advantageous as this mitigates temperature peaks which can otherwise arise due to concentrated heat loads in individual rooms. Solid building components usually have a higher thermal conductivity, so thermal coupling is improved by these. In addition, implementation of the interior walls as a solid construction may also offer advantages for fire protection and sound-proofing of school buildings.

Fig. 9: Classroom in a Passive House school in Frankfurt-Riedberg. The ceiling is suspended only in the area with the ductwork (the supply air slot can be seen here). A pin-board on the rear wall of the room acts as an acoustic element in addition.

Architecture: 4a, Stuttgart / Building Services: ICRZ Ing. Cons. Ruth + Zimmermann, Neuenhagen

4.4 Utilisation of daylight

The artificial lighting is usually the main electricity load in educational buildings. Measures for improving the utilisation of daylight can therefore lead to considerable energy savings.

The usual criterion for evaluation is the so-called daylight factor which describes the ratio of horizontal illuminance of a point in the room to the illuminance of a vertical surface outside. A daylight factor of between 2 and 6 % as specified for workplaces is recommended for classrooms (see [Chuard 1993]).

The daylight factor can be improved through appropriate window geometries. Besides the absolute size of the window, in particular a large lintel height (ceiling level) provides for a good level of daylight deep into the room. In contrast, glazing that is below the work level (e.g. at desk height in schools) is almost pointless.

The reflection coefficient of the room surfaces also has a considerable influence. Light colours can double the daylight factors in areas that are further away from the windows and lead to a more uniform distribution of illuminance in addition (see [AkkP 33]).

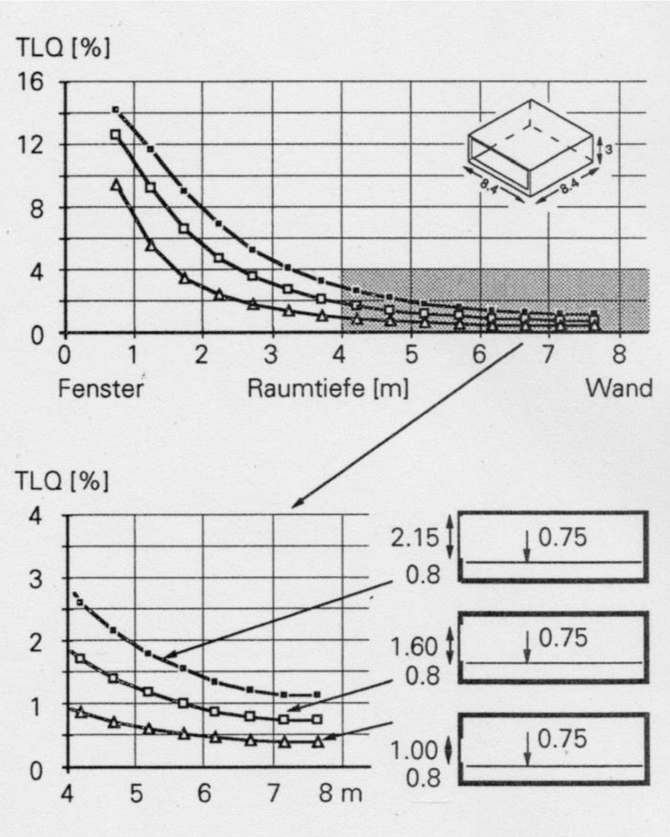


Fig. 10: Influence of the window size on the daylight factor.
(Source: [Chuard 1993])

Raumtiefe=room depth, Fenster=window, Wand=wall

5 Building Envelope

5.1 Exterior walls

The building components of the façade especially have a big influence on the energy balance of a building (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) due to their high share of the total building envelope surface area (typically around 30 %). Passive House suitable heat transfer coefficients of the exterior wall area are between 0.10 and 0.15 W/(m²K). As feasibility studies have shown, this level of insulation is within the cost-effective range even in the context of an energy retrofit (see [Kah et al. 2008]).

Superinsulated constructions have proven successful in practice with all common methods of construction. Potential weak points in the insulating envelope in the form of attachment elements and other penetrations need to be given greater attention because they can increase the U-value of a façade as a whole and can therefore also increase the heating demand of the building.

A detailed description of the following statements can be found in the Protocol Volume No. 35 of the Research Group for Cost-effective Passive Houses [AkkP 35], which deals with the minimisation of thermal bridges in the façade area among other things, and the comprehensive handbook on "Retrofits using Passive House components" („Altbaumodernisierung mit Passivhauskomponenten“) [Bastian et al. 2010], in which basic principles and detailed background information about façade insulation can be found which are also relevant for new constructions.

5.1.1 Insulation thicknesses and thermal conductivities for superinsulated Passive House façades

Experience shows that the exterior wall insulation thicknesses of a Passive House building are usually 20 to 30 cm with a thermal conductivity of λ = 0.035 W/(mK) (it is always the rated value of the thermal conductivity that is relevant) – depending on the specified boundary conditions and possibility of optimisation of other building components.

Expanded polystyrene (EPS) achieves a thermal conductivity of λ = 0.035 W/(mK). EPS with a thermal conductivity up to λ = 0.031 W/(mK) has also been available for some time as a result of advancements (addition of opacifiers that absorb or reflect infrared radiation) [Albrecht 2010].

If the Construction Materials Class A is specified due to fire protection requirements, then mineral wool is usually the best choice of insulation material. With a thickness of up to 200 cm, mineral wool insulation panels achieve a thermal conductivity of

λ = 0.035 W/(mK), and more recently, even λ = 0.032 W/(mK). With larger insulation thicknesses the insulation material is twisted for reasons of stability so that the heat flow then runs parallel to the fibres, this type of insulation is termed mineral wool lamella. In this way, mineral wool with a thickness greater than 200 cm achieves a thermal conductivity of just λ = 0.040 W/(mK).

A high-performance insulation material (such as polyurethane or phenolic rigid foam) with λ-values of up to 0.022 W/(mK) can also be chosen in areas where the insulation thickness must be reduced for constructive reasons. For example, the thermal bridge effect between the masonry and a roller shutter box that is flush with the façade can be reduced using such materials.

In addition, superinsulated constructions may also be created using many other insulation materials, such as wood fibres, cellulose, flax, hemp, cork, reed, grass or straw. In part, these materials are installed in the form of panels and bales or as loose insulation – usually in timber constructions. In addition to the construction of the façade, the insulation thickness must also be adjusted for the characteristics of the respective product.

The Passive House Institute has tested a number of Passive House suitable constructions with all their connection details. Information and exact specific values are available on the internet (www.passivehouse.com).

5.1.2 Special requirements for educational-use buildings

Special requirements with regard to fire protection and protection of the façade from vandalism exist for the exterior walls of educational buildings.

Fire protection

According to the respective regional building codes, certain fire protection requirements for the building envelope must be met depending on the building category. Because schools and children's day-care centres belong in the special constructions category, more extensive demands may also be stipulated by the fire safety authorities. However, in the context of the guidelines for school buildings, no other requirements apply for fire characteristics of façade systems apart from those in the regional building codes.

For exterior wall cladding including the thermal insulation and substructures, the Building Ordinance of the state of Hesse [HBO 2003] for example demands the Building Material Class B2 (normal flammability) for the Building Categories 1 to 3, and the Building Material Class B1 (low flammability) for the Building Categories 4 and 5, where in the case of substructures the Building Material Class B1 only suffices if the spread of fire remains contained for long enough.

With the use of EPS insulation material with a Passive House suitable insulation thickness, additional fire protection measures must be undertaken in order to achieve the Building Material Class B1. The spread of fire across the façade from one storey to another can be restricted and emergency exits kept free of dripping burning substances by installing fire barriers (A1 insulation material in the area of the windows) or fire bars (strips of A1 insulation material around the circumference of the building). The German trade association of composite insulation systems Fachverband WDVS e.V. sets out guidelines for the necessity of the respective variants depending on the insulation thickness and window installation situations (including high insulated constructions) [Kotthoff 2009]. These specifications have been included in building authority approvals as current standards. Any worsening of the U-value in some areas due to the A1 insulation material must be taken into account in the energy balance.

Fig. 11: **Albert Schweizer Gymnasium in Alsfeld, fire barriers. Architecture: BLFP, Friedberg**

Protection against vandalism

When executing the façades of educational buildings, special attention should be given to the ground floor area that is prone to mechanical shock. Depending on the intensity of use, there are several possibilities for protecting the base areas of composite insulation systems from damage. Besides the use of so-called armouring mesh in the plaster layer, special base plates or vandalism-proof protective plates are frequently also embedded in the insulation layer. A thermal bridge addition must also be taken into account in the energy balance here in addition to a slight reduction in the insulation thickness, due to any anchors that may be necessary. Another possibility is the use of façade systems containing carbon fibres in areas that are prone to mechanical shock.

Alternatively, the CIS system in the area at risk can naturally also be replaced by other façade constructions such as a curtain wall façade only for the ground floor (Fig. 12), or concrete facing formwork.

Fig. 12: Curtain wall façade in some parts of the ground floor, Albert Schweitzer Gymnasium in Alsfeld. Architecture: BLFP, Friedberg.

Facing bricks (synthetic resin-bonded panels) or ceramic surfaces – tiles, panels or strips like those used in the Albert Einstein school in Schwalbach (see Fig. 36) that are often available provide a thermal bridge free solution with the appearance of a clinker façade.

5.1.3 External thermal insulation composite system ETICS

ETICS systems are often chosen for educational buildings, probably for cost reasons. Compared to curtain wall or front-mounted façades, these have the advantage that the insulation layer is not interrupted by a substructure. Even thermal bridge minimised anchors have a noticeable influence on the resulting heat transfer coefficient of the building component (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, Curtain Wall Façades).

Polystyrene insulation panels with insulation thicknesses up to Passive House level can be applied in normal cases (without structurally relevant dowelling). As a rule, additional dowelling is required by the manufacturer for modernisation projects in which the insulation panels are installed on existing plaster. In these cases it may be worthwhile to attempt demolition/removal, which can help to save considerable costs.

Fig. 13: **Façades with CIS. Left: Albert Schweitzer Gymnasium in Alsfeld. Architecture: BLFP, Friedberg. Right: Sports hall in Heidelberg. Architecture: ap 88, Heidelberg**

Additional dowelling is always necessary with mineral wool panels. Mineral wool lamellas with a thickness of up to 200 cm can be applied using adhesive, for larger thicknesses additional dowelling will also be necessary here (see [Information Sheet 2005]).

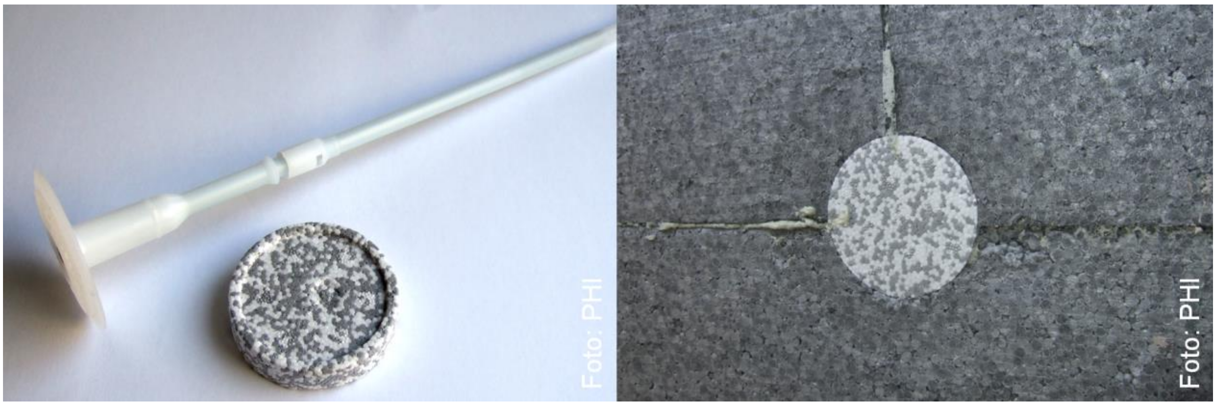


Fig. 14: **Left: High-grade steel dowel for compound insulation systems, with a plastic sleeve and insulation plug. Right: Countersunk dowels are sealed with cylindrical insulation plugs.**

The offset that frequently exists between the wall insulation and perimeter insulation is often formed with the aid of a special base profile. Unfortunately, this is often implemented as an aluminium or steel sheet metal profile and thus causes significant thermal bridge losses. Base profiles made of plastic are now available on the market which are adequate from the practical construction point of view and are almost thermal bridge free. In many cases, a continuous base profile is not necessary at all. It is enough to form a dripping edge using a plastic profile with plastering mesh. If the base profile is omitted, it may be necessary to secure the first row of insulation blocks constructively using dowels.

5.1.4 Curtain wall façades

To ensure protection of the thermal insulation and to have diverse design possibilities, a curtain wall façade is preferred over CIS, particularly for schools and children's day-care centres. Superinsulated constructions can also be implemented as curtain wall façades.

A deciding factor for the insulation of a curtain wall façade is that only fire-proof insulation materials which must also be waterproof may be used behind the cladding on account of the stack effect. Mineral wool panels with fleece backing are usually chosen for this purpose.

With a curtain wall/rainscreen façade, care must be given to windproof execution of the thermal insulation because compared to CIS the insulation of the curtain wall/rainscreen façade is not automatically protected by a layer of plaster from cold air flow passing through it.

Moreover, special attention must be given to the reduction of thermal bridges caused by anchoring elements. With conventional substructures, the entire insulation layer is penetrated by construction steel or aluminium and these result in a massive worsening of the U-value even with thermal separation from the solid wall by means of an insulating washer made of PVC. For example, the thermal bridge effects of a conventional aluminium substructure can increase the U-value of the uninterrupted building element by more than double (see [AkkP 35])!

Building authority approval is necessary for the cladding, substructure and the anchoring elements. The many realised examples particularly in the area of schools and children's day-care centres show that developing thermal bridge minimised solutions has proved successful. (The Passive House Institute has certified a number of thermal bridge minimised constructions in this area too, see www.passivehouse.com). If suitable building authority approved substructures are not available on the market for an ambitious construction project, it may make sense to strive for approval in that individual case. In some instances a structural analysis will also suffice.

In order to reduce the thermal bridge losses through the substructure, it is advisable to adopt the following principles [AkkP 35]:

- Select materials with a lower thermal conductivity (e.g. high-grade steel instead of aluminium or normal steel, GRP, laminated wood, carbon fibre)
- Use thermal separation elements
- Geometric optimisation: minimised cross-sections, timber framework construction with a higher load-bearing capacity for reduced material use

- A few thick penetrations are better than many thin penetrations

In contrast, the insulation holders which additionally penetrate the thermal insulation usually aren't a problem. There are even absolutely thermal bridge free insulation holders available which are fastened to the substructure of the façade cladding and keep the insulation in place from the outside.

Different thermal bridge minimised substructures were already examined in the Protocol Volume No. 35 "Thermal bridges and supporting frames" of the Research Group for Cost-effective Passive Houses [Schnieders 2007].

A simple solution for example is the crosswise laying of squared timbers and filling in the intermediate spaces with insulation material. Attachment of the outer squared timbers then won't have to take place through the entire insulation into the load-bearing wall. When calculating the heat transfer coefficient, the corresponding proportion of wood in the respective insulation layer must be taken into account. One possibility for reducing the proportion of wood in the insulation is to use wooden I-joists which are used in purely timber constructions as well as for insulating solid walls. Although the I-joists extend from the outer insulation layer up to the load-bearing wall, but are dissolved in straps and narrow webs of hard fibreboard. A ladder-shaped variant of this I-joist results in even lower proportions of wood in the insulation layer; this was used for example in the Albert Schweitzer Gymnasium in Alsfeld (Fig. 15, left).

When insulating I-joists care should be taken that the recesses in the area of the web are also completely filled, which can be achieved by inserting matching strips of insulation material or by using blown-in insulation materials.

Fig. 15: **Left: substructure of ladder-shaped suspended wooden I-joists in the Albert Schweitzer Gymnasium in Alsfeld. Architecture: BLFP, Friedberg. Right: wood/metal substructure**

Another possibility is to choose a mixed construction (Fig. 15, right), although this is not quite so optimal in terms of energy. U-profiles on a thermal separator are attached to the wall, which hold a vertical squared timber in front of the wall at a distance of a layer of insulation. The cladding (in this case: fibre cement panels) can be directly attached to this squared timber [Schnieders 2007].

Recently various manufactures have been offering thermal bridge free mounting brackets made of synthetic or fibre-composite materials. Such a system was implemented for the curtain wall façade of a school complex in Neckargemünd (by S+T Fassaden). The thermal bridges here are negligible; however, care must be taken that the mounting brackets are well-covered by the insulation and that windtightness of the insulation layer is ensured.

Fig. 16: **School complex in Neckargemünd, curtain-wall façade with plastic mounting brackets. Architecture: Donnig und Unterstab, Rastatt.**

5.1.5 Double-shell masonry - exposed brickwork

Double-shell masonry constructions are also possible in energy efficient educational-use buildings and have already been realised, albeit in smaller numbers. However, some considerations relating to the reduction of thermal bridges are necessary. On account of their high conductivity, anchoring elements made of construction steel should be replaced by high-grade steel anchors or – if possible – anchors made of fibre-reinforced plastic. High-grade steel anchors for double-shell masonry constructions are approved for a shell distance of up to 20 cm. Experience has shown that this insulation thickness is inadequate for the Passive House Standard. However, ordinary anchors may buckle with larger shell distances, therefore articulated anchors have been developed which are available with a shell distance of up to 35 cm that have been approval for such applications in individual cases [Bastian et al. 2010].

Additional loads, for example due to wall openings, are usually transferred by high-grade steel brackets. These are available with a shell distance of up to 35 cm with building authority approval. Such high-grade steel brackets can be avoided at the base of the wall by means of a foundation for the facing wall.

All additional thermal bridge losses caused by anchoring of the façade should be diligently minimised and must be taken into account in the energy balance.

Fig. 17: Clinker façade of the Justus-Liebig school in Waldshut. Architecture: Harter und Kanzler, Freiburg / Energy concept: Stahl und Weiß, Freiburg. (Picture: Stahl und Weiß). [AkkP 33]

5.1.6 Monolithic constructions

Various superinsulated monolithic construction systems recently came on the market, such as bricks with a λ value of 0.07 W/(mK) or porous concrete blocks. Passive House suitable formwork blocks are also available. With correspondingly low requirements for load transfer through the outer walls, such building systems are also suitable for kindergartens and schools. In order to minimise the proportion of reinforced concrete in the façade, the transfer of additional loads by the building core may also be possible here.

Some of these building systems barely achieve the U-value of 0.15 W/(m²K) for the exterior wall that is required by the Passive House Standard. When choosing such a system, the other boundary conditions of the building (e.g. surface area to volume ratio, solar gains, U-values of other exterior components, thermal bridges, building services) should be optimised in order to avoid exceeding a heating demand of 15 kWh/(m³a).

5.1.7 Lightweight wooden wall construction

Purely lightweight wooden wall constructions with a low thermal storage mass are less advisable in educational-use buildings. Simulations have shown that with the high internal loads, an adequate thermal storage capacity on the room side is advisable for thermal comfort in summer. This recommendation is met e.g. in mixed constructions if the internal structure is solid (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

**Fig. 18: Left: Passive House sports hall in Unterschleißheim built as a mixed construction.
Architecture: PSA-Architekten, Munich.
Right: Passive House sports hall of the Zentgrafenschule built as a timber construction, Frankfurt a.M. / Architecture: D'Inka Scheible Hoffmann Architekten.**

An example of a Passive House school realised as a mixed construction is the Montessori school in Aufkirchen. Here, an inner skeleton of reinforced concrete was combined with an outer shell of prefabricated timber structural elements. Special attention was given to the reduction of thermal bridges and to airtightness across the surface as well as at all connection points. The airtightness test resulted in an excellent n_{50} value of 0.09 h^{-1}.

Fig. 19: **Montessori school in Aufkirchen, by Walbrunn Grotz Vallentin Architekten, Bockhorn. Left: reinforced concrete skeleton. Right: Exterior wall as a lightweight timber construction. [AkkP 33] (Pictures: G. Vallentin)**

A carefully planned and executed airtight layer does not only serve to prevent heat losses but is also a guarantee for structural integrity especially in the case of timber constructions. The airtightness test therefore serves as quality assurance particularly for timber construction methods (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

In the case of educational buildings, the potential construction variants for an exterior wall in a timber construction are no different to those for other building types. On account of the frequently recurring spatial structures in children's day-care centres and schools, prefabricated elements can be applied more economically than, for example, would be the case with a single-family house. Please refer to the "Passive House - energy efficient construction" edition of the Timber Construction Manual published by the Informationsdienst Holz (timber information service in Germany) for general information relating to Passive House timber constructions [Kaufmann/Feist 2002].

5.1.8 Retrofits

For the insulation of existing school buildings - as with residential buildings - attention must also be paid to the load-bearing capacity and any irregularities in the existing walls, and appropriate measures must be taken. In the case of insulation with a composite insulation system, simply using adhesive is not enough. Additionally the insulation panels must often be fixed in place using dowels (demolition attempt). With difficult surfaces, comparatively complicated attachment of the insulation panels using rails may be necessary in order to avoid extensive preparation of the surface. With this fastening method, hollow spaces usually result behind the insulation, therefore outdoor air flow behind the insulation must be prevented by means of appropriate formation of the edge areas of the compound insulation system (base, window connections etc.). However, such fastening systems are approved only for thicknesses up to 200 mm, so it must be checked whether thermal insulation to the Passive House Standard can be achieved in individual cases [Bastian et al. 2010].

Since the renovation of the exterior walls of a school building essentially does not differ from that for a residential building, reference is made here to the handbook "Retrofits using Passive House components" [Bastian et al. 2010]. This addresses problems and presents solutions relating to topics ranging from compound insulation systems and the various curtain wall constructions to cavity insulation of existing facing brickwork. An entire chapter is devoted to the topic of interior insulation.

5.1.9 Thermal bridges in the façade area

Besides the thermal bridges caused by the façade anchors, in every building there are various other places which require special attention in order to avoid excessive heat losses or even structural damage. Some examples of these are Venetian blind cassettes, French doors, connections of porches, escape balconies or passages to existing building parts.

In general, the principle is to avoid thermal bridges whenever possible. Unavoidable thermal bridges can generally be mitigated through substructures of wood or pressure-resistant insulation blocks (e.g. of recycled polyurethane material), in part also in conjunction with special supports made of fibre-reinforced synthetic material. With a reduced insulation thickness in the area of the thermal bridge, it is advisable to opt for products with a better insulation effect (e.g. λ = 0.024 W/(mK)). In general, penetration of the entire insulation thickness by metallic materials should be avoided. If necessary, choosing high-grade steel (λ = 17 W/(mK)) instead of construction steel (λ = 50 W/(mK)) will already bring an improvement.

In order to reduce the size of individual anchors for escape balconies, external staircases or elements connecting to existing building parts, load transfer of such building components should preferably take place separately through free-standing or suspended structures rather than via the façade. In the section on "Balcony connections – thermal bridge optimised solutions" of the Protocol Volume No. 35 of the Research Group for Cost-effective Passive Houses, the issues with such connections are explained and many possible solutions are shown which can be applied in schools and children's day-care centres [Schulz 2007].

Fig. 20: **Left: Fire escape of the Montessori school in Aufkirchen. Walbrunn Grotz Vallentin Architekten, Bockhorn.**
Right: Suspended escape balcony of the Freien Walldorfschule in Bremen Sebaldsbrück. Architects: Prof.W.Dahms and F. Sieber, Bremen.

5.1.10 Airtightness

Like all parts of the building envelope, the exterior walls must also be airtight in order to prevent structural damage and heat losses through leaks. As has already been described in Section **Fehler! Verweisquelle konnte nicht gefunden werden.** (Design), the specification of a single airtight layer all around the perimeter and its consistent application in the planning and execution stages is of great importance. Usually the interior plaster of the wall area is chosen as the airtight layer in the solid construction that is to be built. Here, what matters is that the interior plaster is uninterrupted and is permanently joined with the other building components. Continuous interior plaster is achieved by:

- applying plaster on the masonry under inner window ledges using a spatula in order to prevent air flows through the hollow spaces in the masonry
- plastering the walls up to the bare ceiling
- "pre-plastering" of all areas that will not be visible later on, using a smooth layer of mortar early on at the bare brickwork stage (behind stairs, wall-mounted installations, lightweight and solid interior walls etc.)
- embedding empty sockets in plenty of fresh gypsum mortar
- careful plastering over of interior walls (masonry) as well

Airtight engineered wood panels are often used for lightweight timber constructions which must be joined at the gaps and connections to other building components using suitable adhesive tape and with sufficient movement tolerances. Here, too, the airtight level is usually on the inside of the wall or – at a distance from the inner planking for installations – on the inside of the supporting structure.

In all constructions, special must be given to permanent and preferably easy to create connections of the different building components with each other, so that careful planning of their execution is practicable and permanent airtightness of the building can thus be ensured (see [Peper/Feist 1999]).

The necessity for an airtight layer should not be confused with the requirement for protecting the insulation of the façade against outdoor air passing through it by means of windproof constructions (windtightness).

5.2 Windows and glazing

A thermally high quality of windows not only reduces the transmission heat losses of the building envelope, it also improves thermal comfort in the room due to lower radiation temperature asymmetry. As a result of this, the space can be utilised right up to the window. No heaters in front of or under the windows will be necessary for comfortable conditions if the thermal quality is adequate (see Section 7.1). Passive House suitable windows with heat transfer coefficients $U_W \leq 0.8$ W/(m²K) and triple low-e glazing and insulated window frames meet these high thermal requirements in all Central European climates.

In the context of energy retrofits it is sometimes also possible to use a lower thermal quality of windows provided that heating surfaces already exist near the window area. However, triple low-e glazing is especially interesting from the economic point of view.

In spite of the good insulation values of Passive House suitable windows, their proportion of losses is still far higher compared to opaque building components so that window areas often account for more than 50 % of the transmission heat losses of a Passive House building (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

The designer of a highly efficient educational-use building should be aware of the fundamental characteristics of glazing and window frames so that a critical assessment of the offered products is possible. Of course, there are also other important characteristics besides thermal protection and the energy "gain" function, which are desired and appreciated by the users on a daily basis: a visual link to the outside, daylight utilisation, ventilation and communication through window opening (in the summer). For this reason, windows are seen as particularly "valuable" building components also by the users, and it is especially important to avoid any potential defects.

Some fundamental characteristics and criteria for glazing and insulated window frames will be explained next in detail in order to provide the building designer with important criteria for making decisions. In the following sections, some aspects relating to special types of glazing (Section 5.2.2) and safety with regard to the opening of windows in school buildings (Section 5.2.6) will be explained in more detail.

5.2.1 Triple low-e glazing

With triple low-e glazing, U_g values between 0.5 and 0.8 W/(m^{2}K) are achievable depending on the gas filling, size of the spaces between panes and the type of coating. This is the approximate U-value that is achieved at the centre of the pane with vertically installed uninterrupted glazing! Added to this is the heat loss at the glazing edge. This is dealt with further on in connection with window frames. The U_g value of inclined glazing, e.g. in roof windows, or other sloping glazing is often much higher (about +25 %). As an approximate rule, it can be said that the U_g value for triple low-e glazing increases from 0.60 to 0.75 W/(m^{2}K) if the pane is installed with a 45 °inclination instead of vertically.

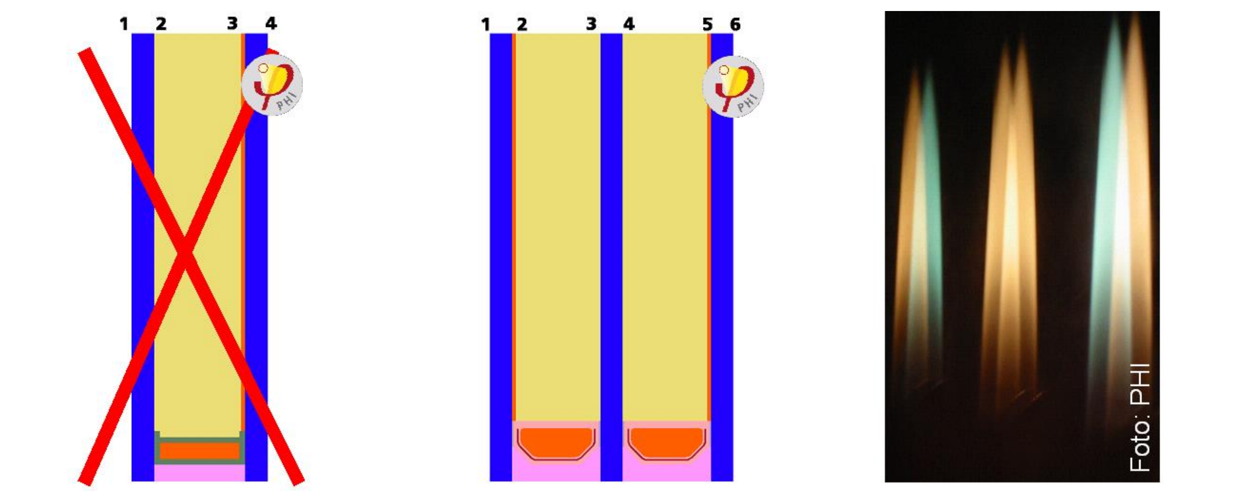
The total solar transmittance of triple low-e glazing is between 0.4 and 0.6 depending on the quality of the coatings. Normally, for Passive House buildings a g-value of more than 0.5 should be strived for. In the Central European climate the energy balance of triple low-e glazing will then always be more favourable than that of double glazing; this is also true of south-facing windows.

The requirement for the g-value can easily be estimated from the so-called Passive House **energy criterion** for glazing. This states that the g-value must not decrease too much at the cost of the U_g value. The following must apply:

$$\mathbf{g \cdot 1.6\ W/(m^2K) \geq U_g}$$

This condition can easily be checked for using the validated data (CE symbol) of the products. If it is met, then it will usually be possible to achieve net solar gains with such glazing during the main winter period provided that the windows are not shaded or unfavourably aligned. This ratio is only an empirical formula, the factor 1.6 applies only for Central Europe (Germany). It is therefore important that the exact specific values of the glazing are ascertained and entered in the [PHPP]. For the project at hand and using the boundary conditions, window orientation and shading given here, it will be calculated whether the quality of the selected glazing i.e. the U_g value and the g-value are suitable or adequate for the building. Further considerations in this respect can also be found in [Krick 2010].

High quality triple low-e glazing consists of three panes, two of which usually have a coating. These selective so-called 'low-emissivity' or 'low-e' coatings act like mirrors which reflect only the heat radiation that is the infrared light, for this reason they are not good at emitting heat. One coating is sufficient for each space between panes in order to reduce radiation exchange between two panes opposite each other. Normally the surfaces 2 and 5 (counting from the outside towards the inside) are coated (Fig. 21).



Coating on 3 g = 64 % $U_g \geq 1.1$ W/(m²K) Aluminium edge bond unsuitable for PH	Coating on 2+5 g = 52 % $U_g = 0.6$ W/(m²K) Thermally separated edge bond	Quick test: position of coatings: Reflections of a flame

Fig. 21: **Sequence of layers and edge bonds of triple low-e glazing. Double glazing with an aluminium edge bond are unsuitable for Passive House buildings. Triple low-e glazing usually has a 'low-e coating' on the surfaces 2 and 5. The Ug-values given here apply for the middle of the pane. The heat losses via the edge bond at the glazing edge must be calculated separately (Ψg value).** ***(Source: PHI)***

Incidentally, 'selective' reflection means that these coatings readily allow visible light to pass through, therefore the panes are transparent for the eye. Transparence in the visible spectral range (τ_{Vis}) is only very minimally reduced by the coatings so that it is almost impossible to differentiate between the visual impact of double and triple low-e glazing.

So-called 'solar control glass' with a purposely decreased g-value is not recommended for Passive House buildings in Central Europe. A separate shading element – roof overhang or roller blind etc. – can prevent overheating in summer far more effectively and can be opened in the winter when the solar heat gains are needed in the building. Venetian blinds can also be divided so that effective glare protection can be achieved in the lower part, while in the upper part the light can be diverted towards the ceiling.

In Central Europe, glazing for a Passive House building should have U_g values less than or equal to 0.8 W/(m²K). Standard glazing assemblies (argon gas filling, space between panes 2 x 16 mm) generally already achieve U_g values of 0.6 W/(m²K). It is possible to meet the energy criterion with various configurations of panes. With the energy balance method the U_g and the g-value must be entered for each combination of panes and coatings used in the project (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**), because additional panes or films for laminated safety glass will reduce the g-value. Tips on how to proceed in the case of special safety requirements can be found further on (Section 5.2.2).

Casement and compound windows that are suitable for Passive House buildings are also commercially available (list of certified products: www.passivehouse.com). These constructions are assessed positively. In these windows, a 'compound' of two low-e double glazing (2+2) is used in combination with an air space in which integrated blinds can be installed for sun shading which are protected from the effects of adverse weather. A 2+1 combination is also possible; this is advantageous particularly in windy coastal areas. In the case of schools, there is the added benefit of protection against vandalism because the blinds are safe from direct access. However, maintenance is easily possible because the double casements of the compound windows can be opened whenever required.

5.2.2 Special glazing

Requirements are placed on glazing in educational buildings both in terms of break resistance and personal protection. Glazing up to a height of 2 m above the stand area must not splinter or fall if damaged [DIN 58125]. This is deemed to be ensured if tempered safety glass, laminated glass, or heat-strengthened glass is used (see excerpt from GUV-SI 8027 further below).

While the use of tempered safety glass doesn't negatively affect the g-value, this is sometimes significantly reduced if laminated glass is used. The reason for this is firstly the fact that the used polyvinyl butyral film (PVB) absorbs some of the incident sunlight. Secondly the greater thickness of the glass that is necessary (2 x 4 mm float glass) decreases the energy transmittance. In cases where requirements for breakage resistance alone are applicable, the possibility of using tempered safety glass should be checked first.

If the glass meets the requirements for impact-resistant glazing, the use of laminated glass panes cannot be avoided. However, the pane build-up can be optimised with reference to the energy-relevant characteristics. The TRAV (technical regulations for the use of accident-proof glazing) provide a number of assemblies which manage with just one laminated glass pane, which are preferable in any case to assemblies with two laminated glass panes. In addition, the position of the laminated glass pane in the pane build-up is of relevance because the reduction of the g-value through a laminated glass pane on the outside is greater than can be achieved through one on the inside.

According to the TRAV, for certain uses a tempered safety glass pane which is more favourable in terms of energy can be used on the outside. This is the case if the impacted side is on the inside and laminated glass is also used on the inside.

If a pane build-up without safety glass has a g-value of 0.50, then this will worsen by up to 5 percentage points if laminated glass is used for the outer pane, i.e. it will become 0.45. If instead the inner pane is made of laminated safety glass, the g value is reduced by only 3 percentage points to 0.47. If the coating of the outer space between the panes is laid on the outside of the middle pane, the g-value is improved by 2 percentage points. In total the pane build-up of impact-resistant glazing can be chosen so that the g-value is reduced only by one percentage point.

Besides the g-value, the U-value of the glazing can also be worsened by the use of laminated glass if the space between panes is reduced as a result of the thicker glass assembly. This is avoidable in most cases because most Passive House suitable window frames still possess sufficient reserves to accommodate glazing units of up to 50 mm or greater. Even the glass assembly described above can be executed with 18 mm space between panes! The limiting factor for the space possible between panes is the size of the panes. If these are too large, the edge bond can no longer bear their weight and the intermediate space must be reduced. This should be enquired about at an early stage when planning the window design.

Based on the above statement, it must be clarified whether tempered safety glass, laminated glass or heat-strengthened glass has to be used. An exception is that there is no need to use break-proof glass if there is an 80 cm high parapet and the window reveal is at least 20 cm deep, or if some other type of protection against falling exists. As has already been shown in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, parapets are a good solution also in relation to the daylight concept.

Excerpt from [GUV-V S 1]: Glazing and transparent areas § 7 (1) In areas occupied by schoolchildren, glazing and other transparent areas must consist of breakage resistant materials up to a height of 2.00 m above the base, or should be adequately shielded.

Explanatory note on § 7 (1): Materials for glazing and other transparent areas are considered to be break-proof if, if no sharp-edged or pointed parts fall out during impact and bending stress (e.g. supporting out of the barrel).

Glazing that is not shielded should be executed using safety glass either as tempered safety glass or laminated glass. Wired glass is not sufficient for meeting the safety objectives. Glazing or other transparent areas are considered to be shielded if e.g.

- there are railings that are at least 1.00 m high and at least 20 cm in front of the glazing, or the glazing is positioned behind planted secured zones,
- in the case of windows the window parapets are at least 80 cm high and the window ledges are at least 20 cm deep,
- cabinets and display cases are located in secondary areas of special subject rooms.

It generally seems reasonable, also for cost reasons, to avoid the use of special glazing as far as possible by means of e.g. window parapets. However, in children's day-care centres, almost room high windows with the corresponding requirements for glazing are usually necessary for a visual connection to the outside. Special glazing is also often unavoidable in sports halls for withstanding ball impacts.

5.2.3 Insulated window frames

Besides the heat losses of the glazing itself, the losses due to an uninsulated window frame are also considerable. With a conventional window frame (U_f = 1.5...2 W/(m^{2}K)) the heat losses are more than twice as high as those with typical triple low-e glazing (U_g = 0.6 W/(m^{2}K)). High quality glazing therefore also includes a well-insulating window frame, because the frame ratios are relatively high with 30 to 40 % for typical window sizes.

In addition, the use of a thermally separated edge bond contributes significantly to a reduction in the heat losses at the glazing edge and can now be considered state-of-the-art for windows in energy efficient buildings (see Fig. 22).

The frame ratio or the glazing ratio generally refers to the building shell dimensions regardless of any extended insulation of the frame. Typical facing frame widths are about 120 mm (reveal and lintel) and 140 mm (parapet) both for optimised thermally insulated frames and standard window frames with an installation depth of 68 mm (IV68). With an average window size of 1.23 m x 1.48 m the frame ratio will be 34 %, for balcony doors (1.1 m x 2.2 m) this will still be 31 %. For smaller windows this quickly increases to more than 40 %. 'Second generation' insulated window frames (see Fig. 22) manage with a facing frame width of about 100 mm. This makes the frame ratio significantly smaller.

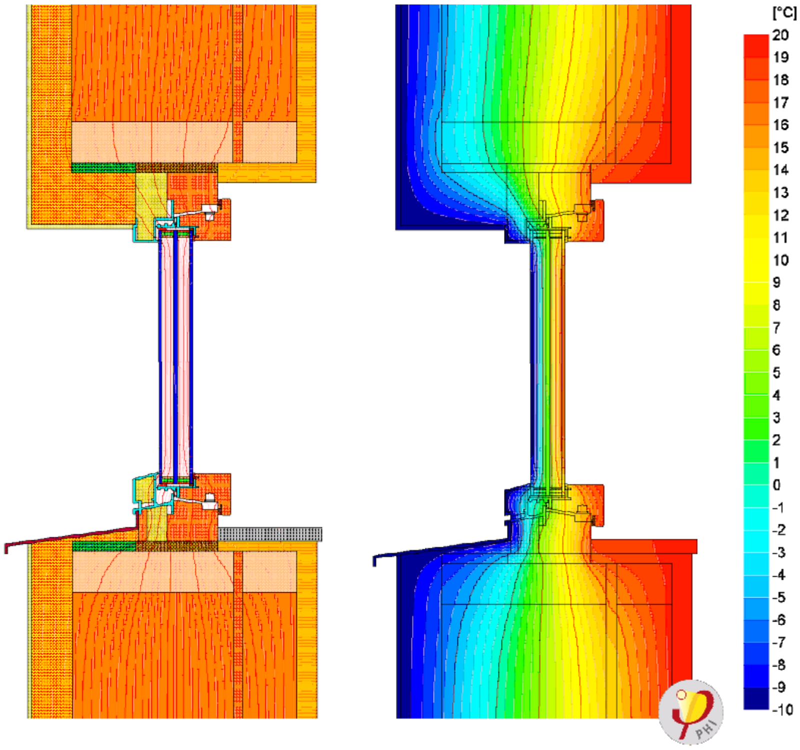


Fig. 22: 'Second generation' insulated window frame: Enlarged installation depth (120 mm) but narrow facing frame width (100 mm), thermally separated edge bond. Many other possible constructions are documented on [www.passiv.de].
U_f = 0.69 W/(m²K) (average value), Ψ_g = 0.033 W/(mK), U_W = 0.77 W/(m²K) for a window size of 1.23 m x 1.48 m and U_g = 0.7 W/(m²K)
(Source: PHI)

The most important measures for thermal optimisation of window frames are described in [AKKP 14] and [Schnieders 2000]. Newer developments can be found in [Kaufmann/ Schnieders 2002] and [AKKP 37] and in a list of manufacturers on www.passivehouse.com. Enlarging the installation depth of the frame in order to be able to accommodate an insulation layer is the first and foremost measure. An installation depth of 68 mm is too small for the Passive House even if thermally optimised materials with a low thermal conductivity as available today are used. A large number of well insulating window frames are available on the market today: sandwich scantlings with wood-Purenit-PUR-Purenit-wood result in an installation depth of about 110 mm. A similar construction is also available with wood-cork-wood-cork-wood (see www.passivehouse.com).

Some manufacturers produce wooden window frames with an insulating shell of cork, PUR, EPS or other insulating materials which are screwed or clipped on to the wooden frame instead of being bonded to this. In this way the construction can be easily dismantled into its parts for disposal. With window frames of synthetic materials the larger chambers of the profiles must be filled with insulation material. Insert strips milled from plate material are widely used. In the case of foam-filled profiles the bulk density of the material must be checked by the manufacturer because this greatly influences the thermal conductivity. The frames of box and compound windows achieve the required insulating value also as solid wood constructions on account of their large installation depth. However, with profiles made of synthetic material the chambers must always be filled with insulation material (see www.passivehouse.com).

In many cases, a facing shell of aluminium can be used to create a maintenance-free surface with improved weather resistance. What is important is that these aluminium profiles run only along the surface of the frame and do not interfere in the insulation layer. This is especially relevant if the frame is to be covered with extended insulation. In that case the aluminium profile must end at the plaster edge as otherwise the extended insulation will become ineffective in part.

The following rule applies when assessing a thermally insulated frame: Regardless of which material is used, care must be taken to ensure that the thermally insulating layer runs through the frame as uninterruptedly and 'straightly' as possible. Individual insulated inserts made of insulating material are not very effective. If you look at the isotherms in the frame profile, Figure 22, they should be as 'short' as possible, i.e. run through the frame profile in a straight line, because each swivel increases the effective surface through which heat is exchanged from the inside to the outside.

For the energy balance, all the necessary data for Passive House suitable windows that have been certified can be found on the Passive House Institute's website (www.passivehouse.com).

Thermally separated edge bond, higher glass insertion depth

Standard window frames have a glass insertion depth of just 15 mm. Furthermore, in a standard triple low-e glazing unit a spacer made of aluminium is used at the glazing edge, which constitutes a considerable thermal bridge.

Mitigation of the thermal bridge at the glazing edge takes place in two ways. A thermally separated spacer made of thin-walled stainless steel sheet metal (wall thickness $\leq$ 0.2 mm) or made of plastic profiles is used at the glazing edge (see [Kaufmann/ Schnieders 2002]). With an identical geometry of the frame profile, this allows the heat losses of a window to be reduced by up to 8 %. Another advantage is that due to the smaller thermal bridge effect, the formation of condensation at the glazing edge is virtually excluded.

A higher glass insertion depth is also thermally advantageous; according to recent studies, 25 to 30 mm are unproblematic (see [Pfluger et al. 2003]). However, newly developed frames have moved away from this because thinner profiles are increasingly sought by architects. For this reason, although the 'second generation' frames have an installation depth of more than 120 mm, their facing widths are only 100 mm (see Fig. 22); work on further improvement of the edge bond is ongoing.

Airtight window connection, suitability for use

Besides the thermal characteristics of a well-insulated window frame described here, airtight implementation of the circumferential seals (up to three sealing levels are now common), impermeability to driving rain, and functional reliability or suitability for use are of course also important for a long service life of the window.

Comfort criterion for Passive House suitable windows

The requirement for a U-value of less than 0.85 W/(m^{2}K) for an installed Passive House suitable window is derived from the requirements for thermal comfort and from the energy balance of the building (see [EN ISO 7730]). An average temperature of more than 17 °C at the inner surface of the window is recommended if a heater under the window is omitted, also in the design case, otherwise a pool of cold air may form near the floor so that comfort is restricted in the vicinity of the window. The requirement for avoiding mould growth results in a surface temperature of at least 13 °C at each point of the inner window surface with normal indoor air humidity levels, i.e. also at the glazing edge. With the thermally separated spacers mentioned previously and a higher glass insertion depth, this can be achieved easily (these criteria are tested for in the context of certification of a Passive House suitable window).

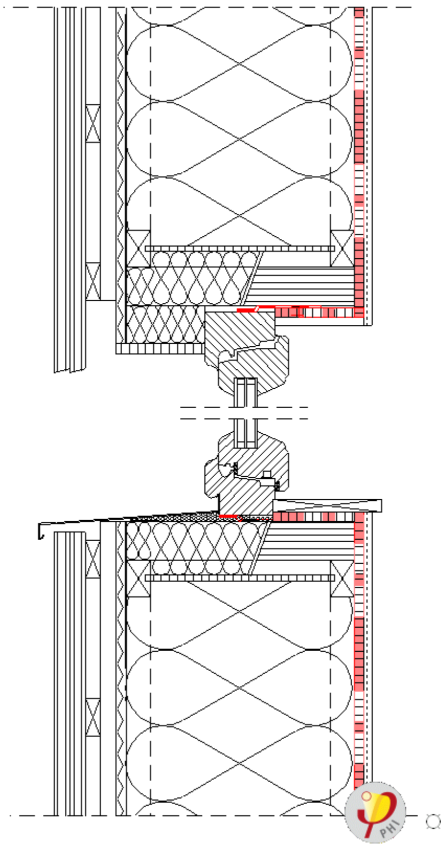


Fig. 23: Optimised installation situation: window in a lightweight timber wall. The window is positioned in the middle of the wall, i.e. in the centre of the insulating layer. The frame can be largely covered with extended insulation at the reveal and the lintel. The thermal bridge effect

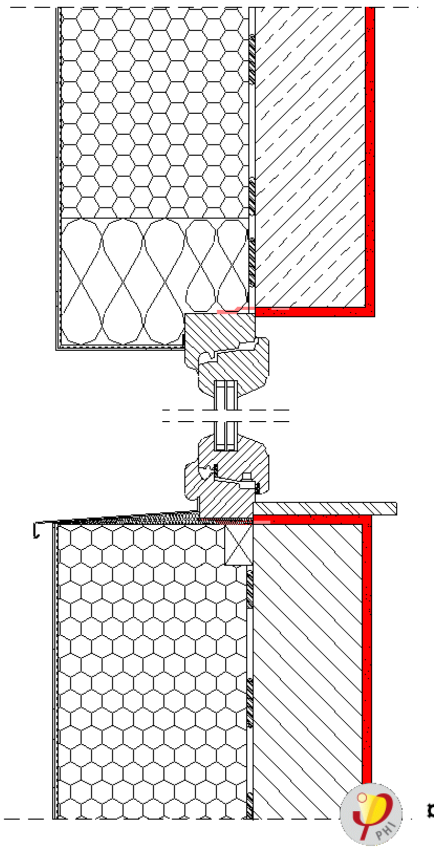


Fig. 24: Optimised installation situation: window with mounting bracket made of wood or recycled polyurethane material in a solid wall construction with a composite insulation system. The window is positioned in front of the masonry and thus moved far enough into

of structurally supporting elements should be taken into account.

$I_{installation}$ ≤ 0.014 W/(m²K)

$U_{W,installed}$ = 0.82 W/(m²K)

(Source: [Kaufmann/Feist 2004])

the insulating layer. The frame can be largely covered with extended insulation at the reveal and the lintel.

$\Psi_{installation}$ ≤ 0.03 W/(m²K)

$U_{W,installed}$ = 0.80 W/(m²K)

(Source: [Kaufmann/Feist 2004])

5.2.4 The installation thermal bridge at the window

A thermal bridge results when a window is installed in the wall. Typical thermal bridge coefficients $\Psi_{installation}$ of the installation details optimised for the Passive House building are 0.03 W/(mK) in the parapet area, because the frame can hardly be covered with extra insulation here due to the window ledge and water draining from the frame. With consistent extended insulation of the reveal and lintel (Fig. 24) it is also possible to achieve negative installation Ψ-values. The mentioned values refer to a wall with $U_{Wall} \leq 0.15$ W/(m²K). The aim is to comply with the limit value of $U_{W,installed} \leq 0.85$ W/(m²K) for the U_W-value of an installed Passive House window.

Fig. 25: Window installation with wooden brackets (below) and steel angles at the sides. Afterwards, a composite insulation system will be applied or the frame will be covered with extended insulation. [Kaufmann/Peper 2009]

In contrast, many conventional installation details exhibit extremely large thermal bridge effects. If the window is not positioned in the insulation layer as shown in Fig. 23 and Fig. 24, and is instead positioned further out from the middle of the wall assembly, affixed to a continuous board, or applied on the masonry in the case of solid constructions with a composite insulation system, then the thermal bridge losses due to unfavourable installation can become so high that in spite of using a thermally optimised window with $U_W \leq 0.8$ W/(m²K), a significant worsening will result for the installed window [Kaufmann/Feist 2004].

In general, the window should preferably be positioned in the insulation layer. This means that in relation to the completed wall with insulation, the window should sit in the middle of the window reveal. Compared to a conventional building, nothing will change for the residents except that the wall as a whole will be slightly thicker.

However, for a solid wall with a composite insulation system, the window must be attached in front of the masonry before the composite insulation system is installed. In Fig. 24 this has been achieved with a mounting bracket. The bracket may consist of wood or recycled PU material, which have a relatively low thermal conductivity. Such a bracket can be seen in Fig. 25. In addition, steel angles are affixed at the sides and above for attaching the window.

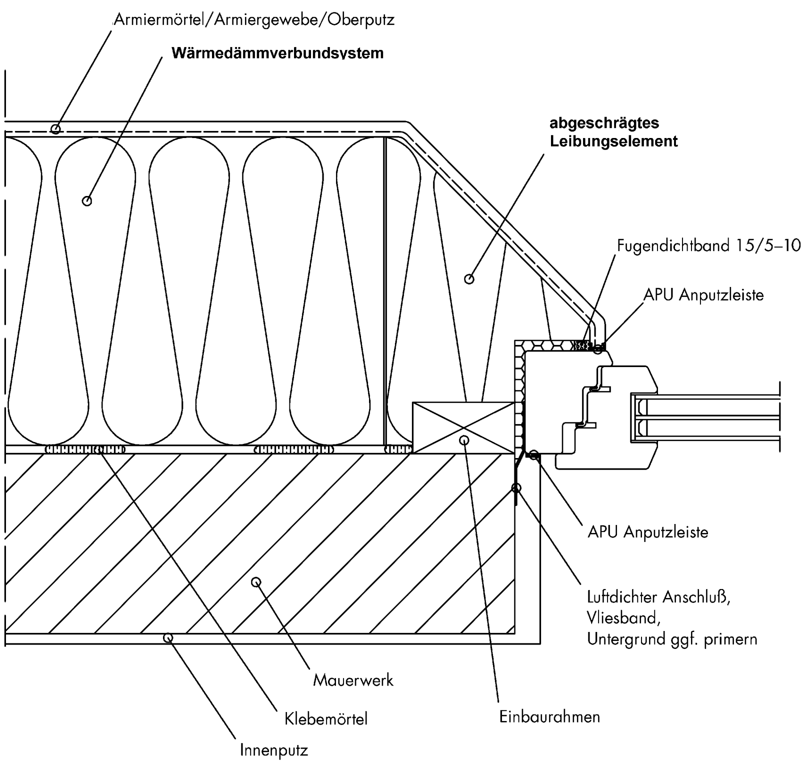


Fig. 26: One manufacturer offers a chamfered reveal element as a ready-made detail solution for their compound insulation system. The effect of insulation extended over the frame is largely maintained, while lateral shading by the reveal is significantly reduced. *(Source: ebök, Tübingen)*

For the certification of windows as Passive House suitable components (see www.passivehouse.com) the installation details for different wall systems which are developed by the window manufacturers are also checked besides the characteristics of the window. When using certified windows the architect can therefore draw on these installation details and does not have to carry out any further thermal bridges examinations.

It may be advantageous to chamfer the outer window reveal so that a large free spatial angle results and sunlight is less strongly shaded by the reveal. For thermal protection it does not matter whether the reveal is right-angled or chamfered. One manufacturer now offers ready-made chamfered moulded parts for the reveal made of mineral wool (fire safety), see Fig. 26. However, for south-facing windows it may make sense to have a lintel that has not been chamfered in order to obtain the desired shading in summer. In individual cases, optimisation should take place in the context of energy balancing (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Roller shutters and Venetian blinds

In principle, the use of roller shutters or Venetian blinds is also possible in Passive House buildings, but their installation causes an additional thermal bridge. If possible, front-mounted roller shutter boxes should be chosen which are positioned in front of an insulation layer that is at least 6 cm thick, so that condensation cannot form on the inner surface, or the solar protection should be suspended completely in front of the façade. With reference to airtightness, it is advantageous if Venetian blinds are operated electrically or by means of a crankshaft. Cable feedthroughs for the drive motor must of course be executed in an airtight manner [Kaufmann/Feist 2004].

5.2.5 External doors

External doors often constitute weak points in terms of thermal protection and airtightness; in addition, they are cost-intensive building components. For these reasons, even before specific products are selected it should be considered whether it is possible to reduce the number of external doors (plant room, store, equipment rooms).

Passive House quality

The door must achieve a U-value $U_{D,installed} \leq 0.80$ W/(m²K) in the installed state, for a test size of 1.10 m x 2.20 m. Airtightness is important: double circumferential door seals should be implemented at the top and both sides, and the threshold should have a single seal at least. The airtightness class 3 according to EN 12207 must be verified under the test climates d and e in accordance with EN 1121 (based on the length of the gaps): $\mathbf{Q_{100} \leq 2.25\ m^3/(hm)}$ at a pressure difference of 100 Pa. The installation of entrance doors must take place in an airtight and thermal bridge minimised manner (also at the door threshold). These values are stated in the certificate of certified Passive House external doors.

As an alternative, conventional entrance doors with high quality thermally insulating glazing can be used in the entrance area. This may be appropriate if only a few entrance doors are required for a larger building, but these will then be subject to high loads because they will be used very frequently (e.g. the main entrance doors of educational-use buildings. In that case it makes sense to choose highly durable conventional door constructions. On account of the large size of educational-use buildings, the lower thermal quality here can be easily compensated through other measures. In spite of this, the frame profiles of such door constructions must meet certain minimum requirements: the thermally separated frame profile muss have a maximum U_f-value of 2.0 W/(m²K). The insulating glazing must comply with the following requirements: $U_g \leq 0.6$ W/(m²K), g-value ≥ 50 %. The glazing should have a thermally separated edge bond (this means **no** aluminium). Airtightness is also important.

As a rule, French doors with a thermal quality in accordance with that described above for windows should be used for group rooms and childcare rooms where the doors are less frequently used.

Practicable solutions for airtightness

In the school in Frankfurt am Riedberg the user behaviour and also the airtightness of the entrance doors during practical operation were examined in more detail [Peper et al 2007]. For permanently airtight entrance doors, compression seals in the threshold area are also recommended. A ledge is required for this type of construction. As a rule, rebate gaskets can also be used in educational buildings with sufficiently low ledges. Brush seals do not achieve an adequate level of airtightness. Fig. 27 shows the door seals of two Passive House schools. Tightly closing doors reduce unwanted infiltration and exfiltration. During operation, correct functioning of the door closer and the door seals should be checked regularly on account of the intensive use.

Fig. 27: **External doors with drop down and compression seal. Entrance doors should have a rebate seal, where possible. Entrance doors of Passive House schools (left: Frankfurt Riedberg, Architecture: 4a, Stuttgart / right: Schulpavillon Walldorf, Architecture: IB W. Herrmann, Walldorf).**

5.2.6 Windows – safety-related and architectural aspects

"Adequate natural ventilation should be possible in all rooms of children's day-care facilities where children are present" - this is stated in paragraph § 7 of the **German statutory accident insurance** regulations for childcare facilities which also applies to other educational-use buildings until the regulations for schools have been revised [GUV-SR S2]. This requirement takes precedence also in the case of educational-use buildings that have been built according to the Passive House construction method irrespective of mandatory mechanical ventilation. In terms of the prerequisites for construction, it must be possible to ventilate the rooms used by persons in educational-use buildings during the summer months independently of the ventilation system. For one thing, this is a measure which can avoid year-round operation of the ventilation system and the associated electricity consumption at least in part. On the other hand, experience has shown that users wish to ventilate via sufficiently large window areas and generally do not accept closed windows or window casements that are too few in number or are too small (see Section 8.2).

For this reason, for example the city of Frankfurt stipulates in its "Guidelines for economically efficient construction" [Linder 2009]: "For natural ventilation, it should be ensured that there are at least 0.1 m² per seat of openable casement windows in classrooms with cross ventilation, and at least 0.3 m² per seat without cross-ventilation. This also applies if a mechanical ventilation system (Passive House) is used." If only bottom-hung windows are foreseen for ventilation then it usually won't be possible to achieve an adequate ventilation cross-section for a classroom or a group room in a day-care centre even with a large number of openable casements. However, a few French windows will be sufficient if side-hung casements are used.

Nevertheless, it is not always possible to use side-hung windows without problem. The statutory accident insurers stipulate in paragraph § 10 Abs.2 [GUV-V S1] that "windows must be designed so that schoolchildren are not endangered during opening and closing as well as in the opened state." For this reason, side-hung window casements are completely avoided or are equipped with turn locks so that the windows can only be opened up to the front edge of the window ledge. However, with this solution the opening area is only slightly bigger than with bottom-hung casements. Statutory accident insurers however specifically point out that their recommendations for achieving the necessary safety are not binding and that "other, at least equally safe solutions" are not excluded, see information relating to implementation instructions [GUV-V S1].

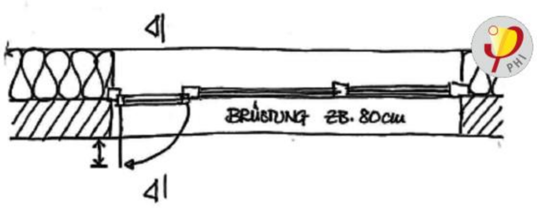


Fig. 28: Narrow openable casements which project only marginally beyond the inner window reveal. Architecture: BLFP, Friedberg / Building Services: Neuplan, Gießen *(Source: PHI [AkkP 33])*

Accordingly, it is worthwhile to take advantage of the advisory services of accident insurers at an early stage during the planning phase, and to find an optimised solution for the respective project with regard to safety and natural ventilation that is necessary also for the Passive House Standard. For example, a potential design might be a narrow side-hung casement which projects only slightly beyond the window ledge due to the deeper reveal resulting from the Passive House suitable window installation.

Another possibility would be to have opening leaves or French windows open against a partition wall or to only use swinging leaves in the skylight area. It must also be clarified whether the windows can be opened by every pupil or only by teachers. Here there can also be a difference in the assessment of the accident risk.

Another aspect which must be kept in mind when allocating the window areas is ensuring natural cooling down at night during the summer months. For example, in educational-use buildings in the city of Frankfurt a.M. measures for natural night-time cooling down are mandatory in order to reduce running costs through shorter operating times of the ventilation system: "in addition, sufficiently large night-time ventilation flaps with appropriate protection against break-ins and insects should be provided in order to avoid overheating in classrooms and group rooms in the summer." [Linder 2009].

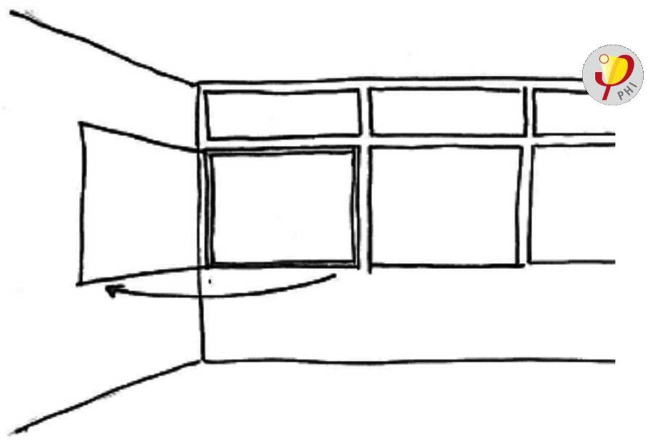


Fig. 29: Window casement opens inwards, but stops against a partition wall in order to avoid the risk of accidents. ***(Source: PHI)***

As with daytime ventilation, the necessary opening cross-sections for natural night-time cooling down are closely associated with the possibility of cross-ventilation through the building in contrast with room-by-room ventilation (see Section 8.4). Because windows are opened outside of the times of use for cooling down at night, the accident insurers' regulations for prevention of accidents are usually not relevant in this case. It is advisable to check these in time; nevertheless, requirements for burglary protection must be clarified.

5.3 Roofs

In general, with roof constructions a distinction can be made between ventilated (cold) and unventilated (warm) roofs. In a ventilated roof the assembly is diffusion-open towards the outside, due to which the assembly appears to be less problematic with regard to moisture. In contrast, in the case of unventilated roofs the outer sealing is diffusion impermeable. In terms of building physics this assembly is more critical and requires special care during planning and execution. In the area of educational-use buildings, at least in new constructions one often finds flat roofs which are usually also executed as unventilated warm roofs.

Both types of constructions are also possible as a superinsulated roof, both as solid constructions and as lightweight constructions made of timber or metal. With the Passive House Standard, roofs should achieve U-values between 0.15 and 0.10 W/(m²K), whereby extremely good U-values can be achieved relatively inexpensively by insulating the high bearing elements of wood in wide-spanning flat roofs (see Fig. 30).

Fig. 30: Assembly of the timber construction roof elements of the Montessori school in Aufkirchen. A load-bearing sub-construction was omitted in favour of large spans and high beams. By using correspondingly thick insulation between the supports, a U-value of 0.10 W/(m²K) was achieved very inexpensively [Vallentin 2006]. Architecture: Walbrunn Grotz Vallentin, Bockhorn. (Picture: G. Vallentin)

The basic principles of building physics apply for superinsulated roof assemblies just as they do for conventional roof assemblies – paying attention to moisture-related requirements for a diffusion-open or diffusion-tight roof is imperative. Besides the avoidance of thermal bridges, careful attention must be given to airtight execution of the construction especially in the roof area (see Section 5.3.4 on airtightness).

The Protocol Volume of the Research Group for Cost-effective Passive House buildings on the subject of „Hochwärmegedämmte Dachkonstruktionen“ ("Highly insulated roof constructions") [AkkP 29] offers a substantiated explanation of the basic principles in terms of building physics and the practical execution of the different roof constructions arising from these. It shows that the requirements for

Passive House suitable roof constructions ensure unproblematic execution in terms of building physics and thus constructions that are failure-free.

5.3.1 Ventilated roof (cold roof)

Ventilated constructions are more common for pitched roofs because greater effort is necessary with flat roofs or sloped flat roofs in order to ensure sufficient ventilation of the construction. The ventilation space must be sufficiently high and the beams must not hinder air flow. In the area of educational-use buildings ventilated roofs are more likely to be found with smaller units such as extensions and smaller children's day-care centres or with existing buildings.

A major advantage of a ventilated construction is seen in the fact that condensation and building moisture can be dried up through ventilation. However, in spite of ventilation, the inner cladding of such a construction must at least be vapour retardant ($s_d \geq 2$ m) in order to prevent excessive amounts of water vapour from entering the construction. The careful and airtight installation of the vapour retarder is also an important point in this respect. Convection of water vapour through leaks can lead to considerable amounts of condensation, which cannot be removed even with a ventilated construction (see [Feist 2004]).

It must also be kept in mind that the load-bearing structure of the roofing usually penetrates the thermal insulation, which leads to additional heat losses in the superinsulated roof and must be taken into account e.g. with the corresponding percentage of wood in the calculation of the heat transfer coefficient.

5.3.2 Unventilated roof (warm roof)

The unventilated flat roof can be executed with smaller construction heights, both in solid and lightweight constructions (timber or metal construction). Both types of constructions are also possible as superinsulated roofs.

Since the upper seal is diffusion-tight in the case of an unventilated roof, the penetration of water vapour must be prevented on the inside by means of a vapour barrier. An essential prerequisite for this is carefully planned and executed airtight installation of the vapour barrier, especially in the area of joints and at the connections to other building components, in order to prevent convection of water vapour. The scheduled pressure test that is necessary in a Passive House building in any case should be used for quality assurance of the roof construction.

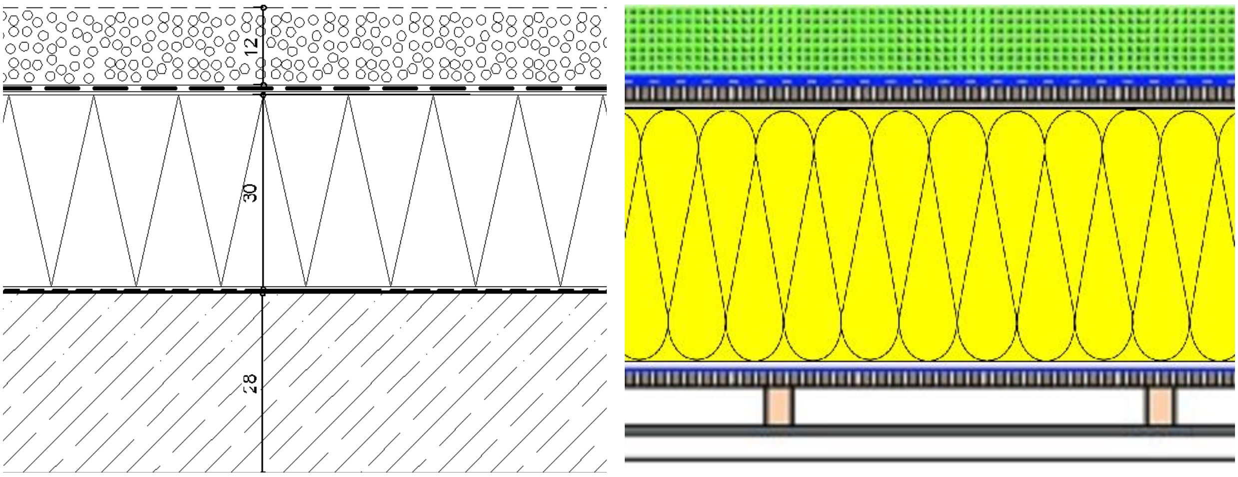


Fig. 31: **Left: Riedberg school in Frankfurt. Unventilated flat roof with solid supporting structure. Source: 4A Architekten, Stuttgart. Right: Montessori school in Aufkirchen. Unventilated greened flat roof with lightweight supporting structure and moisture adaptive vapour retarder.** ***(Source: Walbrunn Grotz Vallentin Architekten, Bockhorn, [AkkP 29])***

In order to make an unventilated construction more fault-tolerant, it is appropriate to have a so-called moisture-adaptive vapour retarder instead of a vapour barrier on the inside (mathematical verification of protection against condensate is necessary for this). This has the property of being sufficiently vapour tight in winter ($s_d \geq 5$ m), and almost diffusion-open ($s_d \leq 0.3$ m) during the drying phase. A construction with a moisture-adaptive vapour retarder must also achieve a good level of airtightness (see [Kah 2004]).

As in the case of ventilated roofs, in warm roofs too it must be ensured that attachment points of any roof coverings that penetrate the insulation layer are executed in a thermal bridge minimised manner. This can be realised e.g. using wooden structures such as wooden I-beams, Z-shaped beams, box beams etc.

However, a metal covering and/or supporting profiles made of metal are also possible as superinsulated roof constructions. Fig. 32 shows a solution for flat roofs. A mounting rail is placed on the thermal insulation and attached to the substructure with long screws. The thermal insulation is fixed in place by this mounting rail system and the metal covering is also held in place at the same time. Because the thermal bridges only occur individually and in a punctiform manner due to the fastening screws, this assembly is comparable with a roof construction consisting of wooden I-beams in respect of the losses through thermal bridges (see [Kah 2004]).

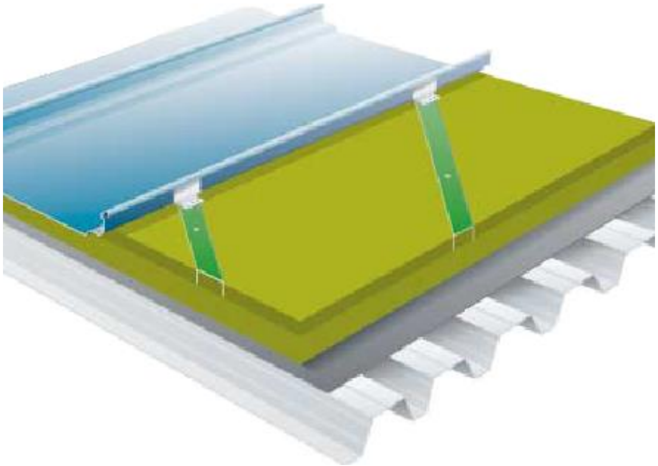


Fig. 32: **Unventilated flat roof with metal cladding (see [Kah 2004]). The metal covering is held in place by means of a mounting rail system and fastening screws, which simultaneously attach the thermal insulation. (Source: Rockwool company brochure)**

The inverted roof constitutes a special feature of warm roofs. In order to reduce temperature fluctuations at the roof sealing membrane, in this construction the thermal insulation is laid above the sealing membrane. Insulation thicknesses that are adequate for Passive House buildings are achieved with factory-bonded extruded polystyrene insulation panels. A water-carrying, diffusion-open separating layer must be laid on top of the thermal insulation in addition. This largely prevents rainwater from running over the roof covering (under the thermal insulation) and causing heat losses as a result. Further explanations relating to this can be found in the Protocol Volume of the Research Group for Cost-effective Passive House buildings on the topic of „Hochwärmegedämmte Dachkonstruktionen“ ("Highly insulated roof constructions") (see [Kah 2004]).

5.3.3 Thermal bridges

As for the rest of the building envelope, with roofs also it must be ensured that the insulating effect of the area is not weakened through thermal bridges. Of course attention must be given to the pencil rule also in the case of a roof, i.e. the principle of a continuous, gap-free insulation envelope enclosing the building all around (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). If thermal bridges are unavoidable, they must be minimised through careful planning and execution. Otherwise, in addition to an increase in the heating demand there is a risk of damage due to the temperature falling below dew point in the area of the thermal bridge. A solution for connecting a solid wall construction to an inclined timber roof construction without an overhang is shown in Fig. 33 and Fig. 34.

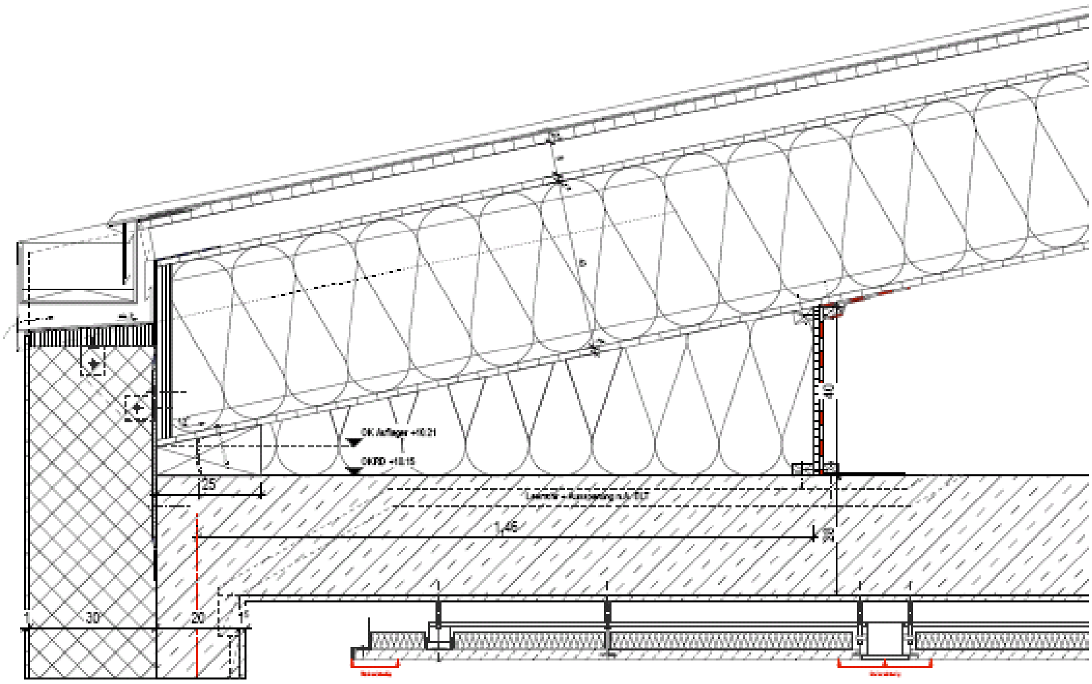


Fig. 33: **Roof connection without overhang, special needs school in Frankfurt a.M.** ***(Source: Hausmann Architekten, Aachen)***

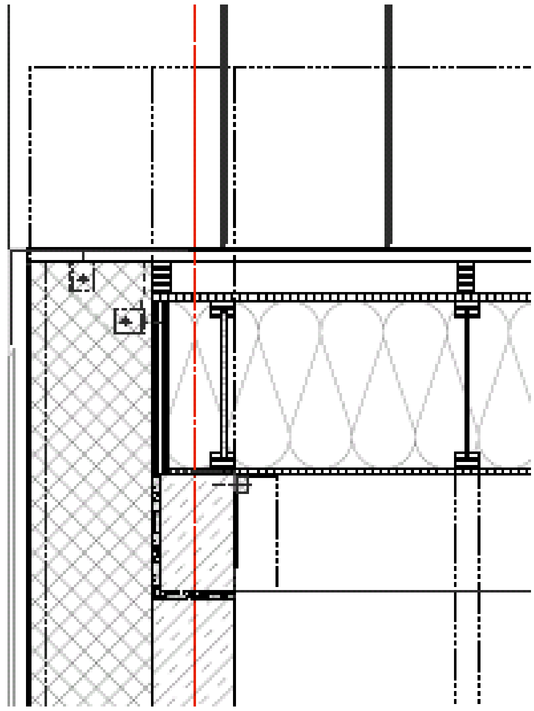


Fig. 34: Verge without roof overhang, special needs school in Frankfurt a.M. ***(Source: Hausmann Architekten, Aachen)***

Flat or inclined roofs of which the roof edges are executed as fascias or overhangs are often chosen for school buildings. A concrete fascia represents a geometric thermal bridge due to the enlarged surface area, even if it is insulated all around. From the structural perspective if it is possible to dispense with a concrete fascia then insulated "boxes" made of engineered wood panels or concrete panels – or as a narrower variant – upturned beams of engineered wood panels should be preferred which merely form the upper finish of the façade insulation (see Fig. 35). These constructions also have the advantage of a hard base for gluing the roof foils, in contrast to an insulated concrete parapet.

Fig. 35: **Fascias made of engineered wood panels. The fascia merely forms the upper finish of the façade insulation. The compound insulation system of the exterior wall is continued up to the horizontal end board. Adalbert-Stifter-Schule in Wiesbaden. Architecture: Hügemeier und Thrun Architekten, Wiesbaden**

If roof overhangs are foreseen, these can be realised in a thermal bridge minimised manner even in solid roof constructions. Thus for example in the Albert-Einstein-Schule in Schwalbach a. Taunus projecting rafters were located in the insulation layer of the roof, as shown in Fig. 36.

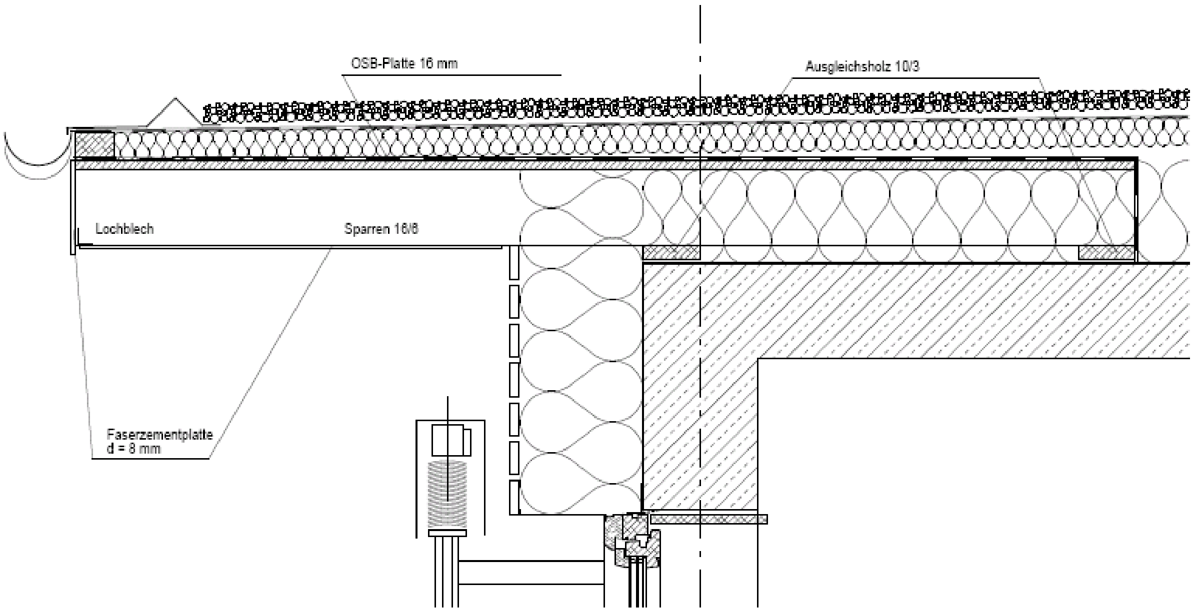


Fig. 36: **Unventilated flat roof with solid supporting construction and thermal bridge minimised overhang. Albert-Einstein-Schule in Schwalbach. Heimel + Wirth - Architekten, Frankfurt.** ***(Source: Heimel + Wirth Architekten)***

Just as in the case of airtightness, with regard to thermal bridges the principle of avoidance also applies for penetrations of the insulation envelope. Thus for example, where possible roof vents should be preferred over a rainwater downpipe on the roof. Internal rainwater downpipes can also be dispensed with if the drainage from flat roofs to the edge areas takes place and can then be routed in front of the façade without thermal bridges.

5.3.4 Airtightness

When it comes to the roof area, the topic of airtightness is especially relevant for reasons of preventing structural damage. In a heated building (during the heating period), there is excess pressure on the top floor almost permanently due to thermal buoyancy (see [Feist 2004], [Peper 2004]). This leads to air flow from the inside (usually more humid air) towards the outside through remaining leaks. This humid air cools down on its way towards the outside and it can no longer "hold" its moisture content in the cooler state (temperature falls below dew point). As a result the moisture may accumulate inside the structure. If water in at least the same amount does not dry out again periodically, the proper functioning of the construction (thermal insulation, structural stability of the construction) will be impaired or even disrupted).

For this reason, besides absolutely indispensable airtightness across the surface, permanently airtight connection of the roof to the other building elements is of particular importance, especially in the case of warm roofs with a roof assembly that is diffusion-tight towards the outside and is confined by a vapour barrier on the inside. With its already high requirements for airtightness, the Passive House Standard specifically offers greater security against structural damage.

On account of the more favourable surface area to volume ratio, larger buildings may often have a lower n_{50} value than the Passive House limit value of $n_{50} \leq 0.6\ h^{-1}$. Fig. 37 shows a list of pressure test results of educational-use buildings. In the case of sports halls in particular, experience has shown that excellent pressure test results are achievable on account of the large and compact building structure.

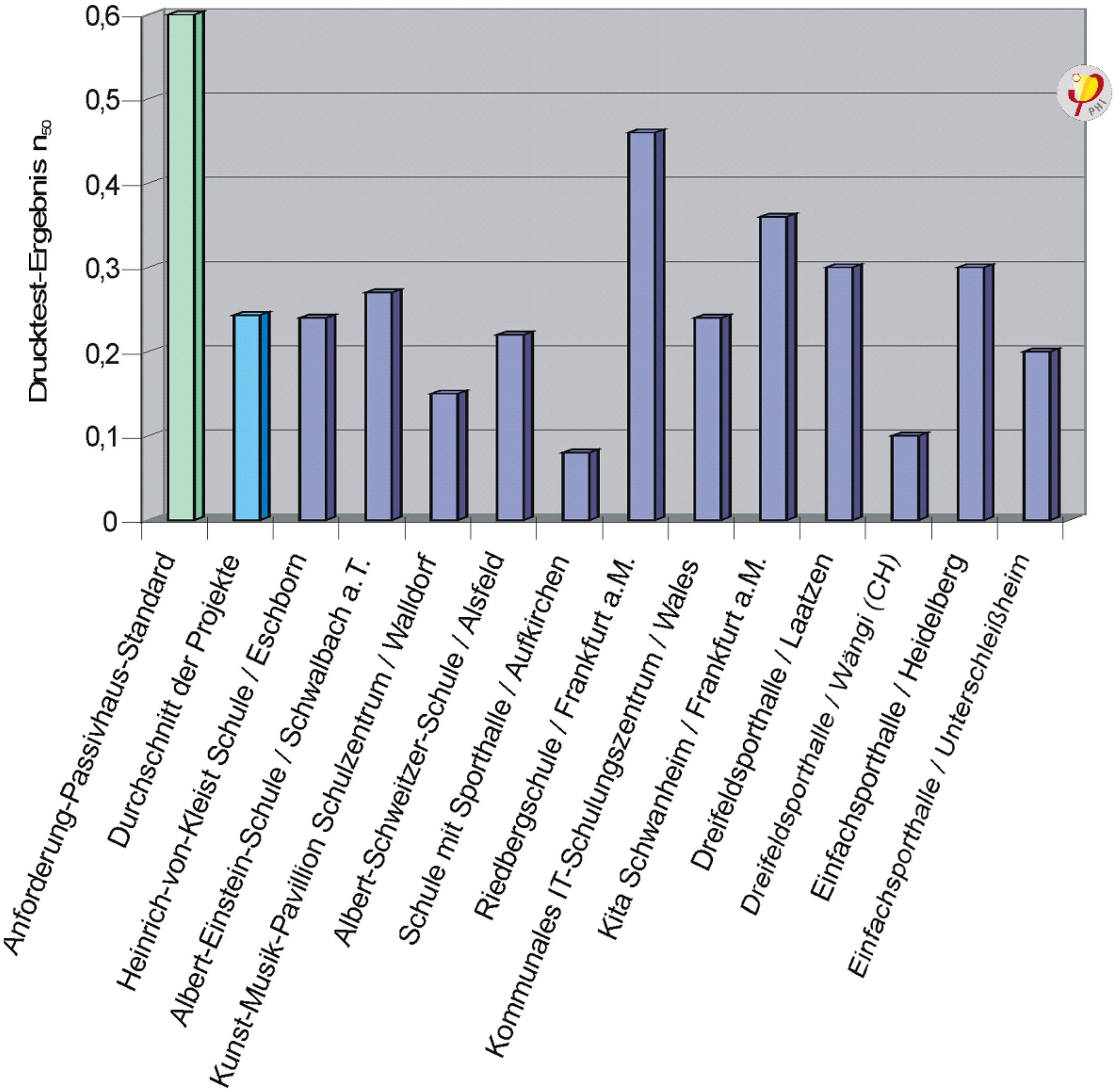


Fig. 37: **Example pressure test results in Passive House buildings for educational use. The value is often much lower than that specified in the Passive House requirement.** ***(Source: PHI)***
Anforderung-Passivhaus-Standard= Passive House Standard requirement, Durchschnitt der Projekte= average of projects, Druck-Test Ergebnis

5.3.4.1 Connections

In order to ensure airtightness in the roof, the materials of the airtight layer must be permanently joined with each other on the one hand, and on the other hand special attention must be given to airtight connection of the roof surface and the wall. Choosing the right kind of connection and materials depending on the type of surface (engineered wood, sheeting, concrete, masonry) is decisive here. The various materials for connections according to the type of building components to be joined are described in [Peper 2004]. For example, there are special flexible adhesive tapes for airtight connection of hard engineered wood boards or membranes which can also withstand structural movements to a certain extent without damage. For example, the connection of engineered wood boards as the airtight layer in the roof and the wall plaster is created using strips of sheeting which are stuck to the engineered wood boards and tightly joined with the plaster by means of a plaster base. Attention should be paid to the manufacturer's instructions when choosing the connection materials, and only products for which permanent bonding of the respective building components is guaranteed should be used.

Fig. 38: **Airtight taping of joints of the engineered wood boards using special adhesive tape. View of the ceiling from underneath in the Walldorf school pavilion. Architecture: IB W. Herrmann, Walldorf.**

Due to the expected structural movements (e.g. roof to wall connection), the sheeting should not be attached to the wall in a taut manner and should instead be installed with sufficient slackness. In this way the connection will also remain airtight if the plaster in these areas becomes cracked due to movements. This has already been confirmed through measurements in many buildings (see [Peper et al 2005a]).

5.3.4.2 Penetrations

The principle of minimising the number of penetrations of the building envelope described in Section **Fehler! Verweisquelle konnte nicht gefunden werden.** (Thermal Bridges) also applies for reasons of airtightness. For example, avoiding downpipe vents via the roof not only reduces heat losses, but also avoids potential leaks.

Some manufacturers supply adhesive collars for necessary penetrations of airtight engineered wood boards or sheeting by cable feed-throughs and pipes. These are offered for diverse applications and with different pipe and cable diameters.

Besides the already mentioned careful planning, the coordination of the trade disciplines and adequate communication are also crucial for airtight execution of penetrations. Fig. 39 shows the consequences of poor planning of the work processes relating to sealing. A cable installed in a wall hasn't been covered with plaster yet but the airtight layer of the roof with PE sheeting has already been joined to the plaster. A significant leak thus exists in the area of the cable feedthrough which can only be sealed with considerable effort later on (see [Peper 2004]).

Fig. 39: **The cable feedthrough in the wall is not plastered in although the roof connection has already been created by joining the sheeting. [Peper 2004]**

Further detailed explanations of problems and example solutions can be found in the article "Highly-insulated roof constructions" by Sören Peper (Research Group for Cost-effective Passive Houses, Protocol Volume 29) [Peper 2004].

5.3.5 Special features in existing buildings

For the highly heat-insulating renovation of flat roofs, the so-called Duo Roof System is a possible construction (see [Kah 2004]): The new insulation layer is applied to the existing roof insulation on a possibly repaired roof waterproofing and above it a water-bearing, diffusion-open separating layer. In a way, an unventilated flat roof is thus combined with an inverted roof (see Section 5.3.2). The roof membrane will then run between the insulation layers and is thus protected from excessive temperature fluctuations. On account of the diffusion-tight sealing membrane over the existing insulation, it must be checked whether a well-functioning diffusion-inhibiting layer is present under the existing insulation; if necessary, this must also be improved.

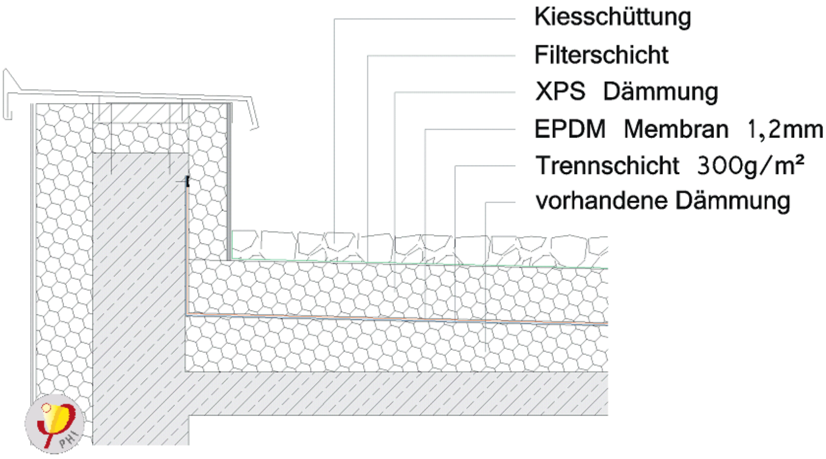


Fig. 40: **In a duo-roof, thermal insulation above the roof membrane that is too thin is doubled.** ***(Source: PHI [Bastian et al. 2010])***
Kiesschüttung…=loose gravel, filter layer, XPS insulation, EPDM membrane 1.2 mm, separation layer 300m/m², existing insulation

Inclined roofs are more common in retrofits of educational-use buildings than they are in new builds. Here the type of roof renovation depends greatly on the span width of the beams or on their dimensions. The rafter heights in existing wooden constructions usually are not sufficient for accommodating the necessary insulation thickness. Here there is the possibility of enlarging the rafters through doubling, lashing on, or adjacently placed I-beams. Frequently, changes to the old rafters are necessary anyway for reasons of structural stability on the one hand, and on the other hand the insulation between the existing rafters can be combined with on-roof insulation or under-rafter insulation.

A large range of possible solutions and a comparison of the described timber constructions with reference to their insulating effect and costs can be found in the article by Berthold Kaufmann in Protocol Volume 29 „Hochwärmegedämmte Dachkonstruktionen“ ("Highly insulated roof constructions") [Kaufmann 2004] and in the handbook "Retrofits using Passive House components" [Bastian et al. 2010]. Examples applied in retrofits are also provided here for ways in which superinsulated roof constructions can be realised with restricted construction heights. The decision is often made in favour of insulation materials with lower thermal conductivities especially in the case of retrofitting from the inside when the existing roof covering is not to be renewed (e.g. polyurethane, λ up to 0.024 W/(mK) is possible) in order to achieve good insulation values [Kaufmann 2004].

It must be ascertained on a case-by-case basis whether the beam height in timber constructions with larger span widths is sufficient for Passive House suitable between-rafter insulation. In metal constructions the primary insulation is realised as on-roof insulation on account of the high thermal conductivity of the beams.

The roof connections should be included in considerations about the position of the insulation, in order to avoid unacceptable thermal bridges in the eaves and verge or fascia area. The main problem here is the increased insulation thickness towards the inside as the thermal bridges at the verge and load bearing partition walls can only be mitigated with difficulty in this case. Compliance with moisture-related requirements and the location of the airtight layer must also be included in the decision relating to the roof assembly.

A frequently met obstacle when insulating the façade are very small roof overhangs. In the area of the verge this can be remedied by means of roof batten extensions which are special U-profiles made of steel (see Fig. 41). In this way, a roof overhang of up to 450 mm can be created for the façade with little effort. In the area of the eaves this extension can be achieved using tapered wood segments (firring). The roof covering in this area is simultaneously raised by the firring so that thermal bridge free connection of the roof or top floor ceiling to the façade insulation can also be achieved here without on-rafter insulation [Bastian et al. 2010].

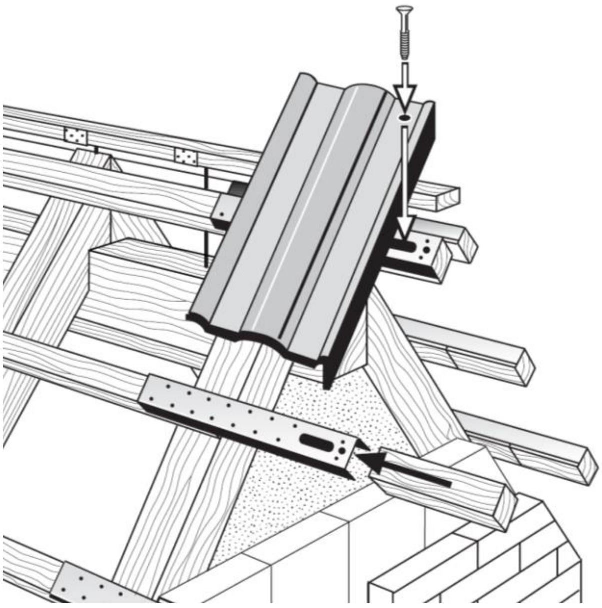


Fig. 41: **<u>Left:</u> adjustment of the roof overhang at the <u>verge</u> for insulation of the gable wall with the aid of U-profiles for roof batten extension *(Source: Fleck GmbH)***
<u>Right:</u> extension at the <u>eaves</u> by means of "firring" on the existing rafter. The connection of the façade insulation to the insulation of the top floor ceiling can be carried out without gaps (Nuremberg, Jean-Paul-Platz, architect: Dr. Burkhard Schulze Darup, Nuremberg).

In the case of educational-use buildings that are to be modernised, a question that often arises concerns dealing with solid projections or ornamental façades e.g. cornices/mouldings. Such building components usually constitute huge thermal bridges and enclosing these in insulation is definitely necessary here. Whether such architectural features determine the character of a building or whether one can dispense with them should always be clarified in each individual case. In the former case reference is made to Protocol Volume No. 32 of the Research Group for Cost-effective Passive Houses which deals with Passive House components and interior insulation in sensitive old buildings (see [AkkP 32]).

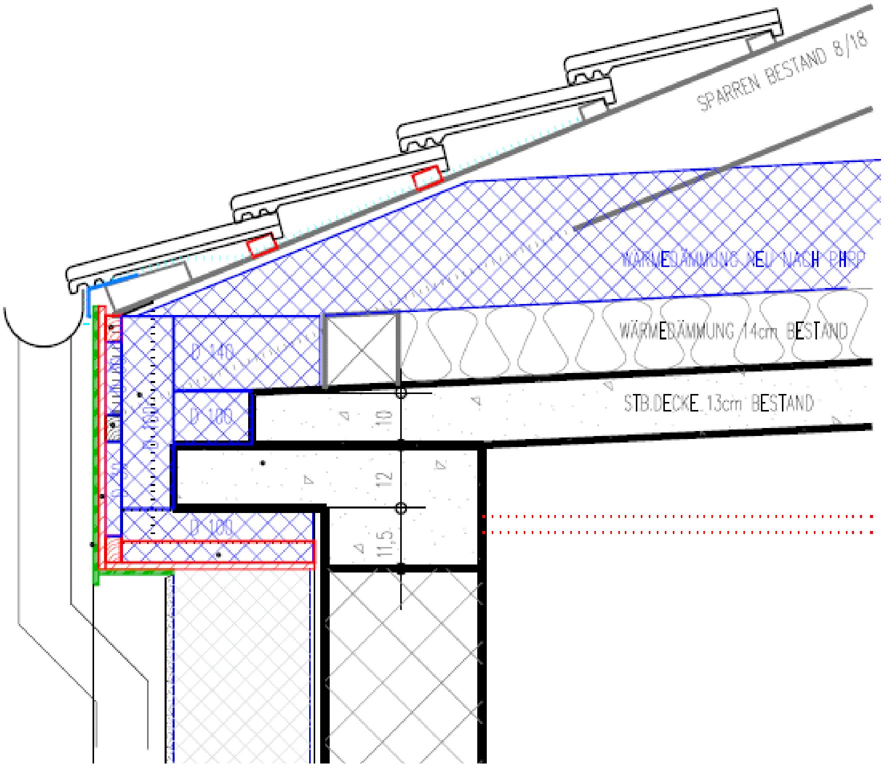
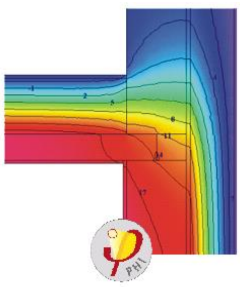
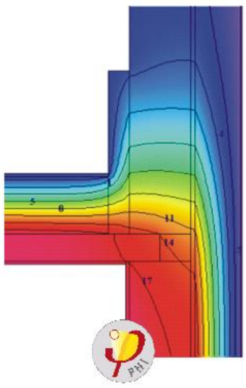
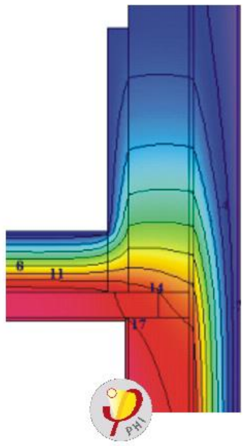
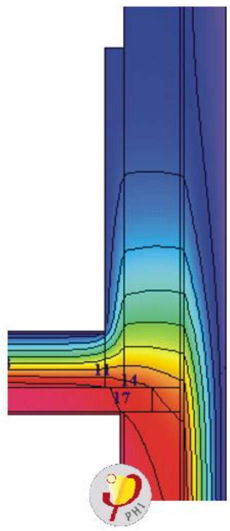


Fig. 42: **Enclosing of existing mouldings, retrofit of a residential building in Schlesierstrasse in Ludwigshafen.** ***(Source: GAG, Ludwigshafen)***

In the case of an unused attic floor and a roof construction that is worth preserving it may be appropriate to simply lay the insulation on the top floor ceiling. Insulation of the top floor ceiling – even without any initiating repair measures – is one of the most profitable thermal protection measures. (See Research Group for Cost-effective Passive Houses "Step-by-step refurbishment with Passive House components" (Protocol Volume No. 39), article by Zeno Bastian [Bastian 2009]).

Nevertheless, thermal bridges result with insulation of the top floor ceiling due to rising gable walls and other partition walls leading into the unheated roof area. Studies in an example building have shown that this quite significant thermal bridge can be halved by a rising gable wall with 10 cm thick and 50 cm high flanking insulation on the inside. A further slight improvement is achieved with a flanking insulation height of 1 m. However, increasing the flanking insulation even further no longer has any significant effect (see Table 1). The same occurs with partition walls. However, the rising walls of the studied example building consist of hollow blocks. In the case of walls with a higher thermal conductivity (solid blocks or reinforced concrete) a higher thermal bridge coefficient is also likely, which may make longer flanking insulation appropriate [Bastian 2009].

Table 1: Connection of the gable wall to the insulated top floor ceiling with different flanking insulation lengths on the inside (length of gable wall: 2 x 10 m). ***(Source: PHI [Bastian 2009])***

			
Size of flanking insulation at the gable wall [cm]:			
none	10 x 50	10 x 100	10 x 150
Thermal bridge coefficient Ψ-value [W/(m²K)]			
0.127	0.064	0.055	0.055

Thermal bridges generally should not occur at the top of stairwells. If these are enclosed all around in thermal insulation as part of the heated zone (including a thermally insulated and airtight door towards the roof area), then ideally penetrations of the insulation layer will not result here.

Carrying out retrofits in a step-by-step manner – instead of all at once – may also be appropriate in the case of educational buildings. Most energy saving measures for existing buildings will only be cost-effective if work on the relevant building component is needed anyway. Despite all the advantages of complete modernisations, this principle usually cannot be observed for all building components, because not all components will need to be renovated to a similar extent. The particular challenge when carrying out a step-by-step modernisation is to take into account the effects of the individually implemented measures on other energy-saving measures which will be carried out years later in some circumstances. The Research Group for Cost-effective Passive Houses "Step-by-step refurbishment with Passive House components" (Protocol Volume No. 39) deals with this issue in great detail and demonstrates based on many examples that an optimal final state can also be achieved through modernisations that are not carried out all at once [AkkP 39].

5.4 Cold basements

5.4.1 General requirements

The lower end of the heated building volume towards the cold basement or towards the ground presents a special challenge with regard to thermal protection. The construction loads and traffic loads must be safely transferred into the foundation ground. Due to larger span widths and multiple floors, these loads are often greater than in residential buildings. At the same time, thermal bridges caused by walls or supports which penetrate the insulation layer must be avoided or at least significantly mitigated as far as possible. However, problems with thermal bridges will be mitigated if during the heating period the soil always has a higher average temperature than the outdoor air, so that the heat losses are lower with the same level of thermal protection.

The higher average temperature of the ground and the basement in the main winter period compared to the outdoor temperature is taken into account in energy balancing methods using temperature correction factors. Often, overall factors are applied. More accurate calculations determine the influence of the soil depending on the building and its location. A corresponding method has been incorporated into the Passive House planning tool [PHPP] ("Ground" worksheet in accordance with [EN ISO 13370]). Underground car parks below heated buildings are an exception. Due to the high amount of air flow for removing fumes the temperatures in the garage are closer to the outdoor temperatures (temperature correction factor close to 1).

Usually, buildings for educational use don't have a pronounced demand for unheated storage areas, therefore a full basement with the thermal envelope at the basement ceiling level tends to be the exception. For a partial basement with plant rooms, it is recommended that these areas are integrated into the thermal envelope in order to allow maximum utilisation of the heat losses caused by heat generation, storage and distribution for heating the building.

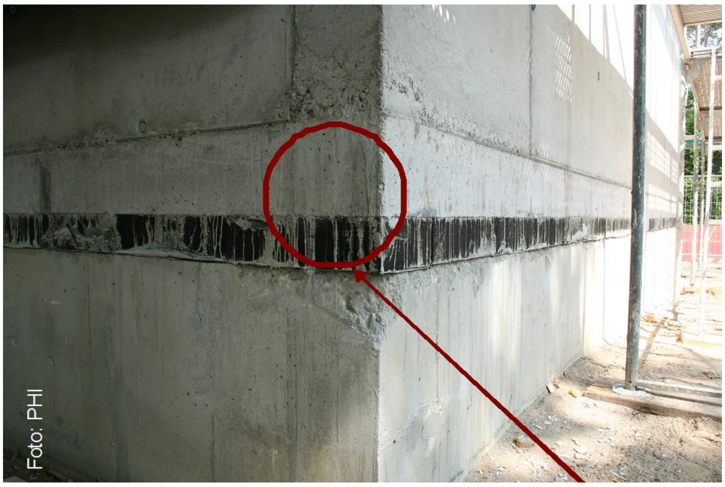
Nevertheless, if a cold basement is implemented, then thermal insulation can be installed on or under the basement ceiling. A combination of insulation on and under the basement ceiling is also possible. As exterior insulation, insulation under the basement ceiling is on the right side in terms of building physics. However, if a large number of beams become necessary due to large span widths, insulation under the basement ceiling will become more elaborate and the beams will constitute thermal bridges even when completely enclosed in insulation. In addition, creating an insulation layer underneath the basement ceiling insulation can be quite complicated if many installation lines have to be integrated.

Insulation panels can simply be applied to the basement ceiling from underneath using adhesive, screws or dowels. A high quality visible surface for the insulation is generally unnecessary in the basement area. However, a smooth plaster coat on the insulation panels is imperative in order to minimise heat losses through convection in the gaps between and above the panels. For the same reason, when using insulation panels preference should be given to prefabricated products with a tongue-and-groove system with which the panels can be joined in a largely gap-free manner. Such panels are also available on the market as sandwich constructions with an already prepared visible surface. If a small installation height is desired then high-performance insulation materials can be used, for example made of PUR, or even vacuum insulation in partial areas. In the case of several pipes it may be appropriate to create a suspended ceiling which can then be filled with blown-in insulation material or packed with insulation.

5.4.2 Thermal bridges

5.4.2.1 Masonry walls

As described in the beginning, walls and supports should not penetrate the basement ceiling insulation without thermal separation in order to avoid high heat losses caused by these thermal bridges. Using offset blocks with a reduced thermal conductivity for masonry walls is a tried and tested and low-cost solution in housing construction. Depending on the position of the insulation level in the masonry layer, these are used directly below or above the basement ceiling. Different materials can be used, such as porous concrete, lightweight concrete, lime-sandstone, bricks, or foam glass, so that all the commonly used compressive strength categories for masonry construction can be covered. In this way, a reduction in thermal bridge losses of the otherwise continuous masonry wall of approx. 50 to 90 % can be achieved (see [AkkP 35]). This is generally the most cost-effective variant for solid constructions.



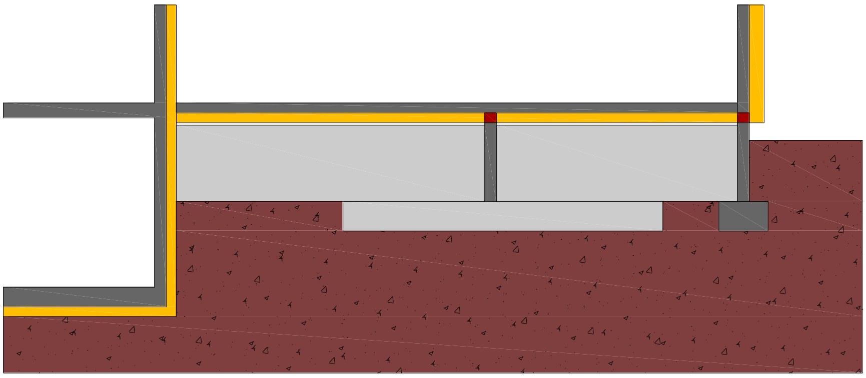


Fig. 43: **Thermal separation of the basement walls by means of foam glass panels, Schul-Pavillon Walldorf / Architecture: IB W. Herrmann, Walldorf.**

5.4.2.2 Reinforced concrete walls and columns

The solution with offset blocks is naturally ruled out in the case of reinforced concrete walls. However, penetrating reinforced concrete walls represent a massive thermal bridge, but it is possible to achieve a significant improvement simply through the use of reinforced concrete columns instead of walls. In this way, despite the higher degree of reinforcement of columns the heat losses can be reduced by about two-thirds due to the considerably smaller cross-section of the columns. It only makes a slight difference for the amount of heat losses whether columns with a large cross-section and less reinforcement, or narrower columns with more reinforcement are used for transferring the same load.

A reduction in the heat losses by about a half can be achieved by means of so-called flanking insulation. For this, about 1 m of the column is wrapped in 10 cm thick thermal insulation after the basement ceiling has been insulated. Lengths greater than 1 m will only lead to a slight reduction in the heat losses.

5.4.3 Airtightness

Insulation on the basement ceiling in principle constitutes interior insulation, with the familiar building physics relevant risk of condensation forming on the cold side of the insulation if executed incorrectly. In the case of insulation on the basement ceiling, in general the airtight layer should therefore lie on the upper side of the insulation - i.e. in the warm area, which is correct in terms of building physics. This does not apply for very small insulation thicknesses which are supplemented with insulation underneath the basement ceiling.

For insulation under the basement ceiling the reinforced concrete ceiling can form the airtight layer. Even then, the airtight layer of the exterior walls should be connected carefully; for example, this means that the wall plaster must be consistently continued down to the unfinished floor.

5.4.4 Basement stairs

Entrances to cold basements represent a special challenge in the creation of a continuous, airtight and thermally insulating building envelope. In the case of basements meant for bicycle storage or for rarely used storage cellars it may therefore make sense to dispense with an internal basement staircase and realise access from the outside instead. If internal stairs to the basement are necessary for use-related reasons, the staircase can be situated either within the heated building volume or outside this (see Fig. 45). In the former case, the airtight and thermally insulated basement door will be at the lower end of the stairs, in the latter case it will be at the upper end of the basement stairs. Sufficient space must be foreseen in the building planning for insulation of the envelope areas of the basement entrance.

Fig. 44: Ceiling insulation and flanking insulation of the walls of the basement staircase after modernisation (source [Kaufmann et al. 2009])

An open entrance to the basement with a connected air space between the heated building volume and the cold basement should be avoided as this leads to extremely high heat losses. When preparing the energy balance of the building using the [PHPP], these losses can be estimated approximately using an equivalent heat transfer coefficient of 12 W/(m²K) for the staircase cross-section if heat transfer takes place downwards from above [Peper et al 2005].

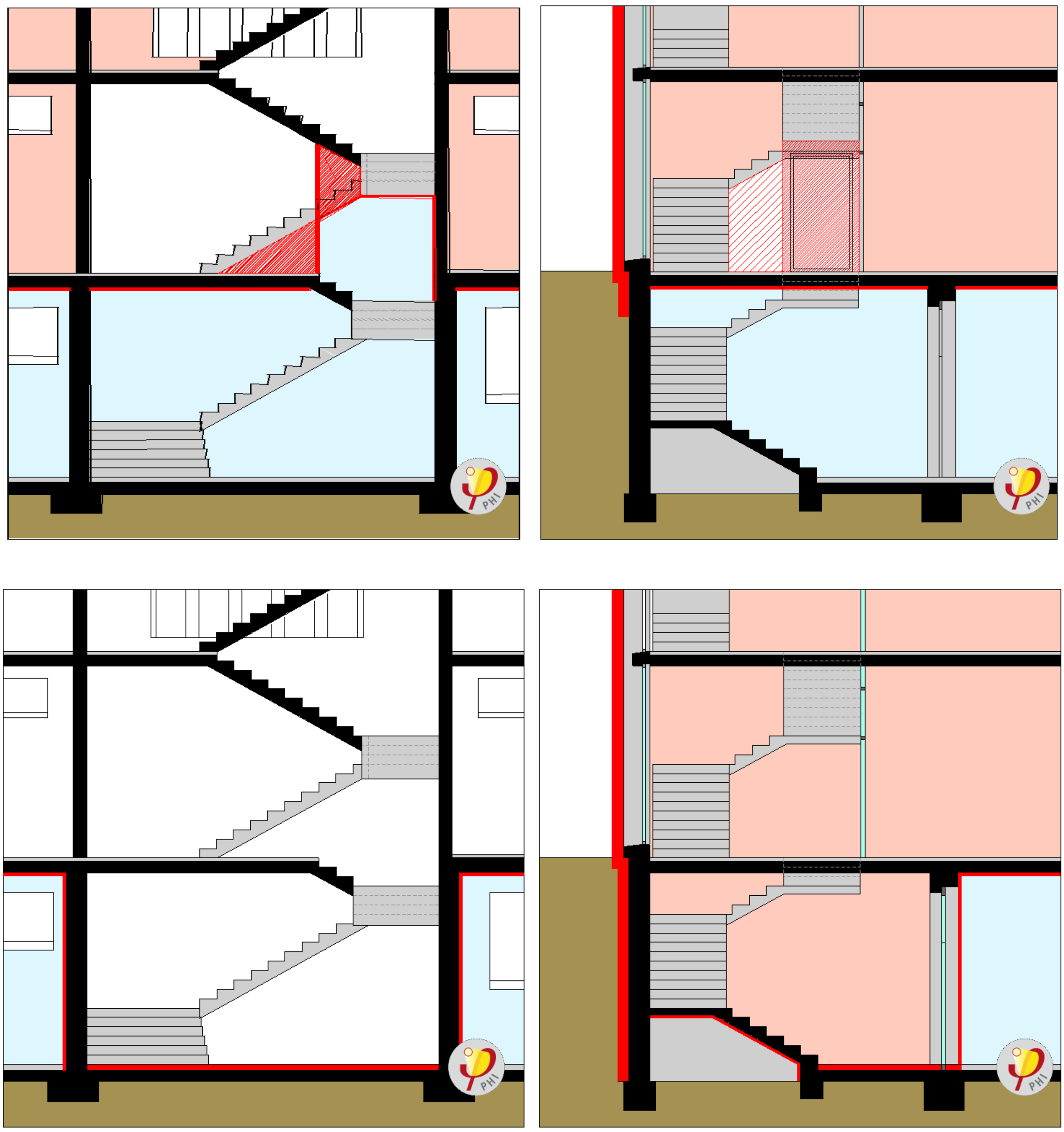


Fig. 45: **Entrance to basement outside of the heated building volume (above) or within this (below).** ***(Source: PHI)***

5.4.5 Specific features with modernisations

The possibilities for integration of the basement into the heated building envelope are restricted in modernisation measures. Enclosing the foundation in insulation is no longer possible afterwards and digging out the exterior walls of the basement is associated with considerable costs. This is often only worthwhile if the basement walls have to be renovated from the outside anyway, e.g. for reasons of protection against moisture. The position of the interior insulation in the basement area must be considered carefully because the offset point from the exterior insulation to the interior insulation is associated with significant thermal bridges. These can, and must be, mitigated in such a way that problems in terms of building physics (temperature falling below dew point) do not result; even so, they limit the energy savings that can be achieved with this modernisation measure.

5.4.5.1 Insulation on the basement ceiling

For this reason the thermal insulation is usually applied in the area of the basement ceiling during modernisation, i.e. the basement remains unheated. However, various difficulties arise when applying larger insulation thicknesses above the basement ceiling due to raising of the finished floor level caused by this. Thus, besides a reduced ceiling height, the clearance height of existing doors will also decrease. Apart from this, a step may possibly result at the transition to the staircase. For this reason, as a rule only high-performance insulation materials such as vacuum insulation are possible for insulation on the basement ceiling only as these achieve a good insulating effect with extremely small thicknesses. If the insulation thickness under the basement ceiling is restricted due to a small room height, it may be appropriate to supplement this with a few centimetres of insulation above the basement ceiling.

5.4.5.2 Insulation under the basement ceiling

A particularly low-cost form of subsequent building insulation is insulation under the basement ceiling. There are often limitations here on account of the already quite small room heights in basements which do not permit large insulation thicknesses. In addition, when executing the basement ceiling insulation it must be ensured that doors or windows with just a small distance between the upper edge and the ceiling can still swing wide open after installation of the basement ceiling insulation. Pipes for water and heating are often found near the basement ceiling which may make it difficult to attach insulation panels. Shut-off valves etc. must still be easily accessible and must not be covered by insulation materials. If the basement ceiling is damp, the cause of moisture accumulation must first be found and eliminated before the thermal insulation can be installed.

5.4.5.3 Flanking insulation of walls and columns

Walls and columns which penetrate the insulation layer act as thermal bridges. Since the solution with offset blocks as described in Section 5.4.2.1 is usually ruled out in existing buildings because the effort for cutting open walls and replacing a complete brick course is too high, the only option remaining is to reduce heat losses by means of flanking insulation similar to that described in Section 5.4.2.2. As a general rule of thumb, a length of 50 cm for the flanking insulation is adequate for masonry walls, while about 1 m is advisable for reinforced concrete walls and columns on account of their higher thermal conductivity. The flanking insulation should be executed both on the interior walls as well as on exterior walls. The exterior wall insulation should be extended downwards beyond the basement ceiling at least to the top of the ground. This will also prevent the formation of condensation by raising the interior surface temperature at the edge of the basement ceiling.

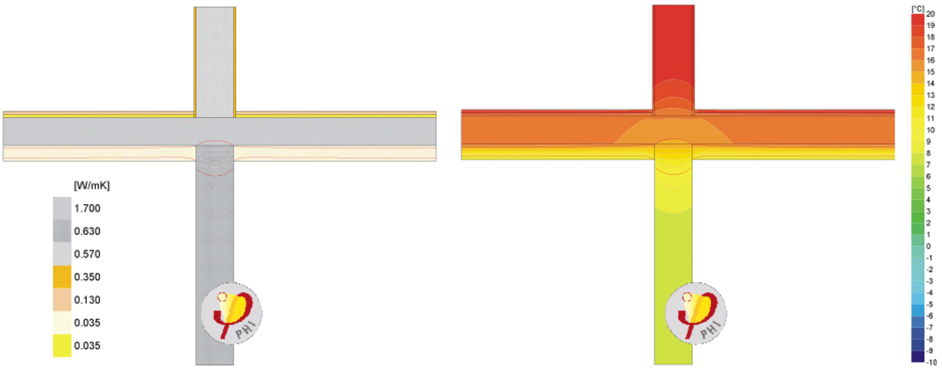
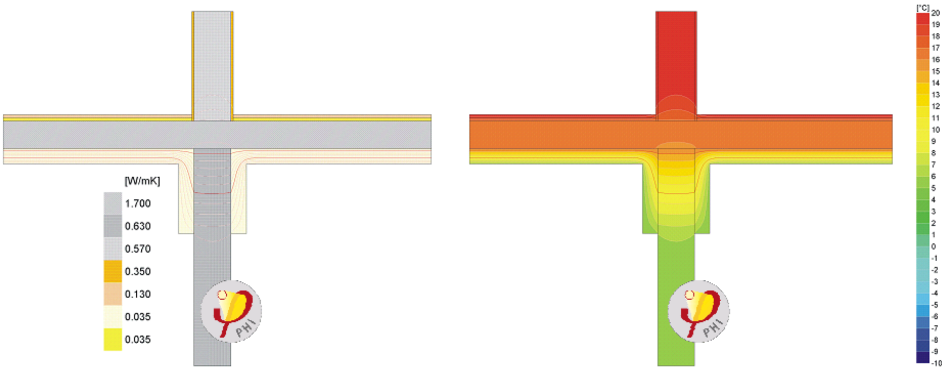
Interior wall of basement (masonry) to basement ceiling (U = 0.249 W/(m²K) **without flanking insulation** 		
flanking insulation	**Ψ value of wall [W/(mK)]**	**additional heat loss per 1 m of wall [W]**
none	0.322	4.83
interior wall of basement (masonry) to basement ceiling (U = 0.249 W/(m²K) **with flanking insulation 55 cm x 100 mm** 		
flanking insulation	**Ψ value of wall [W/(mK)]**	**additional heat loss per 1 m of wall [W]**
55 cm x 100 mm	0.135	2.03

Fig. 46: **Interior wall of basement, without (above) and with (below) flanking insulation *(Source: [Kaufmann 2009])***

5.4.5.4 Airtightness

Existing reinforced concrete ceilings can be used as the airtight layer, in which case a major share of the insulation thickness should then be below the basement ceiling in order to avoid the temperature at the basement ceiling falling below dew point. For other ceiling constructions, for example reinforced brick ceilings it must be checked whether additional measures for achieving airtightness are necessary. For example, this may mean the laying of anhydrite screed directly on the unfinished ceiling or additional airtight sheeting.

5.4.5.5 Staircase to basement

If the building has an open staircase leading to the unheated basement, it is advisable to create a defined finish with an airtight and thermally insulated cellar door. As a rule it will be easier to realise this finish at the upper end of the staircase. If the stairs are to be thermally insulated at the top then the insulation thickness must be based on the step height so that deviating slopes at the first or the last step can be avoided. The geometry of the airtight and thermally insulated building envelope in the area of the basement entrance can be relatively complex. Careful consideration with the help of several sectional drawings or a three-dimensional model is needed for achieving an optimal solution.

5.4.5.6 Damp basement

Due to retrofitting of the basement ceiling with thermal insulation the desired objective of a significant reduction in the heat flow from the heated building volume into the unheated basement will be achieved. However, this also has the consequence that the average temperature in the basement will drop. With the same amount of absolute humidity, the relative air humidity in the basement will then rise, which can lead to damage from moisture and mould growth in the worst case. An effective countermeasure is to raise the temperature of the interior surface of the exterior walls of the basement by extending the exterior wall insulation up to at least the top of the ground. Ventilation of the basement will only have a positive effect if it takes place according to humidity levels i.e. when the air in the basement has a higher absolute moisture content than the outdoor air. This can be realised using an extract air system with a humidity sensor. The study "Influence of basement ceiling insulation on moisture levels in basement spaces" (see [Schnieders 2009]) presents the interrelationships in a comprehensive way. This can be downloaded free of charge from www.passivehouse.com.

5.5 Insulation of the floor slab

Buildings for educational use often do not have an unheated basement or only some building parts have a basement, in which case the heated area above the floor slab is directly adjacent to the ground. The necessary thermal insulation can be positioned either above or below the floor slab, or in both ways. The heat losses especially of buildings that have a large base area can be reduced even further through additional use of an insulation skirt in the perimeter area.

The reduction factor for heat losses towards the ground can be determined in the "Ground" worksheet of the [PHPP] (see Section 5.4.1).

5.5.1 Insulation on the floor slab

Insulation on the floor slab can be implemented inexpensively because there are no high requirements relating to compressive strength and moisture resistance of insulation materials, therefore low-cost standard insulation materials such as EPS can be used.

A disadvantage is that the interior and exterior walls penetrate the insulation layer and form thermal bridges as a result. With masonry walls these heat losses can be reduced by using offset blocks with a low thermal conductivity as with the basement ceiling insulation (see Section 5.4.2.1). Because this is not possible with reinforced concrete walls and columns, at least combining this with a single layer of thermal insulation under the floor slab is recommended here.

In principle, thermal insulation only above the floor slab constitutes interior insulation, therefore it must be checked whether the temperatures on the upper side of the floor slab can fall to the extent that unacceptable moisture accumulation cannot be ruled out. An increase in the surface temperature of the edge area that is at most risk can be achieved by installing a short insulation skirt (ca. 50 cm) in the perimeter area. Apart from this, the insulation thickness on the floor slab should be limited to a maximum of 250 mm. In deviation from the recommendations for interior insulation of exterior walls, a vapour retarder must not be positioned above the thermal insulation because otherwise moisture from the ground diffusing through the horizontal barrier on the floor slab can accumulate inside the thermal insulation. This topic is dealt with in detail in [AkkP27].

5.5.2 Insulation under the floor slab

Positioning the thermal insulation under the floor slab has some advantages with reference to the avoidance of thermal bridges. The insulation layer is not interrupted by any walls and can join seamlessly with the thermal envelope in the exterior wall area. However, special attention must be given to a continuous insulation layer in the foundation area.

5.5.2.1 Slab foundations

Load-bearing floor slabs without further foundations (foundation slabs) constitute the best solution in terms of building physics because these can be executed in a completely thermal bridge free manner. The loads are transferred to the ground through the insulation material under the floor slab. This should have building authority approval for this application. Such approval is now also available for Passive House suitable insulation thicknesses (up to 30 cm).

5.5.2.2 Strip footings

Pad and strip footings are a low-cost alternative to foundation slabs if the construction ground is good. It is important that the insulation layer below the footing is also uninterrupted, as otherwise the heat losses will increase drastically. Porous lightweight mortar (λ = 0.11 W/(mK)) can accommodate extremely high permanent compressive stresses of up to 1 MN/m². Foam glass panels (0.38 MN/m²; λ = 0.055 W/(mK)) or XPS (0.25 MN/m²; λ = 0.040 W/(mK)) can be used for slightly lower stresses [AkkP35]. If necessary, less expensive thermal insulation that is suitable for use in the soil can be used under the floor slab.

For load transfer reasons, footings often have to be widened if they are insulated underneath. From a certain depth of the footing in the soil, it must be considered whether insulation underneath makes sense. With flanking insulation of differential walls, insulation around and under the actual foundations can be neglected, depending on the depth.

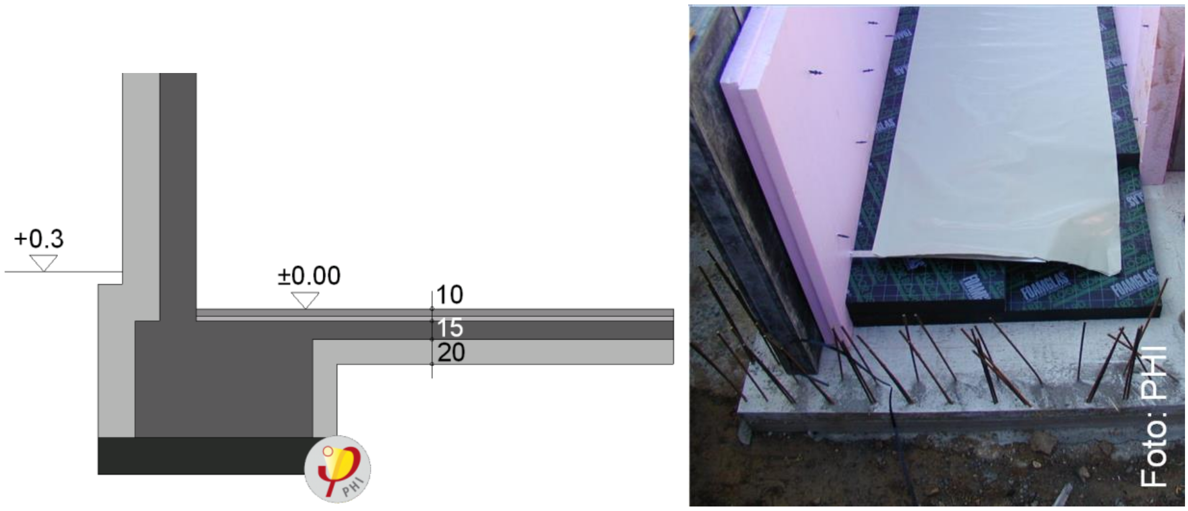


Fig. 47: **Insulation around a strip foundation with XPS at the sides and foam glass panels underneath. Heinrich-von-Kleist School, Eschborn**
Architecture: Heimel + Wirth, Frankfurt

Compared to a single slab foundation, footings always lead to slightly higher heat losses due to the enlarged surface area even when they are completely enclosed in insulation.

5.5.2.3 Deep foundations

If construction ground with an adequate load-bearing capacity is only available at deeper depths, then pile foundations can be used for large buildings. However, the bored piles will penetrate the insulation layer and thus increase the heat losses. An alternative to deep foundations is soil replacement or soil improvement.

5.5.2.4 Insulation skirts

Insulation skirts enclose the heat under the floor slab like a bell. The consequently higher soil temperatures enable the use of less thick floor slab insulation and reduce the losses via remaining thermal bridges. Insulation skirts may be an appropriate solution especially in the case of existing building modernisation (see Section 5.5.3).

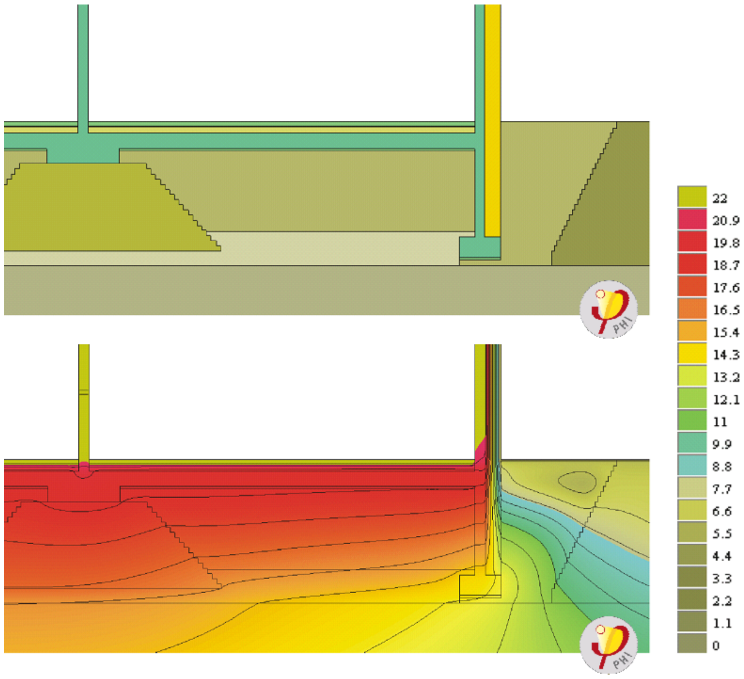


Fig. 48: **Insulation skirt as an extension of the exterior wall insulation into the ground up to the footing (in combination with 12 cm insulation on the floor slab here). The result of the dynamic simulation (picture below) shows the state on 1st January of the sixth year (steady-state conditions). It is clearly apparent that the soil under the floor slab has warmed up significantly so that the heat losses through the floor slab are greatly reduced.** ***(Source: PHI)***

5.5.3 Special features in modernisations

In the case of existing building modernisation, thermal insulation under the floor slab isn't possible of course, but insulation thicknesses that can be applied on the floor slab subsequently are often also limited, similarly to insulation on the basement ceiling (see Section 5.4.5.1).

The solution is to install an additional insulation skirt at the perimeter of the building. This measure is particularly appropriate if the base area already has to be dug up due to sealing or drainage measures. In principle, vertical insulation skirts are more effective than horizontal insulation skirts. Quite high soil temperatures can be achieved with this after a certain period of time for settling, especially in the case of buildings with a large base area and uncomplicated contours, so the heat losses are reduced significantly. Despite this, thermal insulation should also be installed on the surface of the floor slab whenever possible, even if it is only a few centimetres thick.

The effect of the insulation skirt can be estimated using the "Ground" worksheet of the PHPP. More accurate results can be obtained with a dynamic simulation, but this is much more complicated. Unfortunately, soil surveys often aren't available in the case of existing buildings, therefore important input values can only be assumed approximately for the simulation.

5.6 Highly efficient building envelopes in brief

An airtight and highly insulated building envelope is essential for energy efficient buildings. Investments in improved thermal protection are particularly profitable and ensure the structural integrity of buildings. The key aspects of highly efficient building envelopes are summarised below.

- The building envelope must be very-well insulated all around. Connections between building components must be carefully planned with regard to thermal bridges and airtightness.
- Façade U-values between 0.10 and 0.15 W/(m²K) are recommended (20 to 30 cm thermal insulation; WLZ 035).
- Highly insulated exterior walls can be constructed with all commonly used construction methods (EIFS, curtain wall façades, cavity walls, monolithic constructions). Thermal bridge minimised substructures and anchors must be used for curtain wall and cavity wall façades.
- In principle, all insulation materials can be used. The decision for using a particular insulation material also depends on questions relating to costs or fire safety among other things.
- In areas prone to shocks the façade insulation should be protected against vandalism (specially reinforced EIFS, hard façades).
- Adequate thermal storage mass of the building structure is advisable on account of temporarily high internal loads resulting from the building use. As a rule, mixed constructions with solid internal building components are unproblematic.
- The building envelope must be airtight. In solid constructions the interior plaster must be continuous (also behind wall-mounted installations). Joints and connections must be carefully taped in the case of lightweight timber constructions.
- Superinsulated roof constructions can be created with all common construction methods (reinforced concrete, timber or metal supporting framework). The U-values of the building components must also be in the range between 0.10 and 0.15 W/(m²K).
- Due to the design of warm roofs, special care is needed when planning and executing the work for airtightness. The high requirements for airtightness of the Passive House Standard provide increased protection against structural damage.
- Insulation of high timber load-bearing elements of roofs with large span widths has proved to be a cost-effective variant.

- In the context of an energy retrofit, when considering the position of the insulation in the roof area, all connections must be taken into account in order to avoid unacceptable thermal bridges. Existing projections and ledges must be completely covered with insulation in each case.
- With unused roof areas the insulation layer may be laid on the top floor ceiling. This is an extremely cost-effective variant. All rising building components must be equipped with flanking insulation in order to avoid unacceptable thermal bridges.
- Thermal insulation must be executed without gaps also in the area of the foundations. The insulation can be positioned on or under the floor slab; special rules apply in case of insulation on the floor slab (see Section 5.5.1)
- With insulation on the outside, strip foundations must be completely insulated in all cases.
- If the insulation is positioned on the floor slab or in the area of the basement ceiling, load-bearing or bracing building components (columns or reinforced concrete walls) penetrating the thermal insulation should be restricted to a minimum and covered with flanking insulation. Columns should be preferred over walls.
- Non-load-bearing walls should be thermally separated. A range of thermally insulating but compression-resistant masonry blocks or insulation materials are available for this purpose.
- In buildings with cold basements, an entrance located inside the building is critical in terms of heat loss. It must be decided whether this should be positioned within the thermal envelope or outside it. The position of the thermal insulation and the airtight layer should be planned accordingly. In existing buildings, thermal bridges result with both variants and should be mitigated carefully.
- In retrofits of existing buildings, thermal bridges are unavoidable in the area of the basement or at the base of the building. Insulation skirts can often improve conditions here. Thermal bridges should be mitigated at least to the extent that building physics relevant damage is not likely to occur.
- Passive House suitable windows consist of triple low-e glazing and insulated frames. The U-value of the entire window U_W should not exceed 0.80 W/(m²k) (thermally separated edge bond) with standard dimensions. The total energy transmittance of the glazing should be at least 50%.
- The windows should be mounted in the insulation layer in order to reduce thermal bridges.

- With a high thermal quality of (Passive House suitable) windows, there is no need for heating surfaces in front of or under the window (see Section 7.1)
- An adequate number of openable windows should be foreseen for ventilation in summer during the daytime. Side-hung windows are more effective than bottom-hung/tilting windows and are quite compatible with the accident prevention regulations!
- Special glazing types should be avoided as far as possible also for cost reasons e.g. due to window parapets. In case of requirements for break resistance of glazing, preference should be given to tempered safety glass. The laminated glass pane should preferably be on the inner side.
- Airtightness of the building envelope should always be checked by means of a pressure test together with leakage detection. Buildings with large volumes often achieve n_{50} values considerably below the Passive House requirement of 0.6 h^{-1}.
- Modernisation of educational-use buildings can also be carried out in a step-by-step manner. Taking future measures into account at each step is a prerequisite for this.

6 Ventilation

Many studies have shown that air quality in schools is poor (see [ILAT 2002], [Grams et al. 2002], [Bischof 2005], [Fromme et al. 2006], [Heudorf 2006]). Adequate ventilation via windows is hardly realisable on account of the high occupancy rates; added to this is the fact that the high air quantities that are necessary quickly lead to draughts. The reference literature accordingly points to the lack of ventilation during the winter in particular (see [Fromme et al. 2006]). The air quality in schools should however be a matter of importance to us: children are demonstrably more sensitive to air pollution in indoor spaces because they breathe in higher amounts of air in relation to their weight and their organs are still developing (see [Faustman et al. 2000], [Landrigan 1998]). Moreover, schoolchildren spend most of their time in schools apart from their homes. All this has led to the insight that a good quality of air in schools and children's day-care centres can only be practicably ensured by means of controlled ventilation (see [Pfluger 2006], [Kah 2006], [Kah 2006a]).

The associated draughts in winter are one of the reasons for the lack of ventilation via windows by users. Different concepts have been attempted to counteract this. For example, [Zeiler et al. 2009] examined the introduction of outdoor air over the greatest possible area. Other studies have dealt with adequate preheating of outdoor air via heating surfaces and with air quality based regulation of outlet valves for natural ventilation and additional forced ventilation where necessary.

Controlled ventilation with heat recovery seems to be the ideal solution for this as contaminated air is continuously replaced in sufficient amounts. In winter the outdoor air is pre-conditioned by the heat recovery system and introduced into the classrooms and group rooms, and energy is also saved as a side effect.

How much operating energy is required depends on the performance of the systems. Field measurements have shown that controlled ventilation with heat recovery recovers many times the amount of heat from the extract air compared to the operating energy. Measurements have substantiated coefficients of performance (ratio of recovered heat to operating energy) of 10 and higher (see [Peper et al. 2007]). Of course, a controlled ventilation system requires additional investment resources, but with appropriate planning the extra investment will remain within limits, and together with the energy savings will be economically feasible as an overall concept (see [Bretzke 2009], [Baumgärtner 2009]).

The following section deals with the question of air quality in buildings for educational use, followed by specific planning recommendations for dimensioning and integrating ventilation systems.

6.1 Air quality

The concentration of carbon dioxide (CO_2) is a tried and tested parameter for air quality in indoor spaces, because it is a good indicator of organic emissions by humans and directly relates to the intensity of use of the room. In addition, the amount of CO_2 given off by humans correlates well with the amount of volatile organic compounds (VOC), which are responsible for odours in indoor air (see [Kundi 2006]). It is has been established that well-ventilated rooms reduce complaints relating to impaired well-being, such as tiredness and lack of concentration etc. (see [ECA 1992], [Myhrvold et al. 1996], [Wargocki 2000]).

Indoor air quality is evaluated in the following study in accordance with [EN 13779] based on the measured CO_2 concentrations. A low quality of indoor air exists from 1400 ppm onwards. The [DIN 1946-2] standard which has now been replaced stipulated a reference value of 1000 ppm and a limit value of 1500 ppm.

Table 2: Classification of indoor air quality according to [EN 13779] (assumed CO_2 content of urban outdoor air: 400 ppm)

Typical CO_2 content [ppm]	≤ 800	800…1000	1000...1400	>1400
Classification of indoor air quality	High	Medium	Moderate	Low

There is a whole range of other indoor contaminants in addition, such as abiotic agents from building materials and furniture (VOCs, formaldehyde, plasticisers etc.). With the help of the CO_2 concentrations in indoor air it is also possible to make an approximate assessment relating to the removal of indoor space pollutants.

Another indoor space contaminant which has recently been the subject of much debate is particulate matter. Limit values for mass concentrations of particulate matter in outdoor air came into force with the implementation of the EU Directive 96/62/EG, due to which air pollution in indoor space also generated increased public interest.

Previously there were recommendations only for the maximum concentration of particulates; there were no limit values. In particular the composition must also be taken into account in the evaluation, so merely transferring the risk potential of mass concentrations of particulates in outdoor air to air in indoor spaces does not seem acceptable. The actual risk potential of particulates in indoor air is still under debate (see [Gabrio/Volland]). However, the German Indoor Air Hygiene Commission states that "[…] increased concentrations of particulate matter in indoor spaces are undesirable from the hygiene perspective […]." Regardless of the actual risk from different types of particulate matter, it holds true that in principle, low particulate concentrations should be strived for.

To reduce pollution by particulate matter in classrooms, in schools in Frankfurt for example damp cleaning of the classrooms was increased to five times a week during the winter months (see www.Frankfurt.de).

Here too, a ventilation system can significantly reduce indoor pollution through regular and adequate ventilation and through an upstream outdoor air filter (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

6.2 Measurement of indoor air quality

In the context of this handbook, measurements relating to indoor air pollution were carried out in 2 classrooms of a primary school. With the objective of examining different ventilation strategies, ventilation took place manually in one classroom and via a ventilation system in another classroom. For this purpose, a school was chosen which was equipped with a controlled ventilation system and one classroom was set up for the experiment by taping over the ventilation valves.

During the testing period of three weeks, the teachers were requested to ventilate the room conventionally via the windows. In the second classroom the ventilation system remained in operation, and only the outdoor volume flow was varied specifically. The relevant boundary conditions in both rooms were also recorded (opening states of windows and doors, occupancy rate) and the achieved outdoor air change rate was documented. The controlled ventilation system was in continuous operation during the daytime.

6.2.1 CO_2 concentration

For further evaluation the measured data was differentiated according to the type of ventilation (ventilation via windows / controlled ventilation) and the specific amount of the outdoor volume flow. For this the outdoor volume flow was based on the average class size plus teaching staff. The frequency with which the air quality classes described above were achieved during the teaching period was then determined. Each period of time from the first lesson to the last lesson was assessed as one teaching period. No distinction was made between breaks and times spent in specialist subject rooms.

CO_2 values up to 1000 ppm correspond with a medium indoor quality and values up to 1400 ppm correspond with a moderate indoor air quality. Even with a low outdoor volume flow of 13.3 m³/(person h) for mechanical ventilation, the air quality in the primary school classrooms accordingly was medium to moderate during 94 % of the teaching period (see Fig. 50). Further improvements in the air quality were achieved with increasing volume flow rates according to the number of persons. In contrast, with ventilation via windows the indoor air quality was low in the tested classrooms during 30 % of the teaching period (see Fig. 50), whereby the CO_2 concentrations occurring in schools with ventilation via windows are usually more critical than the values observed here (see Fig. 52). As the subsequent evaluation showed, a certain amount of basic air exchange took place through slight leaks in the sealed ventilation valves and due to air exchange with the well-ventilated circulation areas. Evaluation resulted in an occupant-related basic air exchange of around 3 m³/(schoolchild h).

For transferring the results to other school types, a CO_2 balance was prepared for the examined room with the persons as the source and the outdoor air exchange as the sink. It was then possible to validate this model using the increase in CO_2 at the beginning of the teaching period and the measured outdoor volume flows. The best correlation (during the first 45 minutes) resulted for an average source strength of 14 (litres CO_2)/(h schoolchild); this value seems plausible also when compared with the information in reference literature (see [Bischof 2005], [Hehl/Grams 2003]). For older schoolchildren in secondary schools, the source strength per person increases by about 30% to 18 (litres CO_2)/(h schoolchild). The CO_2 concentrations calculated assuming a typical timetable are also shown in Fig. 50.

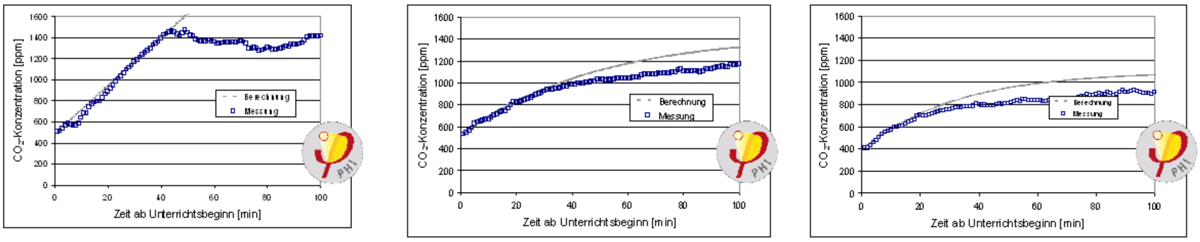


Fig. 49: **Validation of the CO_2 model based on measured data. Outdoor volume flow 0, 13.3 and 20.4 m³/(h schoolchild).** ***(Source: PHI)***
CO2-Konzentration=CO2 concentrations, Zeit ab Unterrichtsbeginn=time from start of lessons, Berechnung=calculated, Messung= measured

The results show that with an adequately dimensioned controlled ventilation system it is possible to achieve good air quality even in classrooms with high occupancy rates. The measurements confirm the dimensioning recommendations given in earlier publications (see [Kah 2006a], [Pfluger 2006]) for person-related air exchange for typical school building uses. Air quantities of 15 to 20 m³/(schoolchild h) result in moderate to medium air quality during the teaching period. For secondary schools this should be at least 17 m³/h per schoolchild.

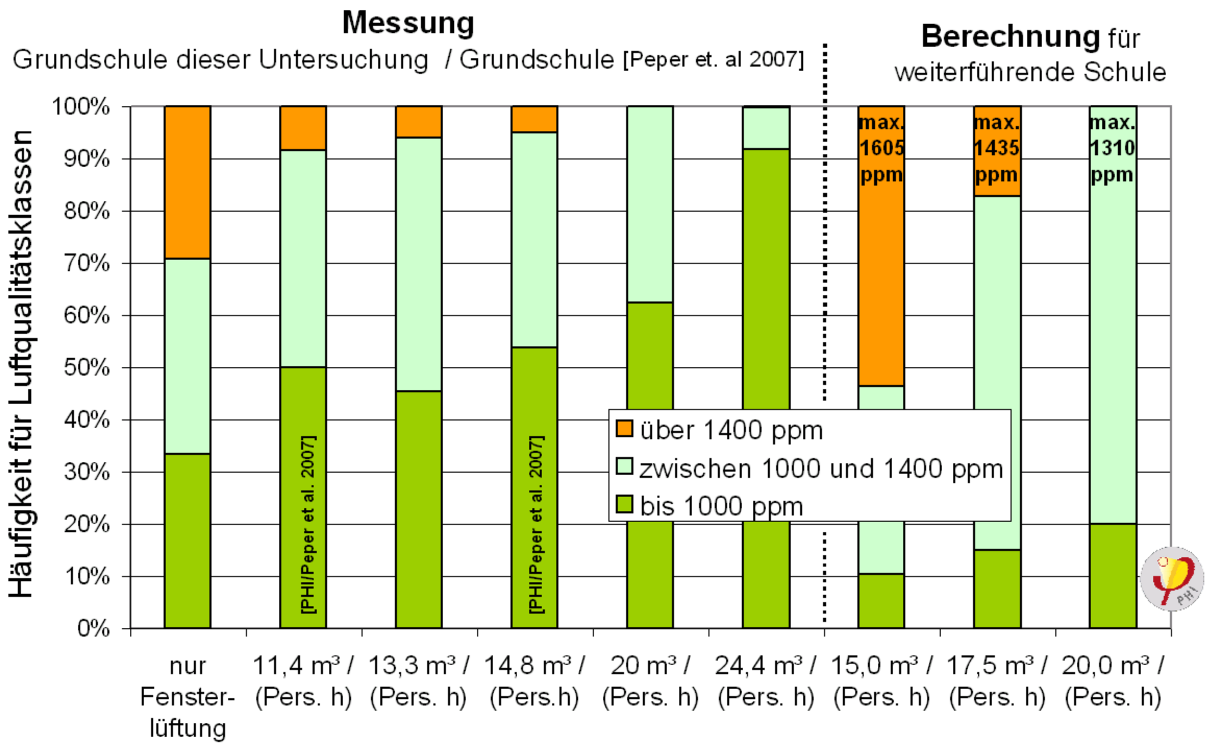
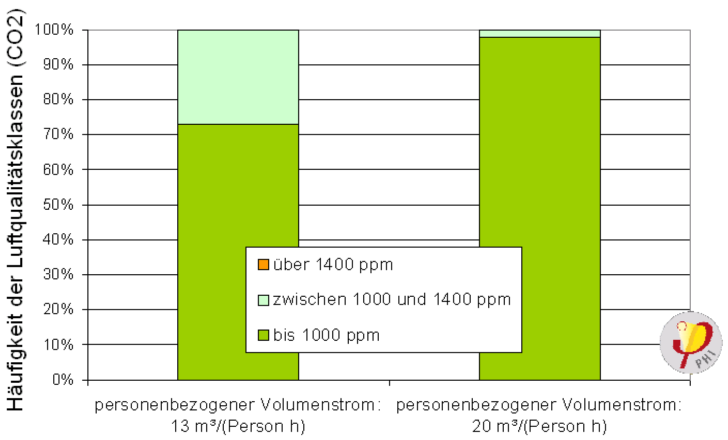


Fig. 50: **Comparison of the frequency of air quality classes occurring with controlled ventilation and ventilation via windows in classrooms. The measured results were supplemented with data from [Peper et al 2007]. According to these, even with 13.3 m³/(person h) the air quality in the primary school classroom was moderate to medium during 94 % of the teaching period. *(Source: PHI)***

Messung…=measurement for primary school tested in this study/primary school [Peper et al. 2007), calculation for a secondary school, Häufigkeit…=frequency of air quality classes, über=over, zwischen… und=between…and, bis=up to, nur Fensterlüftung=only window ventilation

Fig. 51: Field measurement in two group rooms of a children's day-care centre over 14 days during the heating period. Frequency of air quality classes occurring with controlled ventilation. The evaluated period of childcare was from 9:00 am till 16:00 or 16:30 pm. *(Source: PHI)*

Häufigkeit der …. =frequency of air quality classes, personenbezogener Volumenstrom=person-related volume flow rate, über=over, zwischen… und=between…and, bis=up to



As a comparison with the reference literature shows, a significant improvement in the air quality was achieved with controlled ventilation in comparison with conventional ventilation via windows. [Bischof 2005] presents measurements according to which a low indoor air quality prevailed for up to 70 % of the teaching period during the main winter period without controlled ventilation. The peak values observed in the classrooms even approximated the occupational exposure limits (see [Fromme et al. 2006], [ILAG2002]).

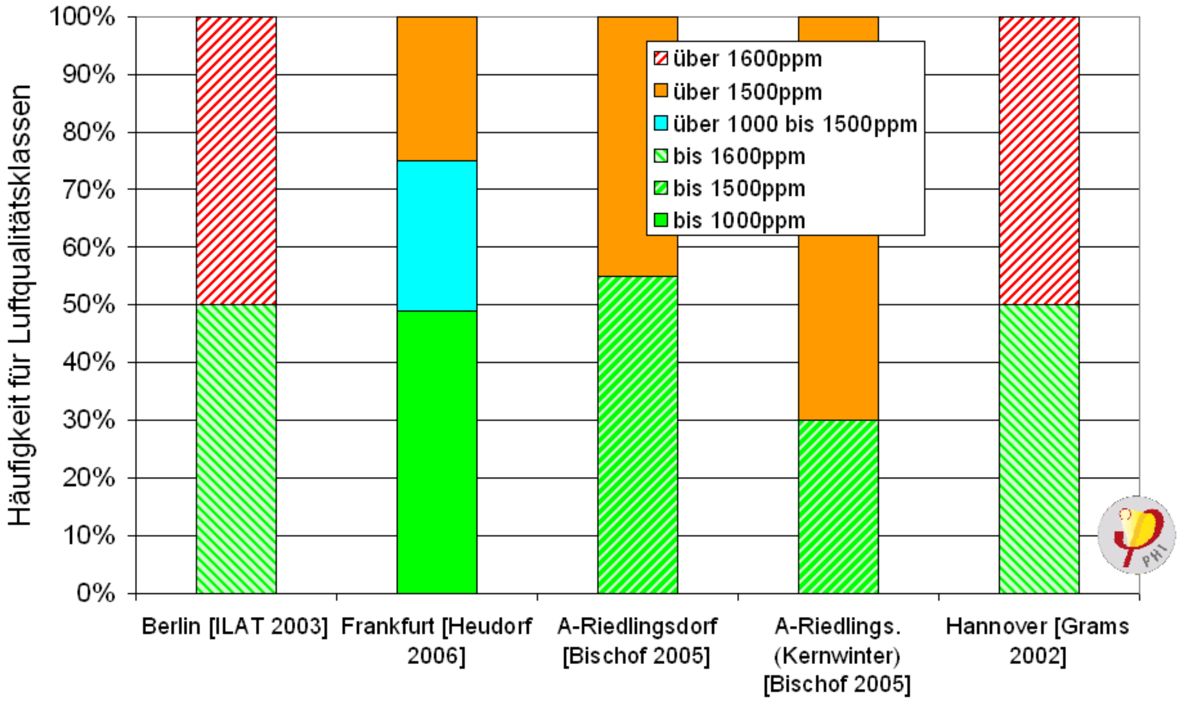


Fig. 52: **Reference literature values relating to the air quality in schools with ventilation via windows. Low indoor air quality exists with CO_2 levels above 1400 ppm.**
(Source: PHI)
Häufigkeit der …. =frequency of air quality classes, über=over, bis=up to

6.2.2 Particulate matter

In the past few years there has been increased focus on pollution by particulate matter in schools and children's day-care centres. Numerous measurements have provided evidence of the sometimes high level of pollution by particulate matter in schools (see [Fromme et al. 2006], [ILAG2002], [Heudorf 2006]). As has already been mentioned, on account of the high level of pollution by particulate matter in schools in Frankfurt, the cleaning intervals in the city's schools have been shortened, resulting in a noticeable impact on the municipal budget.

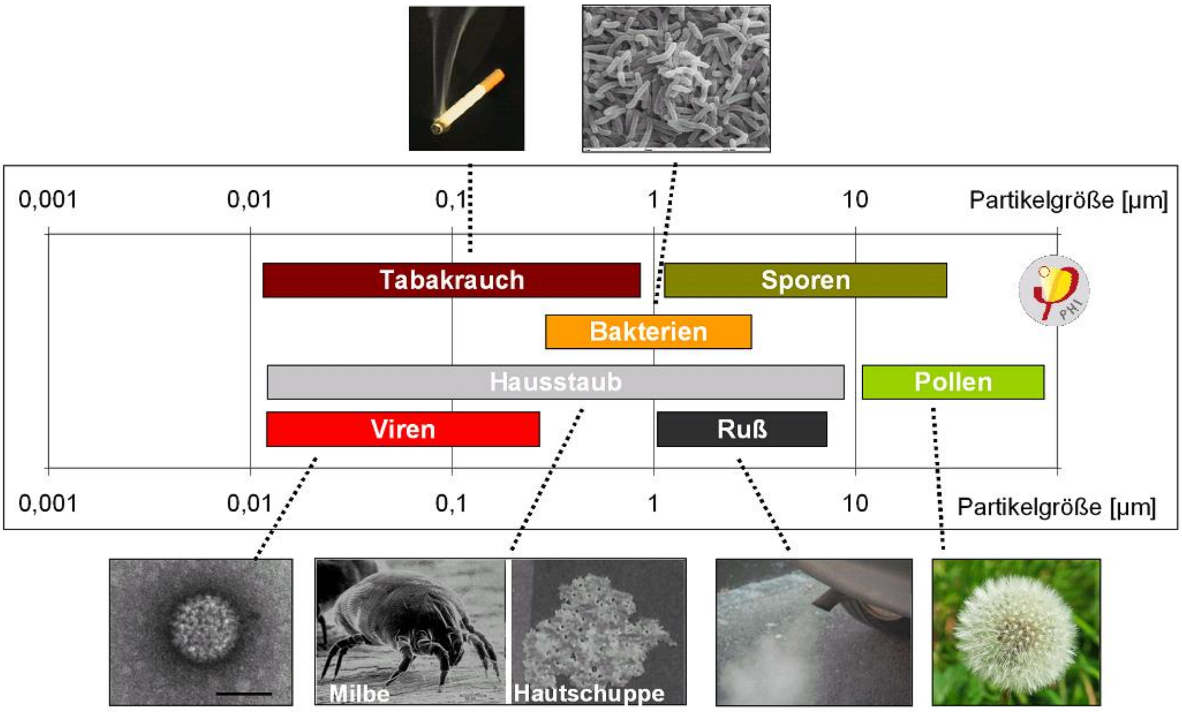


Fig. 53: **Overview (by no means exhaustive) of the particulate matter found in indoor spaces. *(Source: PHI / Pictures: Wikipedia)***
Tabakrauch=tobacco smoke, Sporen=mould spores, Bakterien=bacteria, Hausstaub=house dust, =viruses, Ruß=soot, Milbe=house dust mite, Hautschuppe=dander

Particulate matter is a collective term for airborne particles from diverse sources. The specific potential danger results from the composition and also from the size of the particles. Fine particles are held back by the mucous membranes of the nasopharynx only to a limited extent and therefore reach the respiratory tract, the smallest particles may even reach the pulmonary alveoli.

The focus of this study on particulate matter was mainly on the influence of controlled ventilation on the resulting concentrations of particles. Tests in residential buildings indicate that the use of ventilation systems has a positive effect. Basically, two mechanisms influence the concentrations of particles in indoor spaces:

- On the one hand, particulate matter contained in the outdoor air enters the room with the exchanged air. This is especially true for finer particle fractions ($PM_{2.5}$), because their sources are predominantly located outside. With mechanical ventilation the outdoor air filter mounted in front reduces the entry of dust from outside. This has a clear advantage over ventilation via windows. [Riley et al. 2002] demonstrated for residential spaces that the percentage of outdoor particles in indoor air pollution can be expected to be extremely low only if ventilation systems are used.

- On the other hand, a high internal concentration of particulate matter can be reduced with outdoor air through ventilation provided that the outdoor concentrations are lower. This is the case with the larger particle fractions. [Gabrio/Volland] found that adequate ventilation has a significant effect on pollution by particulate matter in classrooms. Because outdoor air exchange with mechanical ventilation is always higher than with ventilation via windows in practice, it was expected that the ventilation system would also be advantageous here.

The measurements lasting 6 weeks were carried out in a primary school in an inner city location. For this, the particulate concentration was ascertained continuously in the two classrooms and in the outdoor air. The particulate matter monitors used for this measured the number of particles using light scattering (see Section 11.1.2). Conversion to mass concentrations took place according to the monitor manufacturer's instructions.

Measurement of the influence of the ventilation strategy resulted in the following principle findings. This study is documented in more detail in the appendix (see Section 11.1).

Mass fraction PM_{10}:
(simplified: particles that are smaller than 10 µm in diameter)

- The measurements indicate that the amount of the particulate mass fraction PM_{10} is largely determined by the activity of the schoolchildren. The stirring up of deposited dust probably plays a subordinate role for this.
- As [Gabrio/Volland] and [Fromme et al. 2006] have also found, the measurement results indicate that the ventilation strategy and intensity of ventilation has a significant influence on the mass fraction PM_{10} in the classrooms. Furthermore, the influence of different ventilation strategies was also studied in the context of this study. The average particulate content (median PM_{10} values) in the time intervals with controlled ventilation are between 30 and 50 % less than the values obtained with ventilation via windows (see Fig. 54, Fig. 55).

  As an analysis of the decay curve of the mass fraction PM_{10} after the end of school shows, the concentration of particulate matter decreases much faster with ventilation system operation. The findings indicate that the ventilation system is the main sink process for the mass fraction PM_{10} in the examined classrooms.

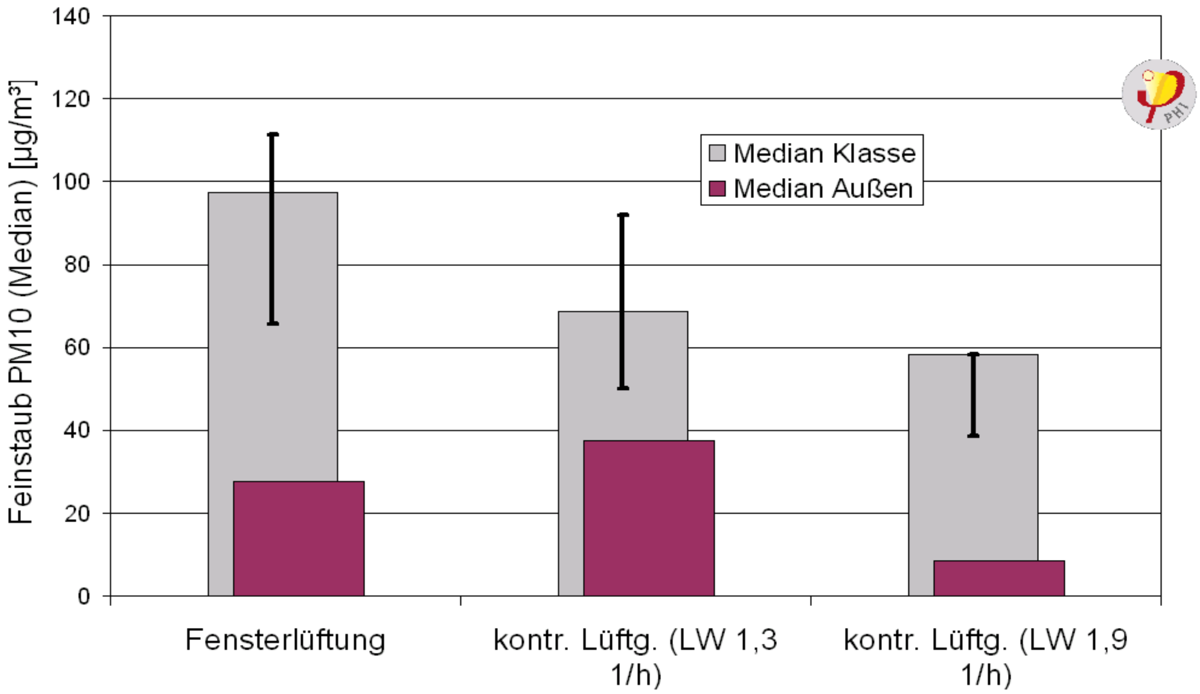


Fig. 54: **Daily medians of fine dust pollution indicate a clear influence of the ventilation strategy on fine dust pollution The average daily medians in class A are around 30 % (air change approx. 1.3 h-1) or 40 % (air change approx. 1.9 h-1) below the average daily median for window ventilation with controlled ventilation.** ***(Source: PHI)***

Feinstaub…=particulate matter PM10 (median), Klasse=classroom, Außen=outside, Fensterlüftung=window ventilation, contr. Lüftg=controlled ventilation, LW=air change rate

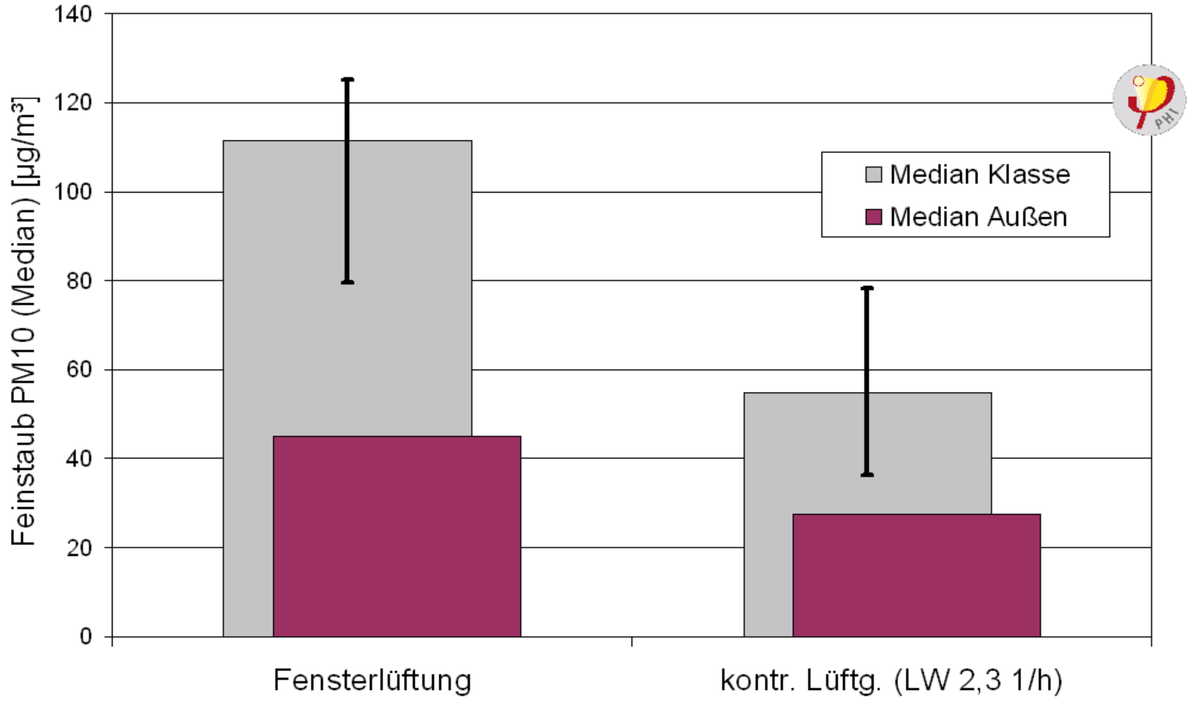


Fig. 55: aily medians of fine dust pollution. In Class B, too, there is on average a significant reduction in fine dust pollution with controlled ventilation. Compared to the period with window ventilation, the average daily medians are even reduced by 50% with controlled ventilation (air exchange approx. 2.3 1/h). ***Source: PHI)***

Mass fraction $PM_{2.5}$:
(simplified: particles that are smaller than 2.5 µm in diameter)

- The supposed influence of controlled ventilation on the particulate matter content ($PM_{2.5}$) compared to ventilation via windows could not be clearly determined on the basis of the measured indoor concentrations. In the ventilation system the filter system reduces the fine particles, but much less outdoor air is exchanged during the times with ventilation via windows. Estimating the air exchange with ventilation via windows on the basis of window opening durations and window configuration leads to outdoor air volume flows which are over 70 % less than with controlled ventilation.
- For testing the assumption that the introduction of fine particles was reduced by controlled ventilation, the particulate matter concentration was measured directly in the supply air and in the outdoor air ducts in an additional measurement.

  The results of the measurement support the assumption that the ventilation system also has a noticeable filtration effect with reference to the concentration of outdoor particulate matter. For particles with diameters smaller than 2 µm, a reduction of around 50 % in the particulate concentration was observed in the supply air of the examined system compared to the outdoor air.

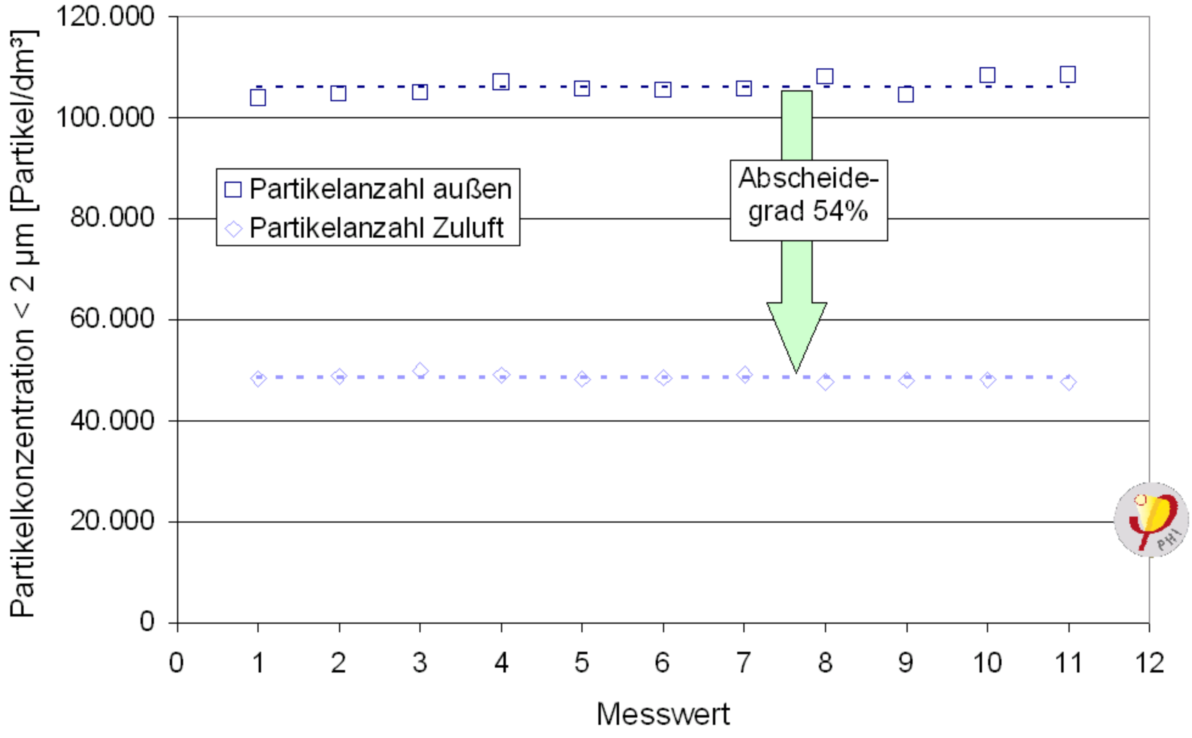


Fig. 56: **Examination of the filtration effect of the ventilation system. The reduced particulate concentration in the supply air compared to the outdoor air indicates a separation efficiency of around 50 %.** ***(Source: PHI)***
Partikelanzahl=number of particles, außen=outside, zuluft=supply air, Abscheidergrad=separation efficiency, Partikelkonzentration=particulate concentration, Messwert=measured value

6.3 Dimensioning the ventilation system

In Section 6.2 recommendations were derived from measurements for dimensioning the air quantities in schools and children's day-care centres. Accordingly, good to medium indoor air quality could be achieved with design values between 15 and 20 m³/(person h). To some extent, these design values differ considerably from the recommended minimum values in the standards. It must be considered that for the building uses examined here the classrooms and group rooms are not permanently occupied. During breaks, specialist subjects in other rooms or times spent in additional areas (exercise areas etc.) and outside, the indoor air is replaced for the next period of use through ventilation. The standards recommend uniform approaches for the user-related supply air demand regardless of the intensity of usage and the age of the users. With that in mind, the differing recommendations seem plausible.

For a moderate to medium air quality, air quantities between 28.8 m³/(h person) and 45 m³/(h person) are recommended in the standards, consequently leading to extremely low indoor air humidity levels unless humidification is additionally foreseen in winter – but this would increase the costs for equipment and would necessitate regular inspections relating to hygiene requirements.

Table 3: Comparison of recommended user-related air quantities and the values given in the reference literature.

	Air quantity [m³/(h person)]
Recommended for schools and children's day-care centres (this handbook, [Kah 2006a], [Pfluger 2006])	15 ... 20
Recommended for secondary schools (this handbook, [Kah 2006a], [Pfluger 2006])	17 to 20
Recommended for sports halls (dimensioned based on the number of persons in accordance with [DIN 18032-1])	60
Other values found in the literature	
SIA, energy efficient school buildings [SIA D 090] (stated for schools)	15
Building code of Denmark [BR 1995] (stated for schools)	18
Building code of Finland [NBC 2003] (stated for schools)	21.6
Low air quality (Category RAL 4) in accordance with [EN 13779]	up to 22

In the interest of reasonable investive and operation-relevant costs, the air quantities should be based on the hygiene-related requirements rather than the upper limits of the comfort requirements.

In sports halls, user-related air quantities of 60 m³/(h person) are recommended in accordance with the standards for sports facilities (see [DIN 18032-1]). For single-sports halls the supply air demand of sportspeople equates to the extract air demand in auxiliary rooms with this dimensioning.

6.4 Concepts for controlled ventilation with heat recovery

Controlled ventilation seems to be an excellent solution especially for educational buildings. Compared to conventional ventilation via windows, an adequate supply of fresh are is provided automatically and can be introduced without draughts even with cold outdoor temperatures. Heat recovery from the extract air also saves energy in addition. Because the ventilation concept has a major influence on the costs for investment, operation and maintenance, this should be integrated early on in the planning process. Coordination with the fire protection concept should also take place at an early stage. Many fire compartments increase the installation costs due to additional fire safety measures.

All rooms must be incorporated into the ventilation concept; the circulation areas and sanitary facilities must also be ventilated. In addition to moderate investment and maintenance costs, low operating costs must also be strived for through low pressure losses of the duct network.

The step towards controlled ventilation is smaller in school sports halls because air supply and air extraction in auxiliary rooms at least already conforms to current construction practice today. The special features of sports hall ventilation will be dealt with in separate sections.

Summer operation should also be considered in the ventilation concept. As a rule, air extraction of the sanitary facilities during usage times is sufficient in the summer; ventilation in the occupied areas can take place through the windows. An adequate number of openable windows should be foreseen for natural ventilation (see Section 5.2 and Section 8.2). Night-time cooling down during warm periods can be supplemented with mechanical ventilation at night.

6.4.1 Centralised or decentralised concepts

First it must be clarified whether a centralised or a decentralised concept for ventilation is to be implemented. Table 4 and Table 5 below provide an overview of the advantages and disadvantages based on [Pfluger 2004] (without any claim to completeness). With centralised solutions, the rooms are supplied by one or a few ventilation units. In decentralised solutions, one unit ventilates only one room or a small number of rooms. Centralised concepts are often implemented in new builds because plant rooms and connections can be taken into account in the planning. A centralised concept is particularly ideal for compact designs since the rooms here can usually be connected with simple, compact duct networks. In contrast, decentralised concepts are usually easier to integrate in existing buildings because less space is required for the ductwork. Furthermore, an additional central plant room for the larger central unit is not necessary. The smaller decentralised units can often be set up in the room itself, possibly in cabinets, or suspended from the ceiling or behind a drywall installation. In doing so, sound emissions from the unit in particular should be assessed critically. Furthermore, fire protection should be coordinated with the ventilation concept as early as possible in order to minimise costs for fire safety measures for the ventilation system. For example, decentralised concepts can be adapted for the fire compartments. Pre-assembled decentralised ventilation systems usually require very little installation effort. Only core drilling for outdoor air and exhaust air openings is necessary besides the device connections.

Table 4: Arguments for and against centralised ventilation concepts. (Source: [Kah 2006a])

Advantages	Disadvantages
- Reduction of the number of outdoor air and exhaust air ducts (wall penetrations, weather protection grilles etc.)	- Relatively high planning effort
- No space demand for heat recovery device outside of the plant room(s)	- Separate room is necessary for the ventilation centre
- Less critical solution in terms of sound transmission because the ventilation unit is installed in a separate room	- Relatively high space demand
- Maintenance and filter replacement focus on the plant room(s)	- Installation of additional fire protection components in the ventilation system is necessary due to crossing of fire compartments etc.
- There is a cost advantage depending on the building design because fewer single components are necessary (ventilation units, frost protection, condensate drain etc.)	

Table 5: Advantages and disadvantages of decentralised ventilation concepts *(Source: [Kah 2006a])*

Advantages	Disadvantages
- More individual controllability	- Penetrations of the exterior wall are necessary in each room with a ventilation unit
- An additional plant room is not necessary because devices can be set up in e.g. in the classrooms	- Noise emission from the decentralised unit in the installation room (e.g. classroom)
- Less planning effort, standardised solutions	- Space demand for individual units e.g. in the classroom, preparation room etc.
	- Filter, frost protection and condensate drain are necessary at each individual unit and associated effort for maintenance.

Fig. 57 shows an example for the integration of decentralised ventilation units during the retrofit of a primary school in Baiersdorf. With these successfully applied solutions, the central units with sound absorbers for two adjacent classrooms are positioned in a drywall installation. The effort for connections and for outdoor air and exhaust air openings could thus be reduced in comparison with a room-by-room approach. With the location near the exterior wall, the lengths of the "cold" ducts are also minimised at the same time (only the length of the sound absorber in principle).

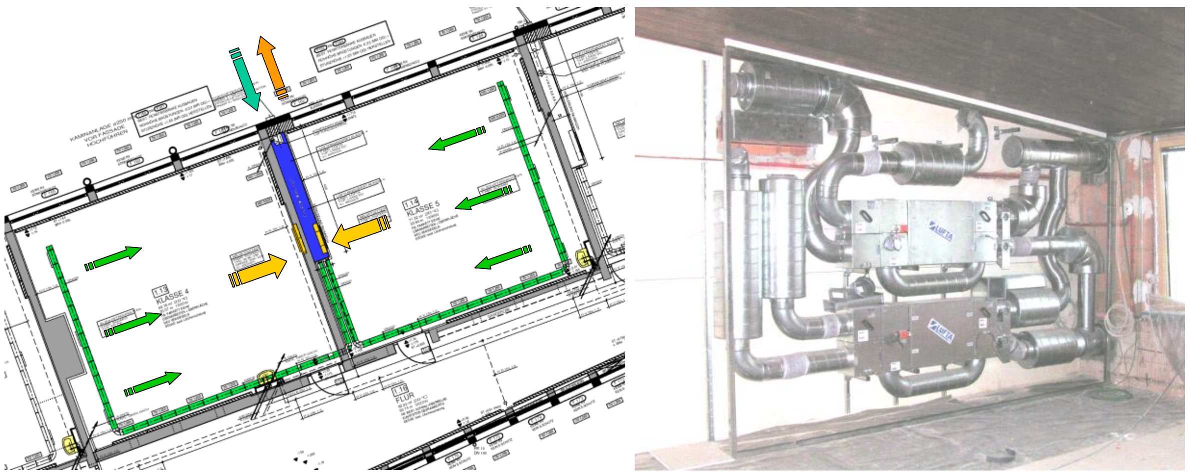


Fig. 57: Decentralised ventilation concept for the overall modernisation of a primary school in Baiersdorf. Two ventilation units for two classrooms next to each other are installed behind a drywall installation.
Architecture: Architekturbüro Haase, Karlstadt / Building Services: Sebrantke, Heroldsbach. (Picture: Architekturbüro Haase)

Another example is the modernisation of a school in Stams (Austria) in which the decentral ventilation unit was installed in a model classroom as a preliminary experiment, so that a direct comparison of air quality for the schoolchildren and teachers could be obtained. According to the architect Raimund Rainer, the school janitor was very quickly convinced because the air in the model classroom was no longer so stale. The ventilation units used already included all the necessary components (ventilation unit including sound absorber, supply air and exhaust air valves, air filter and control unit) so that the effort for installation was extremely small. According to the designer, the measured noise level was around 30 dB (A) (size of the ceiling device 462 mm x 831 mm x 1905 mm (H x B x L) / ventilation unit X-Vent by Airmaster (DK)).


Fig. 58: Decentralised ventilation concept in a modernisation and extension of a school in Stams (Austria). Architect: Raimund Rainer, Innsbruck. (Pictures: Simon Rainer)

A façade-integrated decentralised ventilation solution is provided by the "LiLu" system (www.michaeltribus.com). The ventilation unit including the highly efficient heat recovery system, sound absorber and filter is positioned in the window as a closed element. With integration in the exterior wall the outdoor air and exhaust air ducts are extremely short. The outdoor air and the exhaust air openings are integrated into the window element. Supply air and extract air ducts exit from the top of the ventilation box. Fig. 59 show the integration of the ventilation units in a school annexe in San Vito di Cadore (Southern Tyrol).

Fig. 59: **Window-integrated ventilation system "LiLu" (M. Tribus Architecture, (Ieft) Lana). The ventilation unit with heat recovery including the filter and sound absorber is integrated into the window frame. The outdoor air and exhaust air opening are positioned in the window frame.**
School annexe in San Vito di Cadore (I), Architects R. Damian, C. Da Rin / Passive House architect M. Tribus. (Pictures: M. Tribus)

Fig. 60 shows the tong-shaped connection of the classrooms with the centralised ventilation concept in a Passive House school in Alsfeld (Albert-Schweitzer-Schule). The supply and extract air ducts in the classrooms are largely located in one fire compartment each in order to reduce the number of crossings between fire compartments.

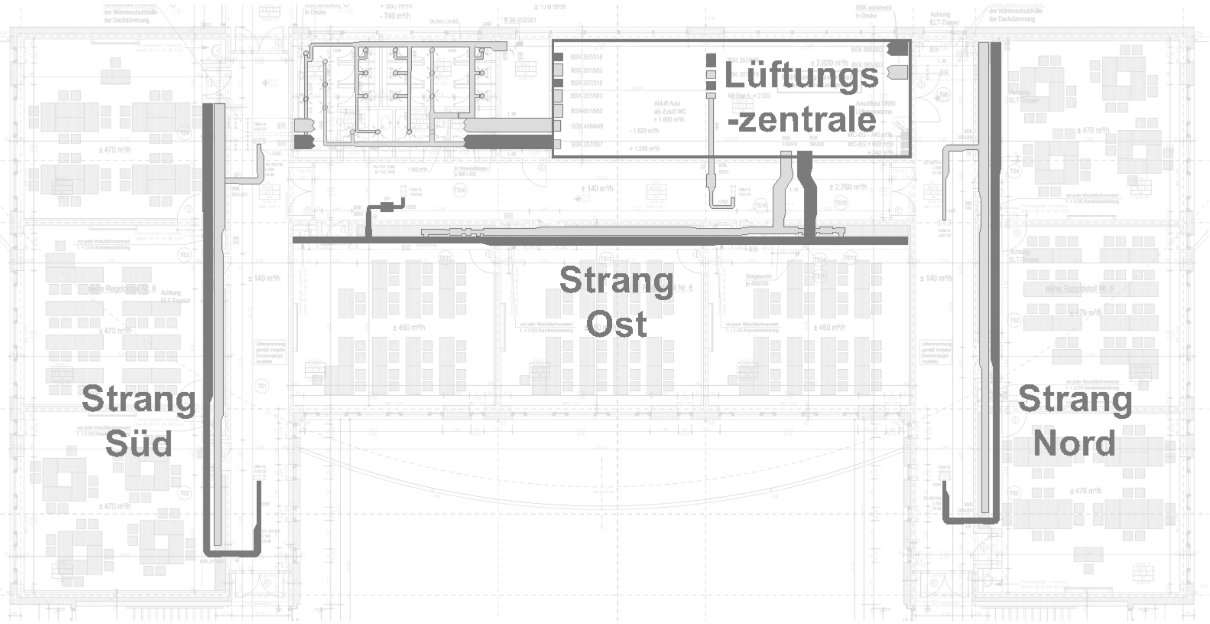


Fig. 60: **Floor layout of the second floor of the Albert-Schweitzer-Schule (Alsfeld) with short supply air and extract air ducts. Architecture: BLFP, Friedberg / Building Services: Neuplan, Gießen *(Source: [AkkP 33]).***

6.4.2 Directed air flow

With centralised ventilation concepts the principle of directed air flow can also be applied which is already familiar in housing construction. Here, the building is divided into supply air (classrooms, group rooms, offices etc.) and extract air zones (sanitary facilities). With appropriate air transfer elements, air flow takes place between the supply air and extract air zones. Circulation areas, foyers, recreation rooms and secondary use rooms can act as air transfer zones. In this way all rooms are incorporated into the ventilation concept and are automatically ventilated as well. Other advantages of this principle are the utilisation of the building structure as a large duct and the additional use of the supply air in the exhaust air areas. With this "double use" of the air in the extract air zones, the total volume flow can be reduced considerably compared to a solution with (duct routed) supply air and extract air in each room. Unlike in residential buildings, the use of air transfer elements in educational-use buildings may be hindered by requirements for fire protection and sound protection to some extent.

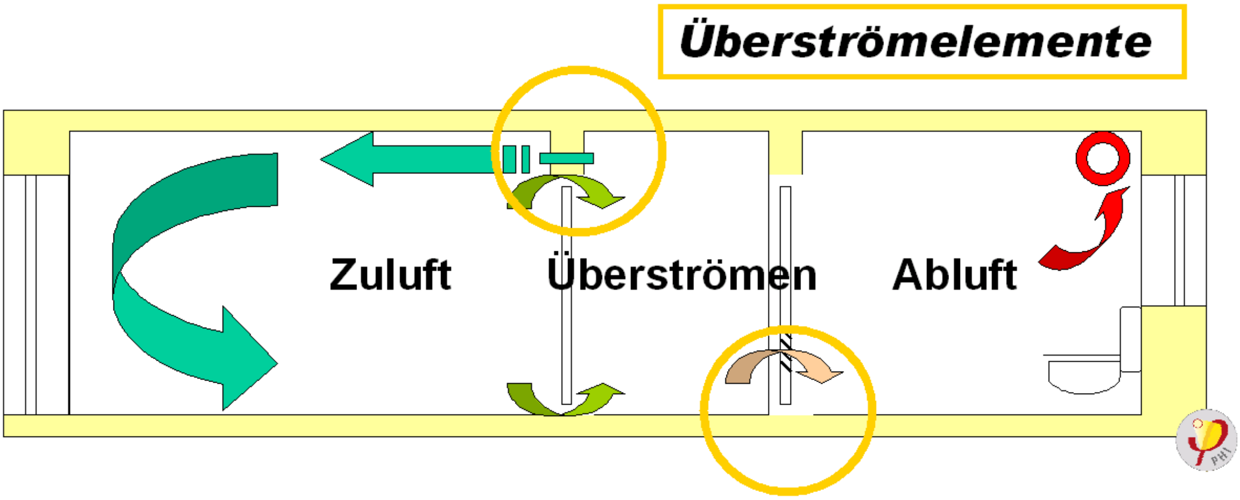


Fig. 61: Principle of directed air flow *(Source: [AkkP 33])*
Zuluft=Supply air, Überströmen= transferred air, Abluft= extract air, Überströmelemente=air transfer elements

The use of the building structure for directed air flow was also implemented in the ventilation concept of the children's day-care centre in Schwanheim. The air flows from the supply air zone with the auxiliary room and group room directly into the sanitary facilities. The air transfer elements also function as sound absorbers.

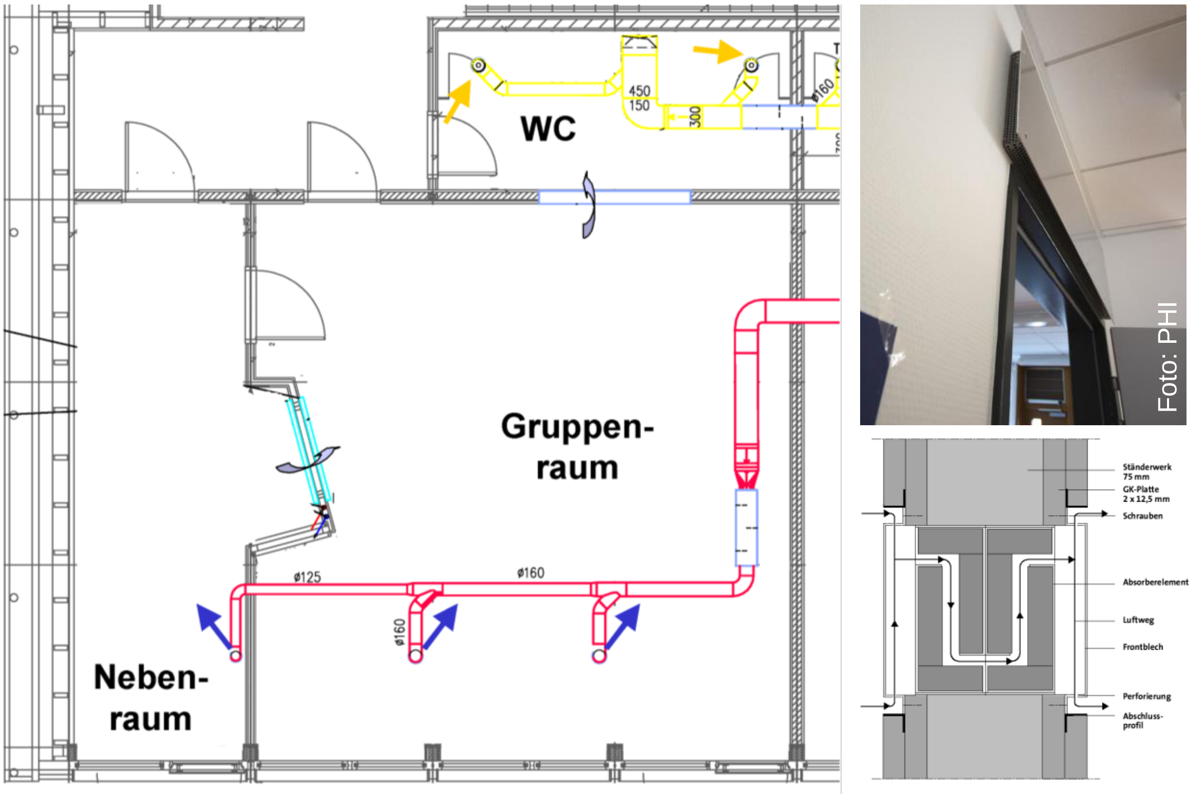


Fig. 62: **Ventilation concept in der children's day-care centre in Schwanheim. The picture on the right shows the air transfer element. Sketch of the elements used (Westaflex Typ 400). Architecture: sdks, Darmstadt / Building Services: IB Gernet, Oberursel**

Gruppenraum=group room, Nebenraum=auxiliary room

When dimensioning the air transfer openings (including the required sound protection and fire protection measures if necessary), it must be ensured that these have adequate cross-sections. The pressure losses of the whole element should not be greater than 5 Pa because otherwise additional infiltration and exfiltration will be induced, which will increase the ventilation heat losses.

The concept of directed air flow was also widely applied in the children's day-care centre "Wiesenbacher Tal" in Neckargemünd. The rooms were zoned into supply air and extract air zones. Air flows through door undercuts and door grilles across the circulation areas to extract air areas. No fire protection requirements apply for the air transfer openings because due to the fire protection concept the rooms can be evacuated directly towards the outside in case of danger.

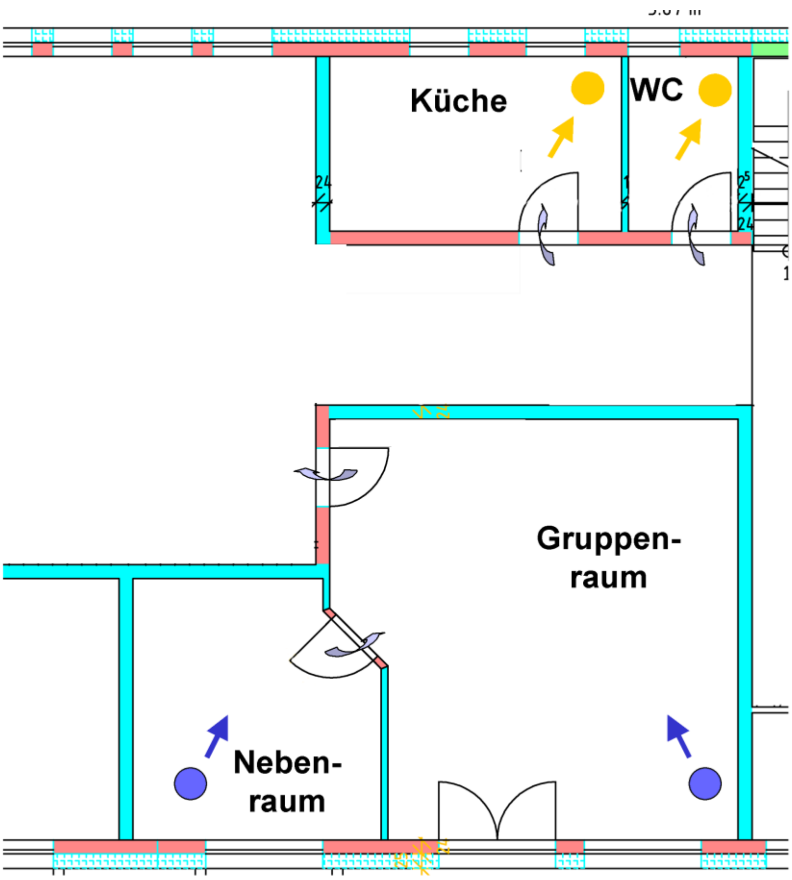


Fig. 63: **Ventilation concept for the children's day-care centre in Neckargemünd (Wiesenbacher Tal). The rooms are zoned into supply air and extract air zones. Architecture: Architekturbüro Merkel, Neckargemünd / Building Services: Planungsbüro Schmitt und Partner, Mauer**
Nebenraum=auxiliary room, Gruppenraum=group room, Küche=kitchen

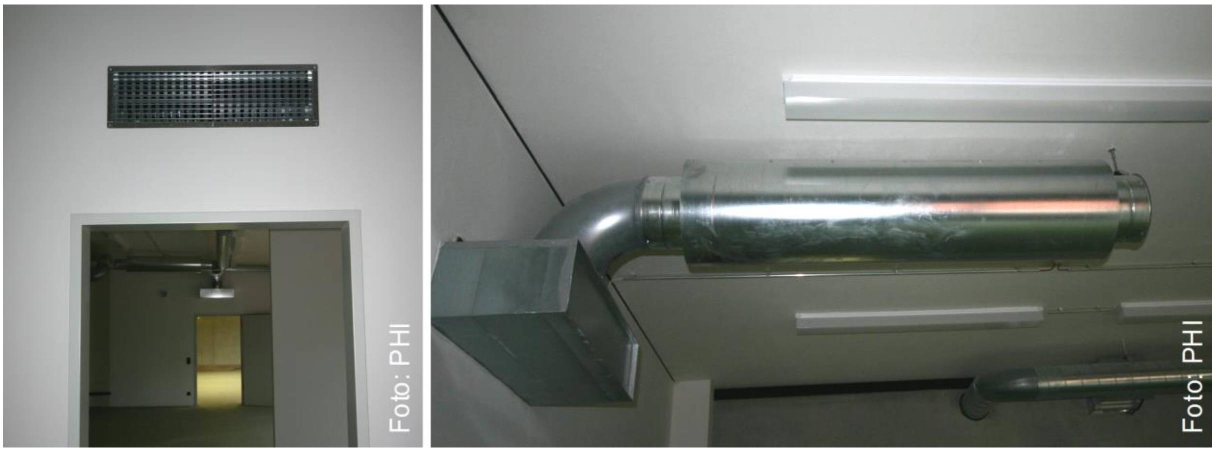


Fig. 64: **Air transfer from the subject room into the preparation room. The sound absorbing air transfer element was assembled using duct sections and built-in components for ducts. Schul-Pavillon Walldorf / Architecture: IB W. Herrmann, Walldorf / Building Services: Gadow + Graeske, Walldorf.**

Supply air and extract air rooms are often separated by a corridor. Air transfer above a suspended ceiling can also be considered if fire protection requirements apply for the corridor. For this, the suspended ceiling must be executed using a fire-resistant material (such as gypsum plasterboard). In this case the air can flow from the classroom or group room, or from above the suspended ceiling in the corridor area into the sanitary areas or other extract air zones. If air transfer solutions are implemented, these must be taken into account in the planning at an early stage and coordinated with the fire protection concept.

As already explained above, it is urgently recommended that *all* rooms are included in the ventilation concept. Due to the formation of fire compartments, many small corridor areas are created, each separated by doors for which fire protection requirements apply. Air supply and extraction in the corridor sections is frequently complicated due to these fire protection constraints. This can be simplified if the doors of the corridor sections are normally kept open by means of magnetic door holders and close only in case of fire (automatically released by interruption of the electrical current e.g. by a smoke detector). Successive corridors can be collectively ventilated using this solution. Furthermore, the fire compartment doors are subjected to less stress, which improves the durability of the doors. In a special needs school in Frankfurt-Nied the entire corridor area is vented via the sanitary area. Introduction of supply air can be reduced to a few points in the corridor area.

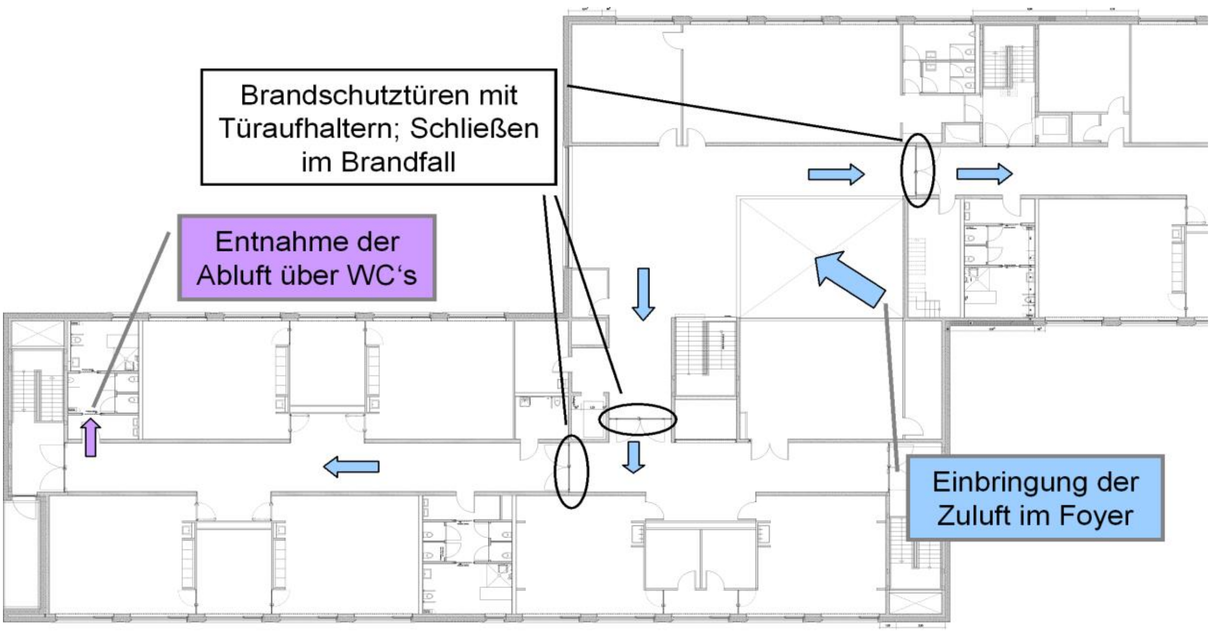


Fig. 65: Door holders on the fire compartment doors facilitate the supply and extraction of air in the circulation area in a Passive House special needs school in Frankfurt (Schule für praktisch Bildbare in Frankfurt-Nied). Supply air is introduced in the foyer and flows across the corridor sections into the WCs. The door holder is released in case of fire and the fire protection doors are closed. Architecture: Hausmann Architekten, Aachen / Building Services: planungsgruppeDrei, Pfungstadt

Brandschutztüren…= fire doors with door holders which close in case of fire, Entnahme der…=air is extracted via the WCs, Einbringung…=supply air is introduced in the foyer

6.4.3 Approaches for reducing the total volume flows

An advantage of the directed air flow principle is the reuse of the air in the extract air zones; with this approach it is possible to reduce the total air quantities. The extent to which this advantage can be availed of depends on the ratio of the supply air demand to the extract air demand. This was studied in [AkkP 33] for school buildings. The supply air and extract air demand was determined for 30 schoolchildren and one teacher. Fig. 66 shows this situation. If supply air and extract air demands are met on a room-by-room basis, this will result in a total air demand of between 700 and 850 m³/h (demand in classroom, associated corridor and part of the sanitary facilities). With directed air flow the extract air demand in the sanitary area is fully met by the transferred air and the corridor is automatically ventilated as well. With directed air flow, the total air quantity in a school building can be reduced by 35 %. The situation in children's day-care centres is similar. In schools and children's day-care centres it is expedient to apply the concept of directed air flow to individual sections. For example, the extract air demand of the sanitary area can be met through transferred air from the adjacent group room.

In contrast, in school sports halls the extract air demand in the auxiliary rooms and the supply air demand in the hall area is almost identical (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). The total air quantity can be reduced by almost half through directed air flow with this building use.

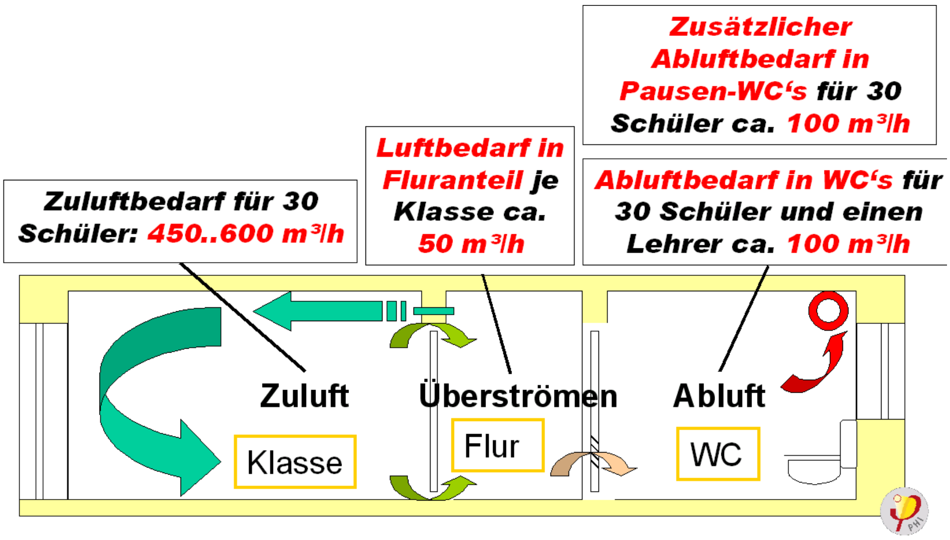


Fig. 66: **Supply air and extract air demand in a school based on one *classroom* *(Source: [AkkP 33])***

Zuluftbedarf…=supply air demand for 30 schoolchildren, Luftbedarf in Fluranteil…=air demand in corridor section per classroom,

Zusätzlicher=additional extract air demand in WCs for 30 schoolchildren in the breaks, Abluftbedarf in WCs…=extract air demand in WCs for 30 schoolchildren and a teacher, Zuluft=supply air, Abluft=extract air, Überströmen=transferred air

Another possibility for reducing the total air quantities in a centralised ventilation system lies in the taking into account of simultaneity. In schools, lessons take place either in the classroom or in subject rooms. Taking the exact occupancy rate into account can lead to a reduction of the total air quantity of around 30 % provided that the ventilation in the rooms can be turned on individually. In children's day-care centres a distinction can be made between the occupancy of a group room or a multi-purpose room. Air can be supplied to and extracted from a dining hall using the air quantities that are freed up by switching off the ventilation in the unused rooms. For optimisation of the air quantities, the relevant rooms must be equipped with motorised dampers. For this optimisation concept it must be kept in mind that the concepts should remain simple and understandable for the user.

The air quantities recommended in Section 6.3 for schools and children's day-care centres assume continuous operation of the ventilation system in the occupied areas during the main period of use. If classrooms and group rooms are only ventilated when these are occupied, then the air quantities should be based on the upper limit of the recommended volume flow range (primary school 17 m³/(h schoolchild) and secondary school 20 m³/(h schoolchild)).

6.4.4 Sports halls

The investment costs for the ventilation system of a Passive House sports hall can be reduced if the supply air demand in the hall area and the extract air demand in the changing rooms/showers is met by one ventilation unit. The extract air demand in the auxiliary rooms and the supply air demand in the hall area are almost identical so that this area is also supplied simultaneously when air transfer of the hall supply air into the changing rooms/showers takes place (see Fig. 67 links). On account of the different temperature requirements in the hall and in the auxiliary room area, the transferred air must be post-heated bevor entering the changing rooms/showers. For example, for this purpose the air can flow in across heaters. For this solution, the fire protection requirements should be checked at an early stage.

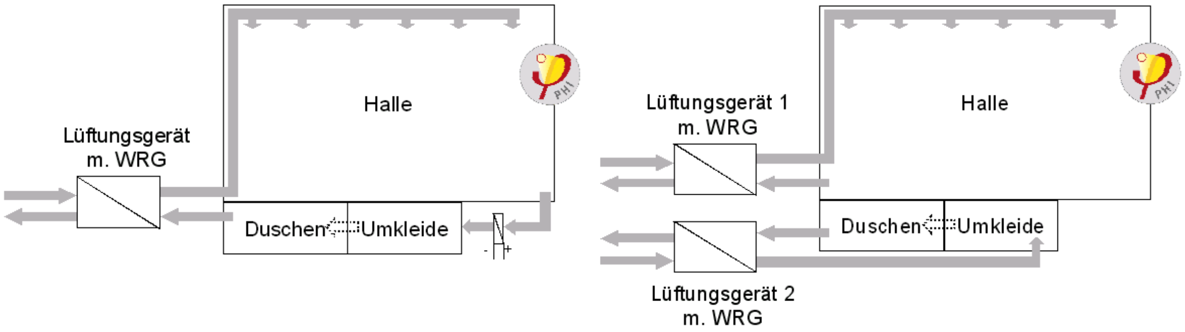


Fig. 67: **Schematic diagram of a ventilation concept for sports halls. Combined supply of the hall area and changing rooms/showers is shown on the left, the supply air of the hall flows into the auxiliary rooms. A separate ventilation system for supplying the hall and changing rooms/shower area is shown on the right.** ***(Source: PHI)***
Lüftungsgerät m. WRG=ventilation unit with HR, Duschen=showers, Umkleide=changing rooms

The ventilation system can be smaller or simplified compared to a ventilation concept with separate ventilation units (see Fig. 67, right). If the changing room/shower areas and sports hall area are each supplied separately with supply air and extract air (see Fig. 67, right) the operating times of the ventilation system in the auxiliary rooms should be limited to the actual demand (e.g. regulation according to humidity levels or by means of a presence detector with sufficient rundown time).

Fig. 68: **Implementation of air transfer in a Passive House sports hall in Reichelsheim. The hall supply air flows into the corridor area through a channel with fire protection measures into the changing rooms. A radiator heats up the air flowing into the changing rooms (the air transfer opening is located behind the radiator).**
Architecture: Eigenbetrieb Gebäudewirtschaft Wetteraukreis & a5 Planung, Bad Nauheim / Building Services: DBH Bachmann, Bad Hersfeld.

6.4.5 Introduction of air

The positioning and choice of supply air and extract air elements must ensure that indoor air pollution is removed and the room is completely flushed through with fresh air. Moreover, the introduction of air should not cause impairment of comfort due to draughts or noise at the air intakes and outlets.

The concept for introduction of air consequently also affects duct routing. The supply air ductwork may be shortened by using jet nozzles. These should be operated with moderate air velocities so that near the façade on the opposite side the jet speed is completely dissipated. For preventing draughts, the risk of draughts in the occupied area according to [EN ISO 7730] should be 10 % at the most. This will result in maximum air velocities of less than or equal to 0.1 m/s in the occupied area (assumed: turbulence intensity 40 %, indoor temperature 20 °C).

Fig. 69: **Slot diffusers (picture on the left) have proved successful. Jet diffusers (picture on the right) should not be operated with high air velocities (it is better to use several outlets) so that draughts are not caused. Passive House school in Frankfurt (left): Architecture: 4a, Stuttgart / Building Services: ICRZ Ing. Cons. Ruth + Zimmermann, Neuenhagen**
Passive House school in Alsfeld (right): Architecture: BLFP, Friedberg / Building Services: Neuplan, Gießen.

Fig. 70: **Air outlets with high induction. Slot diffusers on the left and duct-integrated discharge grilles on the right. The air velocities at the outlet are quickly reduced, draughts caused by the air intake can thus be reduced. The spatial arrangement of the air extraction must ensure complete flushing of the room. Passive House school in Neckargemünd (left): Architecture: Donnig + Unterstab, Rastatt / Building Services: IWP GmbH, Stuttgart**
Passive House building of the Schul-Pavillon Walldorf (right): Architecture: IB W. Herrmann, Walldorf / Building Services: Gadow + Graeske, Walldorf.

<u>**Introduction of air in the case of large halls**</u>

Discussions often arise about how supply air quantities can be suitably introduced into the hall area in such a way that the room is completely flushed through and supplied with fresh air. To clarify the question of which solutions are appropriate and which are unsuitable, CFD simulations (see [FLUENT]) were carried out for a single-court sports hall within the framework of this project. Different positions of the supply air and extract air elements were systematically examined (see Fig. 71).

Fig. 72 shows an example of the air velocities in the hall cross-section for a rather unfavourable variant (The supply air is introduced with a high impulse and at the opposite glazed façade the cold air drop accelerates the flow again). In the area occupied by the sportspeople, none of the examined variants were critical with regard to draughts. Unlike in event halls, the air quantities introduced into school sports halls are considerably smaller, so that the draught-free introduction of supply air is considerably unproblematic compared to event halls. Furthermore, in school sports halls the draughts associated with the introduction of air are usually only of significance in the case of low-movement uses.

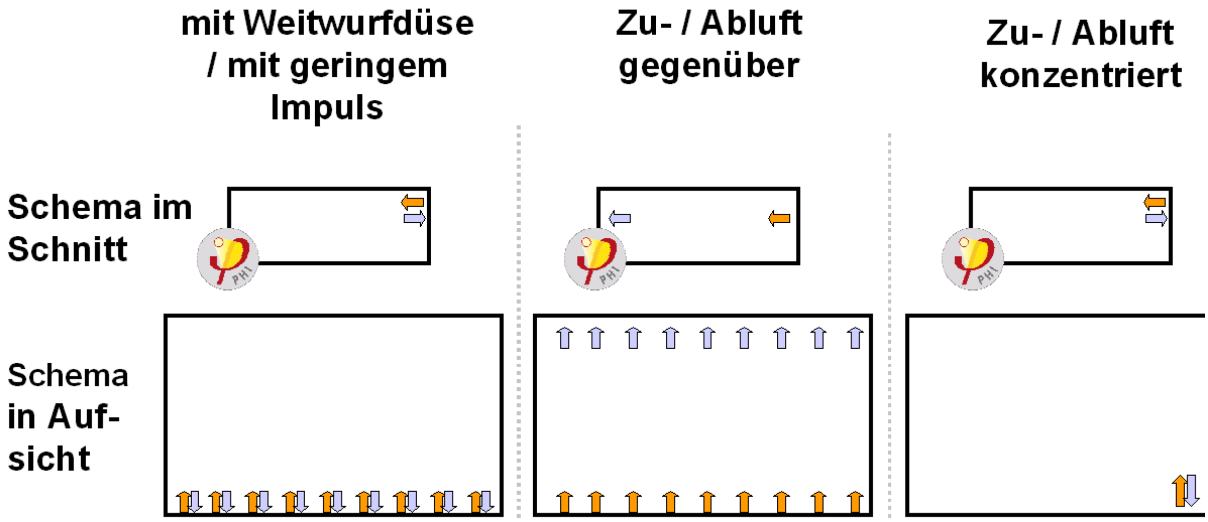


Fig. 71: **Air introduction in the hall area. Boundary conditions: single-court sports hall with sport use / dimensioning of the ventilation system according to demand / 60 m³/(h sportsperson) or an air change rate of ca. 0.7 h^{-1}. *(Source: PHI)***
Mit Weitwürfdüse…=with jet nozzle/with low momentum, Zu-/Abluft gegenüber =Supply air/extract air on opposite sides, Zu-/Abluft konzentriert=supply air/extract air concentrated in one place, Schema im Schnitt=schema in section, Schema in aufsicht= schema in top view

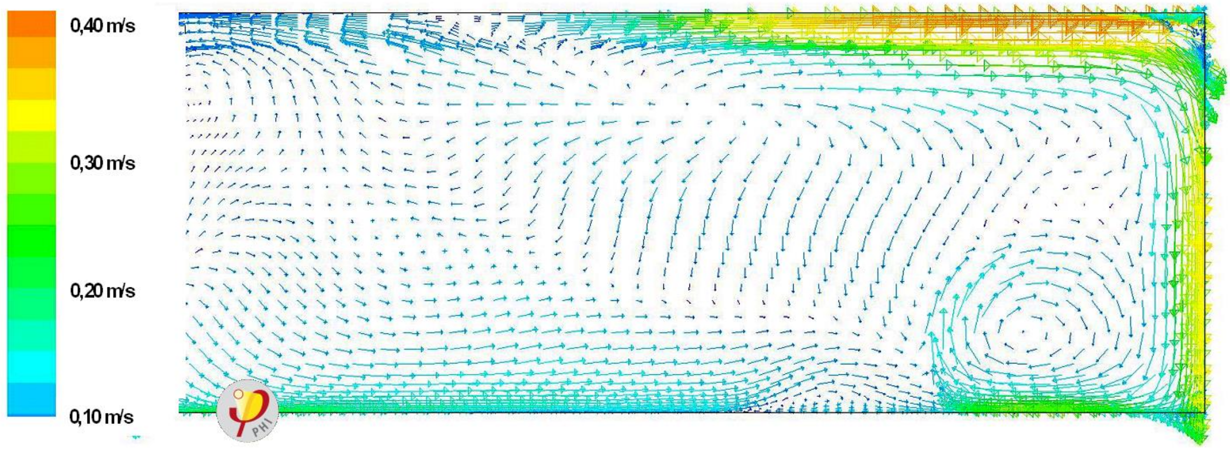


Fig. 72: **Example showing flow velocities in the hall area when air is introduced with high momentum using jet nozzles (from above left). The diagram depicts a vertical cross-section between the nozzles. The arrows representing air flow are coloured according to the air velocities. Cold air descent at the glazed façade (right) increases the air velocities (right). Even in this rather unfavourable case, the air velocities in the occupied zone are not critical. Air introduction with low momentum reduces the velocities occurring at the facade. *(Source: PHI)***

Furthermore, on the basis of the CFD simulations it was examined how effectively indoor air pollution was removed with different positions of the supply air and extract air openings. The ventilation efficiency characterises the effectiveness of a ventilation system. The most effective flow pattern is displacement ventilation (see Fig. 73) with the lowest average age of the indoor air in a zone.

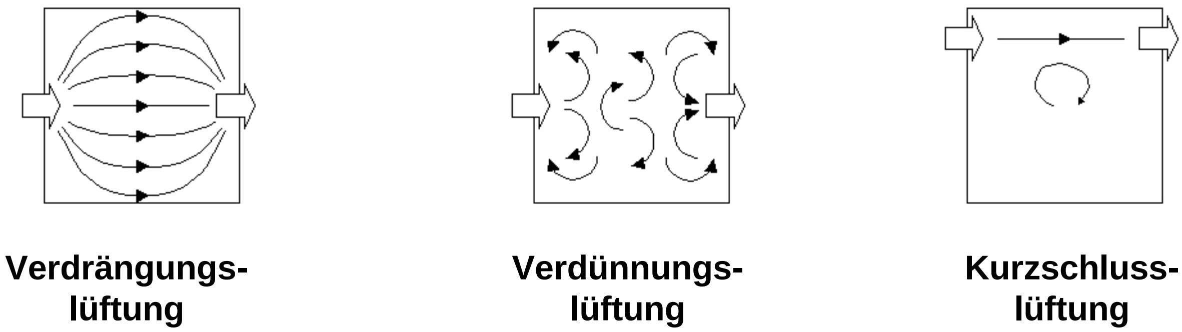


Fig. 73: **Flow patterns illustrating the ventilation efficiency. Indoor air pollution is most effectively removed with displacement ventilation. The indoor air in some parts of the room is renewed less often if short circuiting of air flows occurs. *(Source: Wikipedia).***

Displacement ventilation, mixing (dilution) ventilation, short-circuiting ventilation

To ascertain the ventilation efficiency, the mean age of air is determined and then compared with the shortest possible age of air (with displacement ventilation). The age of air describes the time span between the entry of an air molecule to its reaching the point to be measured in the room. The local age of air is determined by the position of the measurement point in the room and the prevailing flow pattern.

The simulated calculations show very similar results for the examined ventilation concepts. The age of air in the entire hall area is almost identical, this means that largely mixing ventilation takes place here. Short-circuiting effects were negligible even with extremely concentrated introduction and extraction of the air quantities locally (see Fig. 71, right). The results indicate that a more effective flow pattern than mixed air flow cannot be achieved with the rather low air change rates (ca. 0.7 h^{-1}).

Fig. 74 shows an example of the age of air determined using CFD simulations for a variant with jet nozzles (see Fig. 71, left). Furthermore, the analyses show slight advantages for introduction of air with low momentum (about 1 m/s) even for air extraction on the same side. The efficiency of air routing remains comparable but flow noise and pressure drop at the supply air element are reduced. In addition, the air velocities in the room are reduced even further.

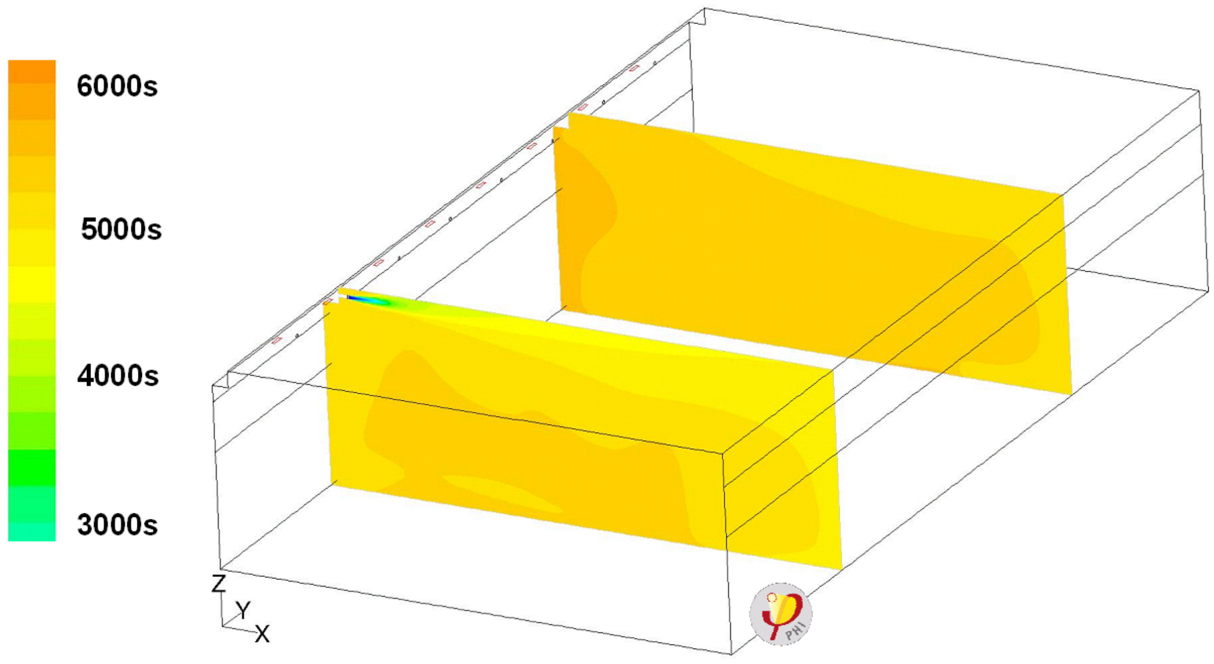


Fig. 74: **This example shows the results for the age of air in two cross-sections of a hall for a variant with jet nozzles. The hall cross-section shows very similar results for the age of air. The results were comparable to those for the other examined variants. The almost identical age of air in the entire hall indicates that mixed air flow is taking place here.** ***(Source: PHI)***

Unlike event halls which require high air quantities, introducing air is considerably less problematic in the case of school sports halls. For the highly insulated single-court sports hall examined here, it was found that the way in which air is introduced in the context of practically relevant ventilation concepts hardly has any effect. The air velocities in the occupied zone are not problematic for the examined variants and no relevant short-circuiting effects occur with the more critical ventilation concepts. Across the spectrum of the examined concepts, the ventilation efficiency is always within the range for mixed ventilation. A slight advantage can be seen for concepts with supply air introduction with low momentum.

6.4.6 Recommendations for ventilation concepts

Both centralised as well as decentralised solutions have specific advantages. Decentralised concepts are often easier to implement in modernisations, while centralised concepts can generally be realised with less investment costs in new builds.

Using the principle of directed air flow, centralised ventilation concepts can be further optimised with reference to the total air quantities and air routing. The necessary air quantities can be reduced in this way; the relevant rooms are automatically included in the ventilation concept and the building structure can be used as a "channel". With the reduction in the total air quantities, smaller central units can be used where necessary. This principle is particularly interesting for school sports halls.

Operating energy is also required for operation of the controlled ventilation system. The pressure loss in the ductwork and in the ventilation unit is decisive for an electrically efficient ventilation system. The ventilation task should also be taken into account at an early stage in the planning. Low flow velocities, short ducts, avoidance of intersection points in ducts and if necessary, coordinated spatial arrangement may help to optimise the pressure losses in the duct network. Experience with projects has shown that pressure loss in one side of the duct network (outdoor air up to supply air or extract air up to exhaust air, without the central unit) preferably should not exceed 200 Pa.

Furthermore, in the case of branching ducts, the duct side with the highest pressure loss especially must be optimised as this side determines the pressure loss of the entire ventilation network. Optimisation of the pressure loss should start with the main flow resistances e.g. through duct widening in the area of the weather protection grilles and built-in parts of ducts (valves, filters, heating coils etc.).

In the plant room sufficient space should be foreseen for the central unit and the duct connections. Extremely compact ventilation units usually have higher internal pressure losses.

Exhaust air and outdoor air ducts are cold (almost external temperature). These ducts should therefore be as short as possible and must be insulated properly (in a diffusion-impermeable manner; recommended minimum insulation thickness 100 mm, WLZ 040). In decentralised ventilation concepts in particular it must be ensured that the "cold ducts" are short (devices should be positioned near the exterior façade). Simple concepts should be strived for in principle.

6.4.7 Strategies for drying filters of central units

In case of non-residential buildings the ventilation system is usually operated intermittently, i.e. the system primarily runs during the usage period but not at night or during weekends or holidays. For this reason, it must be ensured that the outdoor air filters are kept as dry as possible also during the standstill periods. At temperatures above 0 °C the relative air humidity at the outdoor air filters should not be higher than 80 % [VDI 6022]. Falling of the temperature below dew point near the air filters - particularly during standstill of the system - should be prevented at all costs.

Suitable protective strategies must be foreseen when operating the ventilation units in order to exclude permanent moisture penetration in the outdoor air filters. The strategies given below are recommended for this purpose and can be setup directly at the ventilation unit on site. The control must also be prepared for this additional function.

As an option for filter drying in intermittent operation, circulating air operation lasting approx. 15 to 30 minutes before each switch-off of the system by means of supply or exhaust air recirculation is recommended (see Fig. 75). By shutting off the outdoor air valve the outdoor air filter will be protected from (convective) inflow of outdoor air during the standstill periods; the filter should always be positioned within the heated area of the building, otherwise heating of the filter chamber will be necessary. Recirculated supply air should be preferred for reasons of hygiene (see Fig. 76).

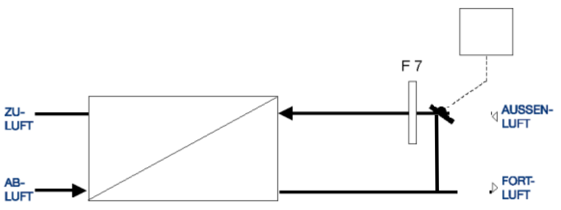
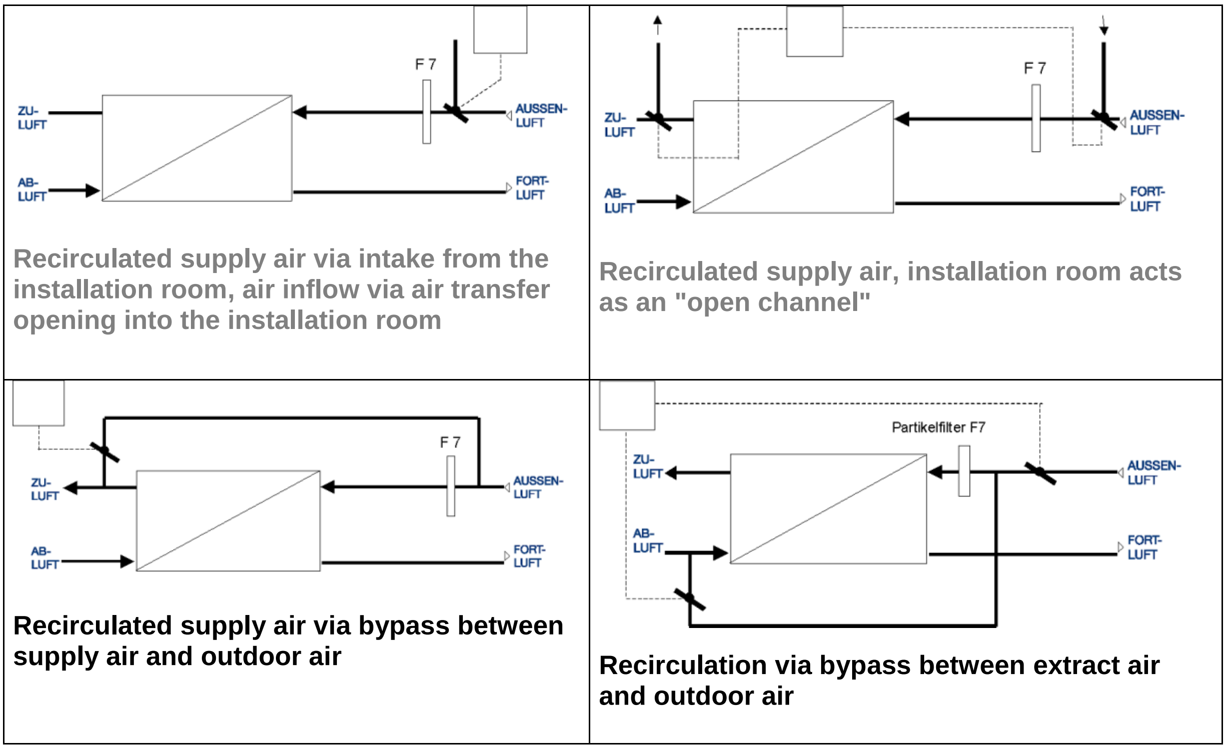


Fig. 75: **Strategies for drying filters in central units. Air recirculation operation by means of supply air or extract air recirculation.**
Aussenluft=outdoor air, Fortluft=exhaust air



Recirculated supply air via intake from the installation room, air inflow via air transfer opening into the installation room

Recirculated supply air, installation room acts as an "open channel"

Recirculated supply air via bypass between supply air and outdoor air

Recirculation via bypass between extract air and outdoor air

Fig. 76: **Strategies for drying of filters in central units (source: [Pfluger 2006]). Each of the corresponding drying states are operated for about 15 to 30 minutes before the system is switched off (e.g. night or weekend setback).**

6.5 Operation of the controlled ventilation system

For the building uses being dealt with here, i.e. schools, children's day-care centres and sports halls, the controlled ventilation system must be operated on a demand-driven basis. On account of the limited period of use, continuous operation of the ventilation system as recommended for residential buildings would negate any energy savings. Despite a ventilation system with heat recovery, the primary energy demand for meeting the ventilation heat losses and the auxiliary energy may almost double with continuous operation compared to adequate ventilation via windows. On the other hand, ventilation operation adjusted to the usage times makes it possible to achieve significant primary energy savings compared to ventilation via windows (see Fig. 77).

Pre-ventilation of the rooms must take place after an interruption in operation before the actual start of use, so that any contaminants that may have accumulated in the indoor air during the standstill period can be removed. In accordance with [EN 15251] the room volume should be replaced at least about two times before the start of use. In schools and children's day-care centres a one-hour pre-ventilation phase is sufficient.

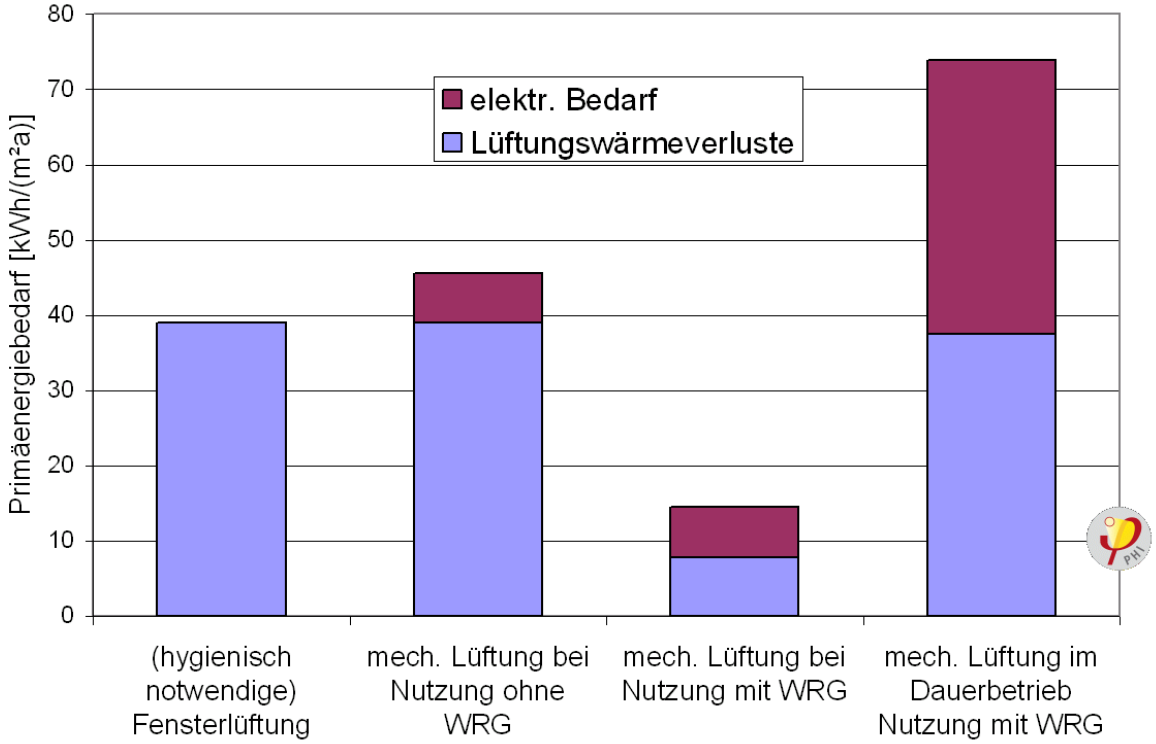
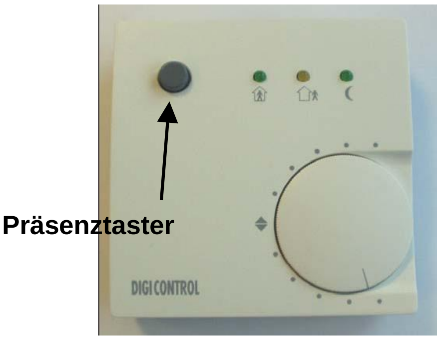


Fig. 77: **Area-weighted primary energy demand for covering the ventilation heat losses plus the auxiliary energy required in a school. The ventilation operation must be adjusted to the usage times of schools and children's day-care centres. Continuous operation of the ventilation system as is customary in residential buildings would run counter to the efforts for saving energy due to the temporary nature of these building uses *(source: [AkkP 33]).***
Assumed: External volume flow per schoolchild 15 m³/h, occupancy rate 0.5 person / m² in classrooms, useful area / net floor area = 75 %, utilisation during schooldays from 7:00 am till 14:00 pm, effective heat recovery efficiency 80 % of HRV.

In school sports hall post-ventilation should be foreseen in addition so that moisture loads in the showers can also be removed. This can be resolved by means of time programmes or moisture-driven control.

As a rule, the occupancy rate in schools deceases in the afternoon. Not all schoolchildren take equal advantage of the all-day programmes; in such cases the ventilation system for example can be operated during the core school hours (e.g. from 8:00 am till 13:00 pm). In the afternoon or evening the ventilation system can be activated on a room basis by means of an occupancy button in selected rooms where appropriate. For this function, motorised valves in the supply air and extract air ducts must be foreseen on a room-by-room basis.

Fig. 78: Outside of the actual core school hours the operating times of the ventilation system and of the heating system can be extended by means of an occupancy button. Passive House school in Neckargemünd: Architecture: Donnig + Unterstab, Rastatt / Building Services: IWP GmbH, Stuttgart.
(Picture: IWP GmbH)



The ventilation operation can be even better adapted to usage with room-by-room demand-dependent regulation. This can take place using accurate time programmes, manual switches, presence detectors, CO_2 sensors or moisture sensors (in the showers of sports halls). In schools, children's day care centres and school sports halls the times of use of the rooms and the number of persons are usually sufficiently known due to timetables and allocation plans. The advantage of operating modes based on the air quality therefore seems small compared to time programmes. The situation is different in larger rooms with unpredictable occupancy rates, e.g. dining rooms, auditoriums, libraries, staff rooms. Regulation with the aid of air quality sensors may be entirely appropriate here.

Largely natural ventilation via openable windows is recommended in the summer. The controlled ventilation system can be used for night-time cooling of the building in summer (see Section 8.4).

Subsequent implementation of the control concept is a decisive step. Specification of the operating times and other parameters should not be left to the service engineer and should instead be coordinated together with the facility manager and the service engineer.

Basically simple concepts and easy operation should be aimed for. The users should be aware at which times and in which season the controlled ventilation system is in operation.

6.6 Kitchens

The necessity for providing meals in schools and children's day-care centres has increased due to the expansion of all-day school supervision. The spectrum ranges from catering solutions with delivery of warm food to complete cooking on-site. With the extent of the kitchen facilities the building services related effort for removing potential heat and moisture loads also quickly increases. As a rule, separate ventilation systems are necessary for kitchen areas. In principle, a kitchen planner should be involved in the planning as early as possible. If the type of kitchen and the food menu are known, the kitchen planner will be able to put together the kitchen devices according to the requirements. The building services concept can then be tailored to this need.

Unfortunately, this is not common practice. Often, the subsequent operator is not yet specified in the planning phase. The ventilation relevant equipment is planned accordingly so that use of complete cooking on-site is possible later on.

When putting together the kitchen devices, choosing energy-saving technology pays off many times over. Efficient kitchen appliances save energy and usually reduce the internal loads and the moisture loads where applicable, which can additionally result in smaller kitchen ventilation systems.

"Overdimensioning" of ventilation technology should be avoided just for economic reasons alone. Moreover, kitchen ventilation systems that are overdimensioned are problematic also in terms of energy efficiency due to the considerable ventilation heat losses associated with the ventilation system.

It is not the case that the higher ventilation heat losses are compensated by the heat dissipating from kitchen appliances, because the supply air must already be warm when it is introduced into the kitchen, in order to avoid the kitchen staff being affected by draughts.

Three examples with kitchen solutions are presented below. Approximately 450 meals are prepared daily in the kitchen of a primary school in Frankfurt-Riedberg (see [Peper et al. 2007]. Compete meals are prepared in the kitchen for which cooking appliances are mainly used and there is an average amount of contamination by grease fumes.

Fig. 79: Kitchen in a primary school in Frankfurt (Riedberg). Kitchen ventilation with heat recovery.

In the kitchen area the extract air is removed via a coffered ceiling. The ventilation performance is around 6500 m³/h. The extract air is passed through a heat recovery system in order to reduce the ventilation heat losses and to preheat the supply air for the kitchen. The filters and the grease condensation surfaces protect the ventilation - system from becoming soiled. However, even so it is normally not possible to work with heat exchangers for heat recovery because the exchanger's surfaces would quickly be contaminated with deposited grease. For this project, a special central unit with a heat recovery unit was used which regularly cleans itself automatically by spraying water and tensides on the exchanger's surfaces on the extract air/exhaust air side. During operation the heating demand for the kitchen's supply air can be reduced by about 65 % with the heat recovery system.

Table 6: Overview of a kitchen in a primary school in Frankfurt (Riedberg)

Type of kitchen	Kitchen for communal catering
Number of meals per day	ca. 450
Connected load of the kitchen appliances	ca. 150 kW
Extract air demand	ca. 6500 m³/h
Reduction in the heating demand for kitchen supply air compared to a conventional kitchen solution	ca. 65 %

About 84 meals are served daily in a children's day-care centre in Frankfurt (Schwanheim). The meals are prepared in the kitchen using cooking devices which produce a rather small amount of grease fumes. The extract air demand during cooking operation is 2000 m³/h. The induction exhaust hood used here introduces most of the supply air untempered directly into the hood area. Due to the induction effect of the directly blown in supply air, indoor air loads are drawn into the hood area and removed with the extract air. The percentage of tempered kitchen supply air can be reduced by about 62 % with this kitchen ventilation concept. With this concept it must be kept in mind that the induction hood supply air duct is cold; the supply air duct must therefore be properly thermally insulated (in a diffusion-tight manner) and should be designed to be as short as possible.

Fig. 80: **Kitchen in a children's day-care centre in Frankfurt (Schwanheim). Kitchen ventilation system with induction hood.**

Table 7: Overview of the kitchen in a children's day-care centre in Frankfurt (Schwanheim)

Type of kitchen	Kitchen for communal catering
Number of meals per day	ca. 84
Connected load of the kitchen appliances	ca. 33 kW
Extract air demand	ca. 2000 m³/h
Reduction in the heating demand for kitchen supply air compared to a conventional kitchen solution	ca. 62 %

The kitchen of a primary and lower secondary school in Wiesbaden was conceived for reheating meals. The meals will be delivered in chilled form and will be heated up in the kitchen. The preparation approximately 80 meals a day is planned. To a smaller extent, it will also be possible to cook complete meals. The food will be reheated using a steam cooker. It was possible to dispense with a separate kitchen ventilation system by selecting special appliances. The moisture loads are largely reduced as a result. For this purpose the combi-steamer is equipped with a condensation hood (an extract air connection is not needed). The moisture loads in the kitchen are significantly reduced by means of a heat recovery system and a heat pump in the dishwasher. A normal household extractor hood is foreseen in addition for the preparation of smaller meals on the cooktop.

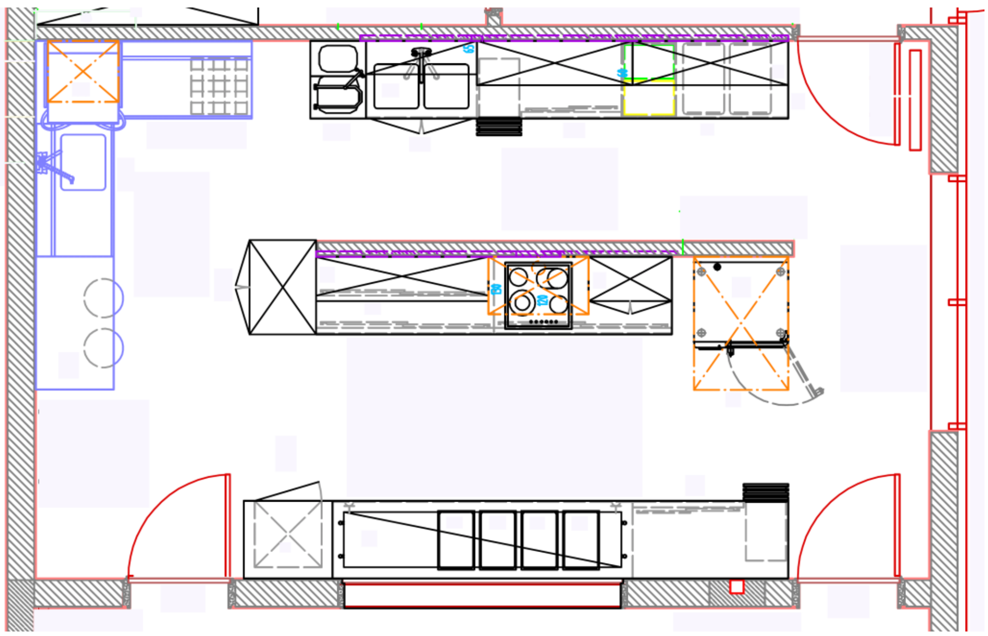


Fig. 81: **Kitchen plan of the Adalbert-Stifter school (Wiesbaden). Kitchen designer: Lacher, Darmstadt, Architecture: Hügemeier + Thrun, Wiesbaden. Through the selection of special kitchen appliances it was possible to dispense with a kitchen ventilation system.**

Table 8: Overview of a school kitchen in Wiesbaden. Through the selection of special kitchen appliances it was possible to dispense with a kitchen ventilation system.

Type of kitchen	Reheating kitchen
Number of meals per day	ca. 80
Connected load of kitchen appliances	ca. 43 kW
Extract air demand	No kitchen ventilation system / household extractor hood for use of the cooktop
Reduction in the heating demand for kitchen supply air compared to a conventional kitchen solution	Up to 100 %

6.7 Efficient ventilation in brief

A controlled ventilation system in educational-use buildings provides for good indoor air quality and in the case of modernisations also reduces the risk of mould growth at points that are critical in terms of building physics (see [AkkP 24]).

The energy-relevant quality is decisive for the success of controlled ventilation. This is possible with highly efficient heat exchangers, flow-optimised duct networks, and efficient fans so that the recovered heat amounts to 10 or 15 times the electricity demand. Measurements have verified the achievable performance figures (see [Peper/Feist 2002], [Peper et al. 2007]).

For acceptance of the controlled ventilation system by users, silent ventilation and draught-free introduction of supply air into the occupied area is imperative. Highly efficient heat recovery raises the supply air temperature close to that of the indoor air and thus creates an essential prerequisite for comfortable conditions in densely occupied rooms.

The recommendations for an energy efficient comfort ventilation system in educational-use buildings are given again below in brief.

<u>Ventilation concept:</u>

- The ventilation system should be taken into account in the planning right from the start. Early coordination with the space allocation plan and fire protection concept is essential.
- All rooms should be included in the ventilation concept. Circulation areas, auxiliary rooms and sanitary facilities must also be included in the ventilation concept with heat recovery.

- The concept of directed air flow should be used in case of centralised ventilation concepts.
- Sufficient space should be foreseen for the ventilation unit.
- Outdoor air and exhaust air ducts should be as short as possible and should be extremely well-insulated. This applies especially for decentralised ventilation concepts.
- Dimensioning of air quantities according to the foreseen number of persons: 15...20 m³/(h person) recommended for schools and children's day-care centres, and 60 m³/(h person) for sports halls.
- Dimensioning of the duct system for low pressure losses. The pressure losses of the supply air and extract air ducts of the ventilation system should be less than 200 Pa for each. Significantly lower pressure losses should be strived for with decentralised ventilation concepts.
- Ventilation should take place silently in the occupied areas of schools and children's day-care centres:

  The sound pressure level in the occupied areas should be ≤ 30 dB(A), lower values should be strived for (especially in sleeping areas of children's day-care centres; sound pressure levels below 25 dB(A) are recommended here, similar to those in residential buildings). Sweden's building directive BFS 2002 permits a maximum level of 30 dB(A) in classrooms. 30 to 40 dB(A) are permitted according to [EN 13779].
- Summer operation should be taken into account in the ventilation concept: ventilating the sanitary facilities during usage is usually adequate in the summer; the occupied areas can be ventilated via windows.
- There should be a concept for night-time ventilation in summer. Possibilities for natural ventilation at night during warm summer periods should always be checked. The mechanical ventilation system should at least be equipped for night-time ventilation (summer bypass; see Section 8.4).

<u>Ventilation unit</u>

- Efficient ventilation units should be used. Recommended electrical efficiency p_{el} (power consumption of the ventilation unit including regulation based on the supply air volume flow): 0.45 ... 0.30 (target value) Wh/m³.

  The specific fan output defined according to [EN 13779] can be used to estimate this value:

  $P_{SFP,\ extract\ air} + P_{SFP,\ supply\ air}$.
- Ventilation units with highly efficient heat recovery should be used. Heat recovery efficiency η_{HRV} ≥ 75 %. For a definition of η_{WRG} see [AkkP 17]. A list of

certified central units can be found on the website of the Passive House Institute (www.passivehouse.com) under the menu option "Certification".

- Low internal/external leakages. The leakages in the ventilation unit should be ≤ 3 %.
- Thermal insulation of the central unit (at least Class T2)
- The ventilation system must be hygienically safe: the ventilation network should always be dry and therefore unproblematic in terms of hygiene. The outdoor air filter may be critical if the ventilation system is switched off when the outdoor air filter has a relatively high moisture content. Measures against permanent moisture penetration should be foreseen (see Section 6.4.7).
- Outside of ventilation operation the outdoor air and exhaust air ducts should be closed by means of suitable valves: ventilation valves in these ducts are necessary in any case for the filter drying strategies. As a rule, the valves are already integrated into the central unit; but an arrangement in the insulation level is better in terms of energy.
- The ventilation system must be operated in a balanced manner. A disbalance can increase the ventilation heat losses:
  - The supply air and extract air volume flows must be adjusted by the contractor before the initial operation.
  - The ventilation unit should have automatic balance adjustment.

<u>Operation / regulation of the ventilation system</u>

- Ventilation operation must be limited to the usage times. Continuous ventilation operation is unsuitable for energy-relevant reasons (see Section 6.5). In primary schools this can be from Monday till Friday from 8:00 am to 14:00 pm. Furthermore, operation can be reduced even further by means of demand-based room-by-room control of the ventilation system. This is possible through:

  - precise time programmes, manual switches, presence detectors, or CO_2 sensors
- In the morning before the start of use, first the building should be pre-ventilated by means of the controlled ventilation system. In this way indoor air contaminants that have accumulated during the night will be removed. About twice the air volume should be exchanged (see [EN 15251]). In the interest of reducing indoor contaminants special attention should be given to low-emission construction materials and products. The pre-ventilation phase should be used for heating up in concepts with supply air heating.
- The ventilation system must be easy to operate. Intervention by the school and day-care centre staff or the facility manager must be possible in the case of events and parents' evenings.

7 Heating

Highly efficient Passive House buildings also need to be heated. However, the heating demand for space heating is extremely small and is lower by a factor of 4 to 6 compared to a conventional new build. The heating demand of 15 kWh/(m²a) (typical values for existing buildings are around 200 kWh/(m²a)) is even insignificant in comparison with existing buildings (see Fig. 4).

In contrast with residential Passive House buildings, temperature setback operation outside of usage times is advisable in the case of the examined educational-use buildings. The indoor temperature falls slowly on account of the good thermal protection. The customary short setback times only save a small amount of heating energy in residential Passive House buildings. The additional effort for a night-time setback or shutdown is therefore considered impractical (see [Feist 2005]).

Conversely, because longer setback periods are possible in educational-use buildings, a relevant amount of heating energy is saved through setback operation here. The required heat outputs are higher in comparison with residential Passive House buildings (without setback operation) due to the reheating processes at the beginning of use. Accordingly, a dynamic heat-up load must also be taken into account for dimensioning the heat output.

All the usual solutions for heat transfer (e.g. radiators) can be used in highly efficient educational-use buildings. Additional heating through post-heating of the supply air quantities that are necessary for good health is also possible if the Passive House criteria are met (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

With a high quality of thermal protection the heating system can usually be simplified: smaller heaters, free positioning of the heaters or even dispensing with heaters and distribution lines can lead to lower investment costs. The same applies for regulation of the heating system. It should be critically assessed what is actually needed, for example, is it possible to dispense with individual room regulation? For radiators, thermostat valves with a fixed setting range (known as public building models) may be an alternative.

7.1 Heating systems

The diversity of possible heating solutions increases with very good thermal insulation, while the type of heating system becomes less relevant. As already mentioned previously, if the Passive House criteria are complied with, it is also possible to heat the building using the ventilation system. In the case of new builds, cost advantages may result with post-heating of the supply air. For modernisations it should first be checked whether the existing heat distribution network can still be utilised. In addition, in many cases thermal bridge minimised execution of the building envelope in the foundations area is often extremely complicated in modernisations and can hardly be practically implemented. This can lead to higher heating loads in the adjacent rooms which can no longer be met via supply air heating. For this reason, heating via static heating surfaces should be chosen for modernisations in general, unless the Passive House criteria are met in the modernised state and thermal bridges can be mitigated to the greatest possible extent.

Importance of window quality

It is only with a thermally high quality of Passive House suitable windows that positioning of heating surfaces and the type of heating system become less relevant for thermal comfort in the room. Fig. 82 shows cold air descent at the façades as a function of the heat transfer coefficient of the window. Consequently, with heat transfer coefficients below 0.8 W/(m²K) of the windows and window heights up to 2 m the air velocities at the façade remain within the comfortable range. Heaters under or in front of the windows are no longer necessary with the recommended quality. The subject of windows was dealt with in detail in Section 5.2.

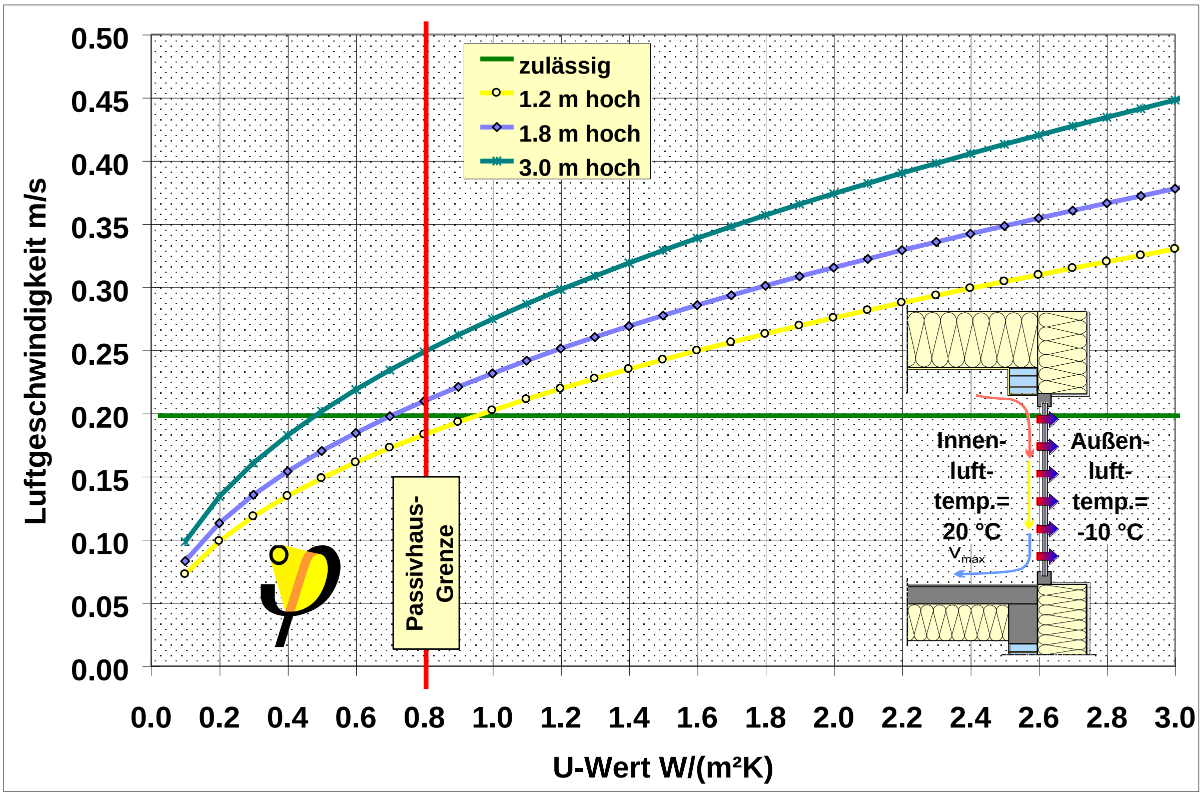


Fig. 82: **Average velocity of cold air descent near the window in dependence on U_W.** ***(Source: [AkkP 14])***

U-Wert=U-value, Passivhaus-Grenze=PH limit, Zulässig=permissible, hoch=high, Luftgeschwindigkeit=air velocity, innenlufttemp.=indoor air temperature, Außenlufttemp.=outdoor air temperature

Supply air heating

The idea underlying supply air heating in residential Passive House buildings is the reduction of investment costs by means of an adapted, simplified heating system. In schools and children's day-care centres, this cost advantage is usually only achievable if a group of rooms can be supplied jointly by means of a post-heating coil. Rooms with comparable load profiles (identical orientation, similar heat losses and utilisation) can then be grouped together. Libraries, auditoriums, or staff rooms differ in this respect from e.g. classrooms.

In practice, it is clear that in schools and children's day-care centres often several groups of rooms would have to be formed and the cost advantage for investment over heating with static heating surfaces in each room will no longer be relevant if simplified heating solutions are used.

In contrast, in school sports halls heating of the hall via supply air is ideal on account of simple and straightforward space allocation (see Section 7.2). For example, in a single-court sports hall of a Passive House school in Reichelsheim the additional investment costs for controlled ventilation for the entire sports hall were offset by the lower costs for the heating system. Instead of the initially calculated underfloor heating system, the hall area is now supplied via supply air heating. A ventilation system would have been necessary for the auxiliary rooms in any case (based on the cost details provided by IB Bachmann, Bad Hersfeld).

Supply air heating for e.g. several classrooms or group rooms via a common post-heating coil may lead to deviation from the setpoint temperatures of up to 2 K with varying occupancy rates. Thermally accessible mass in the rooms and a good level of thermal coupling between the rooms will improve the control characteristics for a group of rooms. Heating of all rooms in a group of rooms should be regulated according to the average indoor temperature of the group of rooms, or according to the room with the lowest indoor temperature (see [Kah 2006]).

Heating by means of a supply air post-heating system should only be chosen if rooms can be grouped meaningfully and if there is actually an investment cost advantage compared to a solution with heating surfaces. The building owner must be consulted in the case of zone-by-zone heating.

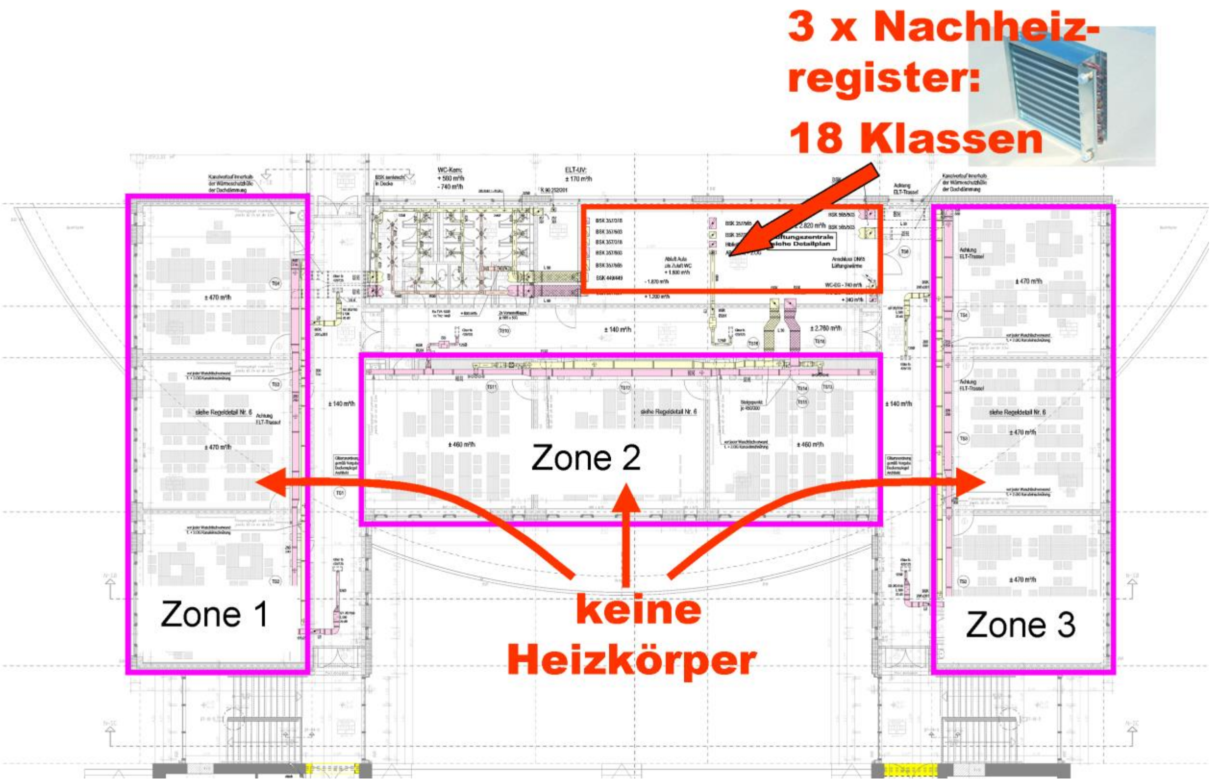


Fig. 83: **Passive House school with supply air post-heating (Albert-Schweitzer-Schule, Alsfeld). Depiction of the zoning of the heating system. The residual heating demand of the 18 classrooms is met by three heating coils located in the ventilation centre *(Source [AkkP 33]).***
Architecture: BLFP, Friedberg / Building Services: Neuplan, Gießen.
keine Heizkörper=no heaters. 3x Nachheizregister 18 Klassen=3 post-heating coils for 18 classrooms

As mentioned above, in contrast to residential-use buildings, setback operation during the night-time is recommended in educational-use buildings. In the case of heating by means of the supply air, the already necessary reheating should take place in the context of pre-ventilation of the indoor spaces before the beginning of use (in the context of a pre-ventilation phase a two-fold indoor air exchange is advisable; see section on ventilation 6.5). For reheating, the supply air should be heated to maximum (up to ca. 50 °C) so that sufficient heat output is transferred into the rooms during the short pre-ventilation phase. Long extended heat-up phases which go beyond the hygienically necessary ventilation system operation would significantly increase the total primary energy demand on account of the additional demand for operating energy.

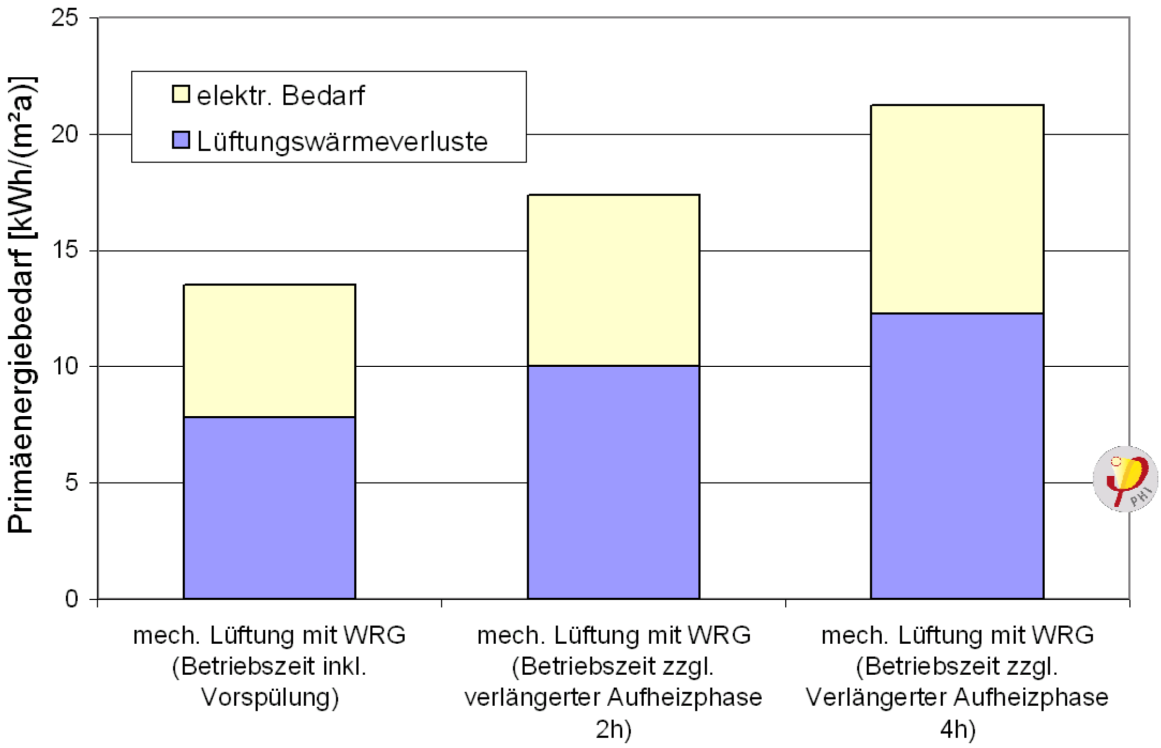


Fig. 84: **Area-weighted primary energy demand for ventilating a school. If ventilation system operation for heat-up is extended beyond the hygienically necessary operating times (including pre-ventilation), the primary energy demand may increase significantly. In the case of supply air heating, reheating within the pre-ventilation phase should always be possible after night setback operation. *(Source: PHI)***

Assumed: outdoor air volume flow per schoolchild 15 m³/h, occupancy rate 0.5 persons / m² in classrooms, useful area / net floor area = 75 %, utilisation on schooldays 7:00 am till 14:00 pm, heat recovery efficiency of HRV 80 %.
Primärenergiebedarf=primary energy demand, mech. Lüftung mit WRG=mechanical ventilation with HR, Betriebszeit inkl. Vorspülung=operating time including pre-ventilation, Betriebszeit zzgl. verlängerte Aufheizphase =operating time plus extended heat-up phase, elektr. Bedarf=electricity demand, Lüftungswärmeverluste=ventilation heat losses

With supply air heating the post-heating coils must therefore be dimensioned for a sufficiently large output for this temperature difference. For each m³/h of volume flow the post-heating coil must be able to transfer an output of 10 W (i.e. 10 kW for 1000 m³/h).

For heating using fixed heating surfaces, the heat-up duration can also be longer because heating and ventilation are decoupled linked in this case.

Heating via fixed heating surfaces

A highly efficient standard of thermal protection also leads to potential simplifications in the case of heating via fixed heating surfaces. First of all, due to the smaller heating loads, smaller heating surfaces can be used compared to conventional buildings. Furthermore, the type of heating surface and its positioning in the room no longer plays a significant role. Heaters are no longer necessary under or in front of the windows due to their good thermal quality.

The choice of heating surface and its positioning may follow other principles e.g.

- Through the specific arrangement of the heating surfaces it is possible to implement the heat distribution network in a compact and cost-effective way (positioning near the interior wall is also possible).
- Where would the heating surface be less conspicuous, or where could this be specifically utilised? In children's day-care centres for example the radiators can be positioned away from the area occupied by children in order to minimise the risk of injury.

Fig. 85: Positioning of the radiators in a Passive House day-care centre for children (Goldstein) in Frankfurt. The positioning of the heating surface plays a subordinate role for its function. Priority may be given to other practical considerations when deciding this.
Architecture: AS&P, Frankfurt / Building Services: IB Schlosser, Oberursel

Underfloor heating systems are very popular in sports halls and children's day-care centres. With the shorter operating times of underfloor heating and an excellent level of thermal protection at the same time, the secondary effect of "keeping the floor warm" becomes less relevant (see [SIA D090]). A similar level of comfort can usually be achieved with floor coverings that feel warm to the feet and well-insulated floor slabs. The heating system is in operation especially for heating up in the morning. Due to the low forward flow temperatures of underfloor or wall surface heating systems, combining these with heat pumps may be appropriate. The efficiency of heat pumps largely depends on the forward flow temperature.

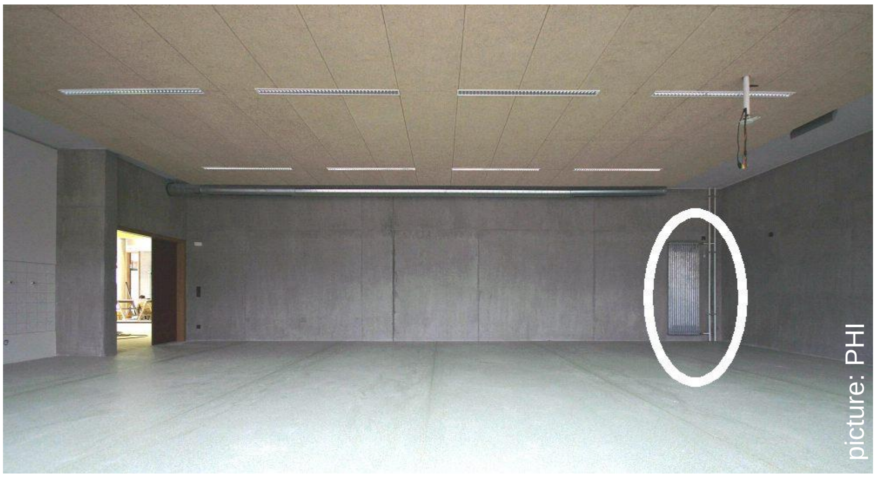


Fig. 86: **Heating via radiators in the Schul-Pavillon Walldorf (picture on the left). Architecture: IB W. Herrmann, Walldorf / Building Services: Gadow + Graeske, Walldorf.**
Positioning of the heater on an adjacent interior wall with compact distribution networks (picture on the right) in a Passive House day-care centre for children (Ginsterhöhe) in Frankfurt.
Architecture: ppplanung architekten, Wiesbaden / Building Services: Planungsbüro Donath, Neu-Isenburg

7.2 A special case of heating: sports hall

Experiences with previous sports hall projects with a lower standard of thermal protection revealed problems with air heating in halls. In part, the critical points in these projects were pronounced temperature stratification in the hall that was observed with the type of heating system, and the high electricity demand for ventilation. In halls with conventional thermal protection, a high rate of air exchange (at least two-fold) is required for providing the necessary heat output. Older sports halls with air heating are therefore often regarded as "power guzzlers" and "energy wasters". The air change rate necessary for heating during sports operations is considerably higher than the hygienically necessary values. In contrast, in sports halls built to the Passive House Standard the heating load can already be met through post-heating of the hygienically necessary air quantities.

For this reason, the issue of temperature stratification in sports halls with excellent thermal protection will first be studied below.

<u>**Temperature distribution in the hall area**</u>

Sports halls usually have room heights of at least 5.5 m in single-court sports halls and 7 m in triple-court sports halls (see [DIN 18032-1]). Convection in the hall area can lead to undesirable temperature stratification in which heat accumulates under the ceiling while the actual occupied area only has a moderate temperature. In the process, temperature increases of 1 K per metre of room height occur in conventional halls (see [ea-nrw 2003]). In sports halls this accumulated heat leads to increased transmission heat losses in the roof area. For this reason, special measures to counteract natural temperature stratification in halls are recommended in the literature: radiant ceiling heating, underfloor heating or ceiling fans (see [Radtke 1997], [Himmelsbach 2005], [ea-nrw 2003]).

Measurements in a Passive House sports hall with air heating (see [Pfletscher/Kah 2004]) indicate that very uniform temperature distribution is achieved on account of the better thermal protection. This result was confirmed using CFD simulations (see [FLUENT], Fig. 87 and Fig. 88). Maximum temperature differences of 2 K were calculated for a hall height of 6 m (i.e. temperature gradients under 0.33 K/m). Heating took place via post-heating of the hygienically necessary air quantities. In contrast, a considerably higher vertical temperature gradient with 1 K/m resulted for a variant with a conventional standard of thermal protection.

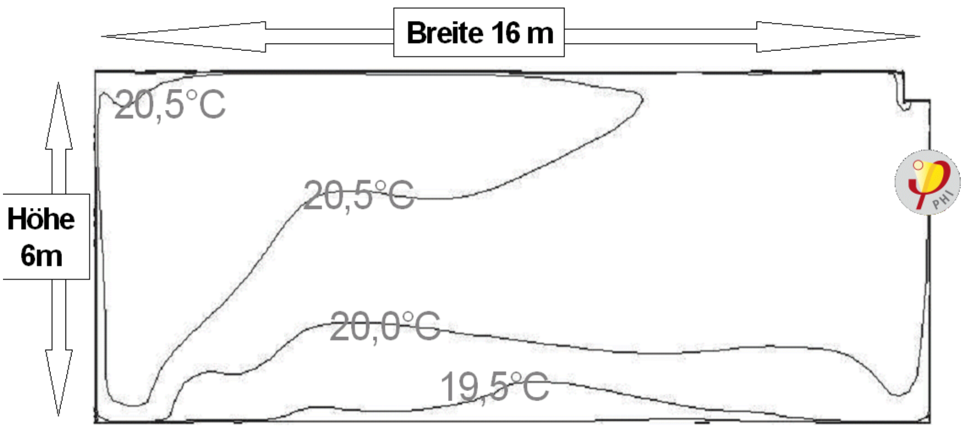


Fig. 87: **Vertical section through a single-court sports hall which is heated via supply air. Lines with an identical temperature are shown for a hall with a highly insulated building envelope. Very uniform temperature distribution is achieved.**
Assumed: outdoor temperature 0 °C, heating via supply air from the top left.
(Source: PHI)

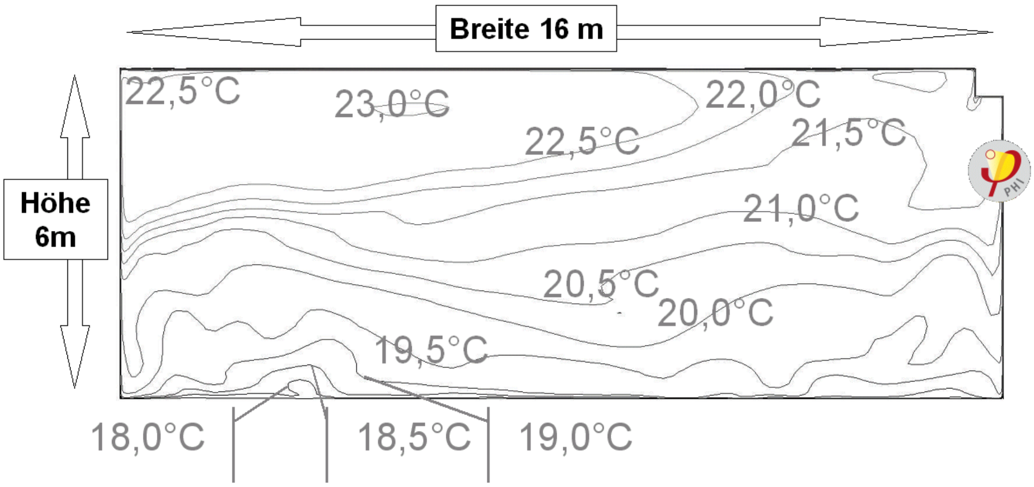
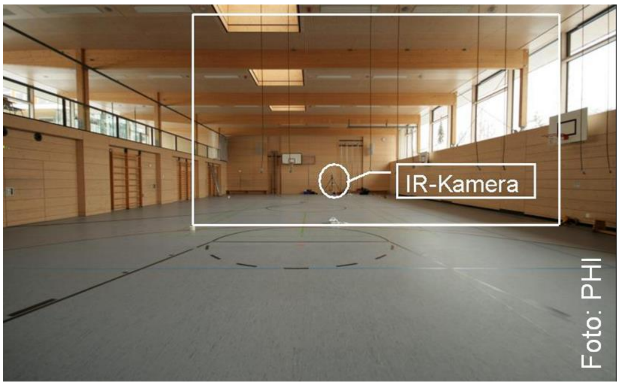


Fig. 88: Vertical section through a single-court sports hall which is heated via supply air. Lines with an identical temperature are shown for a conventionally insulated building envelope. The indoor temperature increases by almost 1 K/m from the bottom to the top.
Assumed: outdoor temperature 0 °C, heating via supply air from the top left. ***(Source: PHI)***

To secure the CFD calculations, temperature measurements were carried out in a Passive House sports hall in addition. Besides measurement with temperature sensors, it was also possible to visualise the temperature profile with the aid of infrared imaging of paper strips (see Fig. 89 and Fig. 90). The measurement survey in the Passive House sports hall showed only minimal temperature differences in the hall area and thus confirmed the CFD simulation.



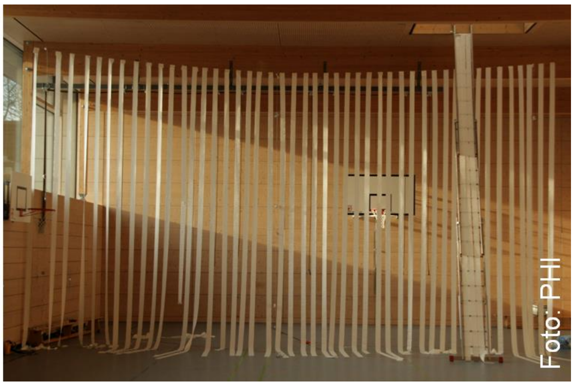


Fig. 89: Measurement setup in the Passive House sports hall. For visualisation of the air temperature in the hall cross-section, paper strips were suspended in the hall and thermal images were prepared. In addition, temperature sensors were suspended at the level of the paper strips.

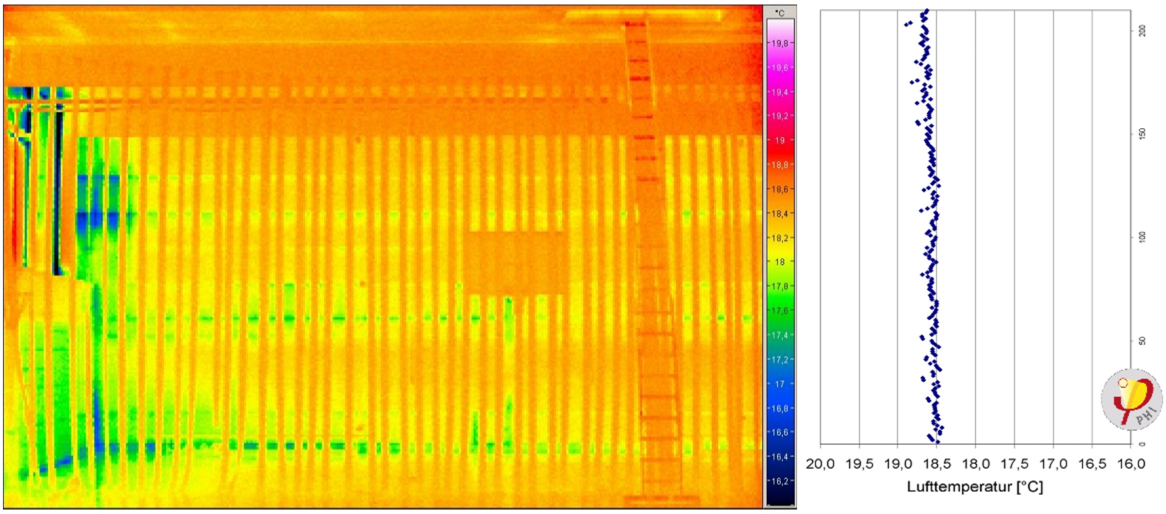


Fig. 90: **Here, temperature distribution in the hall cross-section is shown based on the temperatures of the toilet-paper strips (infrared image). Hardly any temperature stratification can be discerned.**
As in the CFD simulations, the outdoor temperature was 0 °C on average. ***(Source: PHI)***

The extremely uniform temperature distribution persists only under one restriction. Higher outputs are necessary for heating up the sports hall after a night setback even in highly insulated halls, which leads to greater temperature stratification in this period of time (see Fig. 91). After the heat-up process, the stratification dissipates again quickly. Increased transmission heat losses in the roof area can be disregarded on account of the short reheating period.

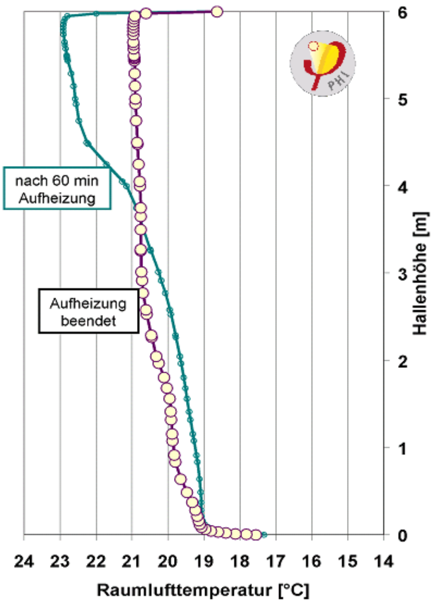


Fig. 91: Temperature stratification in a highly insulated sports hall (height 6 m, CFD calculation) after one hour of reheating and after the end of the reheating process. Stratification dissipates again rapidly with the end of the reheating process. (Source: PHI)
Assumed: outdoor temperature 0 °C, heating via supply air

<u>Heating in sports halls</u>

In contrast to implementation with conventional thermal protection it is apparent that the type of heating system does not play any significant role also in the case of highly insulated sports halls. The hall area can be heated and reheated by post-heating the hygienically necessary air quantities. Even with an excellent standard of thermal protection the temperature stratification remains low also with the supply air heating concept.

Table 9: Assumptions for supply air heating in the hall area

Duration of pre-ventilation / heat-up	2-fold air exchange / 2 h pre-ventilation duration
Supply air flow in single-court sports hall (30 sportspeople)	30 x 60 m³/h = 1800 m³/h
max. temperature difference ΔT / max. heat output	30 K / ca. 33 W/(m² hall area)

As explained in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, combined air supply and venting of the hall and auxiliary rooms is appropriate for sports halls. In this concept the supply air is introduced into the hall area and then flows into the auxiliary areas. On account of the higher temperature requirements in the showers and changing rooms, the incoming air in this area must first be heated. This can take place by means of a heating coil in the corresponding duct section or through appropriate positioning of a heater in front of the inflow opening (see Fig. 68).

7.3 Hot water supply

Generally hot water should be provided in educational use buildings only for kitchens, showers, washrooms and building cleaning. Low heat losses of the heat distribution system are essential for efficient hot water supply in schools and children's day-care centres. In case of central hot water generation, compact and well-insulated (insulated thickness 2 x DN) distribution networks should be ensured with the room layouts. Besides, this will also lead to increased security against legionella bacteria. In schools e.g. hot water usage can be restricted to the actually necessary areas (usually hot water is not necessary in wash basins in toilets and in the classrooms). If the supply points are spread over the entire building, a decentral hot water supply should be considered. Compact continuous-flow heaters should be preferred over electric under-counter appliances.

Unlike in schools, in children's day-care centres hot water is often also required in the sanitary facilities. Self-closing fittings may substantially reduce the hot water demand here.

In sports halls the hot water demand is more dominant in comparison to schools and children's day-care centres. Here too, compact and well-insulated distribution networks can reduce the distribution losses. Moreover, water fittings offer great potentials which usually consist of simple and cost-effective measures such as water-saving fittings for wash basins and showers. The specific use of flow restrictors, thermostatically controlled taps and self-closing fixtures should be decided according to the circumstances.

Despite being well-insulated, hot water storage tanks lose heat continuously, which has to be compensated by the heating system. The larger the storage tank is, the more significant the heat losses will be. Despite these losses the hot water storage tank is often overdimensioned. A water consumption measurement e.g. in modernisations, or measured values from similar buildings carried out in advance can be used for dimensioning a new water supply. Hot water storage tanks should be located as near the point of use as possible in order to minimise distribution losses. A separate heating system or an independent water heating system should be considered in the case of long supply pipes to the hot water storage tank.

With so-called fresh water stations the provided amount of domestic hot water can be decreased greatly. When the tap is opened, the water is heated according to the continuous-flow principle. This can be utilised particularly for prevention of legionella bacteria. The use of solar thermal collectors should be considered for sports halls. In order to prevent overdimensioning here also, a water consumption measurement in advance may be helpful for demand-oriented dimensioning of the solar heating system in this case as well.

7.4 Heat supply

The small heating demand of highly efficient Passive House buildings for educational use can be met with all common heat supply solutions. Heat supply with renewable energy sources is of particular interest besides conventional heating solutions based on gas or oil.

Heat supply on the basis of renewable energy and efficient utilisation of energy are not mutually exclusive alternatives; rather, they gain in importance when combined. As a rule, even renewable energies are only available to a limited extent (e.g. biomass). They can only assume an important role in the energy mix of the building if energy utilisation is efficient. This results in other advantages, for example, with improved efficiency the stock volumes of wood or wood pellets can be smaller.

Furthermore, a high standard of thermal protection provides the right conditions for ambient heat supply. The efficiency of heat pumps depends significantly on the forward flow temperature. With the excellent thermal protection, smaller heating panels (possibly only partial surfaces) with low overtemperatures will be adequate.

In contrast with residential Passive House buildings, a temperature setback at night is recommended for the building uses being considered here. The additional heat-up load must therefore be taken into account when dimensioning the heat supply.

Frequently, the heating system in an existing building provides sufficient reserve capacities to supply a new highly efficient building extension at the same location in addition. With the low heat consumptions – buildings built to the Passive House Standard consume only about a third of the energy used by equivalent existing buildings – the heat loss of the local heating lines can be disproportionately high in relation to the heat consumption of the building extension. With conventional local heating lines that are laid in the ground, the proportion of heat losses can easily reach 30 % of the useful heat consumption (assuming a connection length of 50 m, supplying a Passive House sports hall, only winter operation). In addition to the optimisation of the building extension, the local heating supply lines must not be forgotten in such cases. For this reason, compact and well-insulated supply lines should be strived for, and as far as possible the heat-carrying pipes should be routed within the buildings. If routed within the heated building, any distribution losses that occur can still be utilised to some extent. Moreover, the heat losses from supply lines can be reduced by means of special sand beds in the supply trench (e.g. the product Thermosand by the company Ke Kelit). In the summer, heat supply via longer, buried local heating lines should be avoided.

Fig. 92: **Single-court Passive House sports hall in Heidelberg. Here the low heating demand of the hall was met by the reserve capacities of the heating centre in the existing school, which enabled considerable cost savings.**
Architect: ap88, Heidelberg / Building Services: Planungsbüro Schmitt & Partner, Mauer

If step-by-step modernisation measures are planned (see [AkkP 39]), the heating load will decrease with each thermal protection measure. The final state after completion of all measures should also be taken into consideration when modernising the heat supply system. The heat generator must then also be able to efficiently heat the entire modernised building. While existing buildings may have heating loads between 100 and 180 W/m², the loads in buildings modernised using Passive House components can decrease to the range between 10 and 30 W/m².

7.5 Distribution losses, heat pumps and circulation pumps

In new constructions, heat distribution pipes generally should not be installed in unheated spaces. If this is unavoidable (as e.g. in existing buildings), the pipes here should be as short as possible. Cost-effective insulation thicknesses are at least 2 DN for distribution pipes which are not routed through the heated area (see [Kah et al. 2008]). It is essential that the pipe mounts are not fixed to the pipe itself and should instead be attached to the insulation layer, and that fittings, junctions etc. are also insulated.

Pipes carrying hot water and circulation pipes in heated areas should also be insulated with at least 2 DN. In the summer, well-insulated circulation pipes will also reduce the internal loads.

Insulating with larger insulation thicknesses can be achieved easily and economically in some cases. Pipes under the basement ceiling for example can be routed inside the thermal insulation of the basement ceiling. If the pipes pass through a riser duct then this can often be filled in relatively easily using glass wool insulation or cellulose.

High-efficiency pumps (Efficiency Class A) should always be used in new constructions. For existing buildings, replacing fixed-speed heating pumps with high-efficiency pumps (Efficiency Class A) is generally economically attractive. According to the coupling principle for modernisation measures, the replacement should be combined with already necessary work for maintenance or repairs for the heating system.

7.6 Operation / Regulation

Specification of the heating period

The specification of a heating period with a fixed starting and ending date (e.g. 15.10. till 15.4.) has proved successful in practice. In this way, it will also be comprehensible to the user that the heating system is in operation during this time. With fixed times, it will be easier to communicate other recommendations relating to the mode of operation, e.g. that ventilation via windows is not necessary during the heating period. As a rule, sufficient fresh air is provided through the controlled ventilation. In contrast, outside of the heating period ventilation should take place via windows ("summer operation").

Temperature setback operation

Temperature setback operation outside of the times of use makes sense in schools, children's day-care centres and sports halls built to the Passive House Standard. The indoor temperature does not fall more than 3 K even during extremely cold nights. For example, in schools with morning lessons over 30 % of the heating energy is saved with temperature setback operation in comparison with continuous heating operation.

Implementation of temperature setback operation with heating surfaces is in accordance with common practice. Heating and ventilation are coupled if the heating demand is met through post-heating of the supply air. The operating times of the ventilation system and thus heating should be based strictly on the hygiene-relevant requirements in this case. Extended or even continuous operation of the ventilation system for meeting the heating load should be avoided at all costs (see Fig. 93).

Interruption of operation on weekends or during holiday periods lasts longer. For these cases, temperature back-up mode should be foreseen even if supply air heating is chosen, so that the indoor temperature does not fall below the minimum and so that the subsequent heat-up phases remain on schedule. A standby temperature of 17 °C is recommended. The potential for optimisation is still possible in the case of operating energy of the ventilation system. With a reduced volume flow rate the pressure loss decreases in line with the characteristic curve of the duct network. Disregarding the efficiency curve of the fan leads to a decrease in the power consumption with the cube of the flow rate. Standby operation with a reduced volume flow rate on weekends and during the Christmas holidays should be considered. Again, the supply air temperatures should be selected to be as high as possible (up to 52 °C).

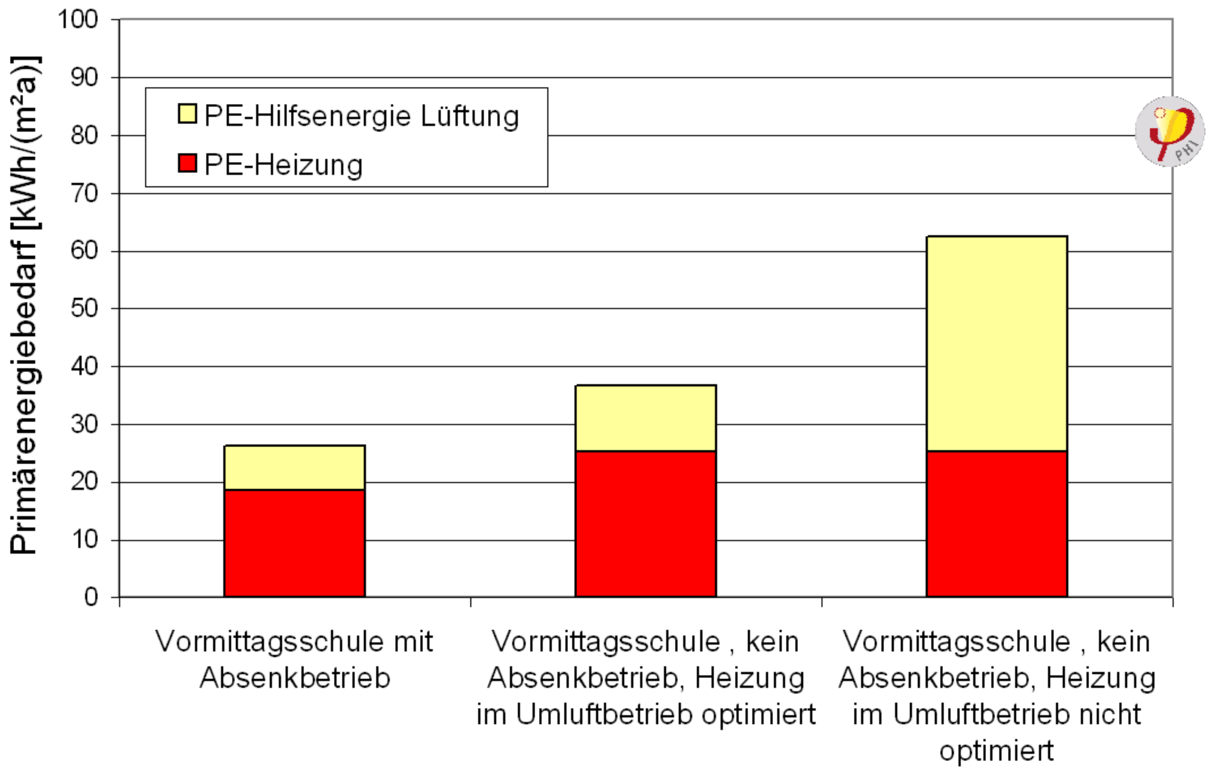


Fig. 93: **Influence of the operation mode on the primary energy demand in the case of supply air heating based on the example of a school. Extended or continuous operation of the ventilation system for heating the building may increase the primary energy demand significantly. *(Source: PHI)***
Assuming: 30 school hours / week, heating via supply air
Vormittagsschule mit Absenkbetrieb…= morning school with setback operation, morning school no setback operation, optimised heating with recirculation mode, morning school no setback operation, heating in recirculation mode not optimised , PE auxiliary energy for ventilation system, PE heating, Primärenergiebedarf=primary energy demand

<u>Regulation of the heat generator</u>

With improved thermal protection, the heating load is more strongly determined by the free heat while in contrast the influence of the outdoor temperature decreases. In schools, children's day-care centres and sports halls heating-up must take place in the morning especially. When the setpoint temperature have been reached, the body heat of occupants and where applicable solar gains will be sufficient to keep the building at the setpoint temperature.

In order to minimise the heat distribution losses, the forward flow temperature should be suitably regulated. For example, in the morning a maximum forward flow temperature can be provided for the heat-up mode, which declines continually during the course of the day. Outdoor temperature-controlled regulation of forward flow temperature does not seem expedient. The heat consumption of the heat circuit would be an appropriate reference value.

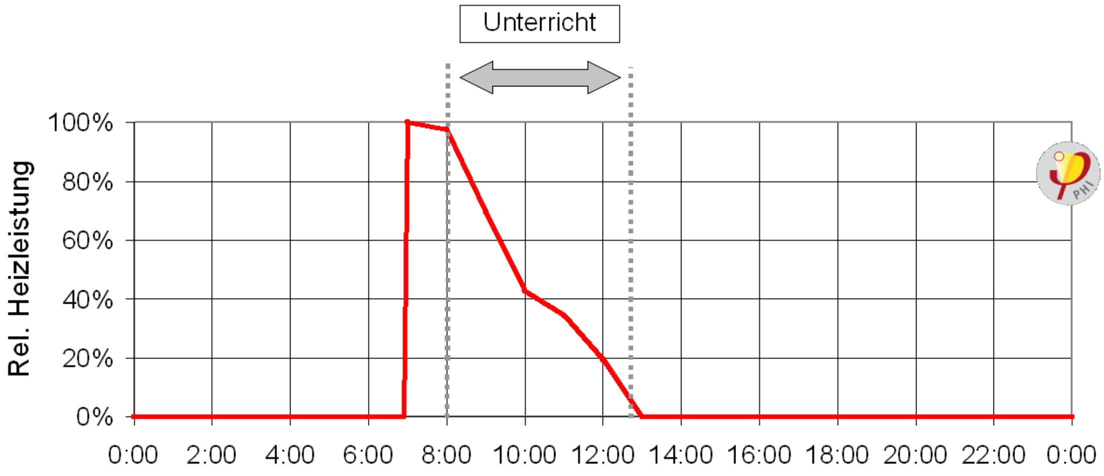


Fig. 94: **Typical progression of heat output on a cold day, using the example of a Passive House school with morning utilisation. The heating operation starts one hour before the start of school (with the pre-ventilation phase). (*Source: PHI*)**

7.7 Heating systems for energy efficient educational use buildings in brief

Passive House buildings also need to be heated, but in comparison to conventional new builds they require much less heating. The heating energy demand is about 70% lower. The energy saving potentials of energy-relevant modernisations with highly efficient components can be as high as 90%. The heating demand of highly efficient Passive House educational-use buildings is about 15 kWh/(m²a). The low energy demand forms the basis for sustainable use of renewable energy.

The heating recommendations for energy efficient educational-use buildings are summarised again below.

Heating

- All common heat transfer solutions (such as radiators) can be used. If the Passive House criteria are met, the building can be heated by post-heating the hygienically necessary supply air quantities in addition.
- With the high standard of thermal insulation the heating system can be simplified. Reduced investments may result as a result of dispensing with heaters in front of or under the windows, smaller heaters and free arrangement of heaters, or even doing away with heaters and distribution lines completely. In

the case of Passive House sports halls, heating the hall via supply air is particularly appropriate.

- Heating via supply air post-heating should only be chosen if meaningful groups of rooms can be formed and an investment cost advantage does actually result, compared to a solution with heating surfaces.
- The type of heating does not play a major role in the case of large sized highly insulated sports halls. Temperature stratification remains extremely low even with the supply air heating concept with an excellent standard of thermal protection.

Hot water generation

- Reduction of losses: compact and well-insulated distribution networks (insulation thickness 2 x DN) should be strived for with central hot water generation. The hot water storage tank should be dimensioned according to the actual demand; unnecessary over-dimensioning should be avoided.
- Hot water taps should be limited to the areas where they are actually necessary (e.g. in schools: no hot water in toilets and classrooms).
- Reduce the hot water demand: water-saving fittings, self-closing taps, flow restrictors, thermostatically controlled taps should be foreseen at frequently used points of use.
- Consider the use of solar collectors for sports halls. As far as possible the collectors should be dimensioned according to the actual demand.

Heat supply

- The space heating demand can be covered using all common heat supply solutions.
- Particularly good conditions exist for the use of renewable energy due to the low space heating demand.
- Heating setback or switch-off operation should be used in energy efficient educational-use buildings. The heat output must be adequately dimensioned for reheating.
- Heat distribution lines should not be routed in unheated rooms if possible. Pipes in unheated areas should be insulated with a thickness of at least 2 x DN.

8 Summer Operation

8.1 Temperature behaviour in summer

What about energy efficient schools, children's day-care centres und sports halls in the summer? Doesn't the good level of thermal protection lead to problems, particularly in connection with the high internal heat gains in schools and children's day-care centres? Systematic simulation calculations were carried out in order to examine this question more precisely. Considerable experience has now been gained in practice in this respect.

Let us assume that a model building has excellent thermal insulation and that only extremely low internal and solar loads arise. The temperatures inside the building would then approximate the daily mean temperature of the outdoor air over several days; in Germany this would be approximately 18 °C in the summer. However, if the building was insulated only to the minimum possible standard and the same internal and solar loads were assumed, then the indoor temperature would follow the outdoor air temperature. The indoor temperature would even rise significantly beyond the outdoor temperature due to the solar gains through the opaque roof areas if the storage masses are small. A good standard of thermal protection is clearly also advantageous in the summer.

Solar and internal loads usually let indoor temperatures rise to values considerably higher than 18 °C in the summer. Minimising the internal and solar loads is therefore a key principle for pleasant summer temperatures.

High occupancy rates associated with high internal heat gains during the usage periods are unavoidable in schools and children's day-care centres. At the same time, the occupied rooms must have sufficiently large window areas (especially high windows) for the utilisation of natural light (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). The solar loads can be greatly reduced through suitable solar protection measures. Appropriate concepts for the efficient use of artificial lighting and computing equipment will also help to decrease the internal loads caused by electrical applications.

Another key aspect for summer comfort is the thermal storage mass of the building. Some of the heat loads can be stored in the building structure, resulting in a much smaller increase in the indoor temperature.

What should be done about the heat loads that remain? The outdoor air offers sufficient cooling potential during most hours in the summer. In a typical summer, outdoor temperatures above 25 °C (see also Fig. 95) occur only about 20 to 120 of the hours of usage in schools and children's day-care centres (taking into account a

6-week summer break). In the remaining hours of usage in summer the indoor temperature can therefore be kept almost at the outdoor temperature level through adequate ventilation. Another principle in the summer therefore is to ventilate, ventilate, ventilate. Furthermore, adequate air exchange is necessary for hygiene-relevant reasons alone.

In general, unlike in cold winter months, ventilation via windows can and should take place in the summer. On the one hand, experience with projects has shown that in summer the users wish to ventilate via windows and on the other hand, the operating energy is still quite significant even with efficient ventilation systems (see Section 8.2).

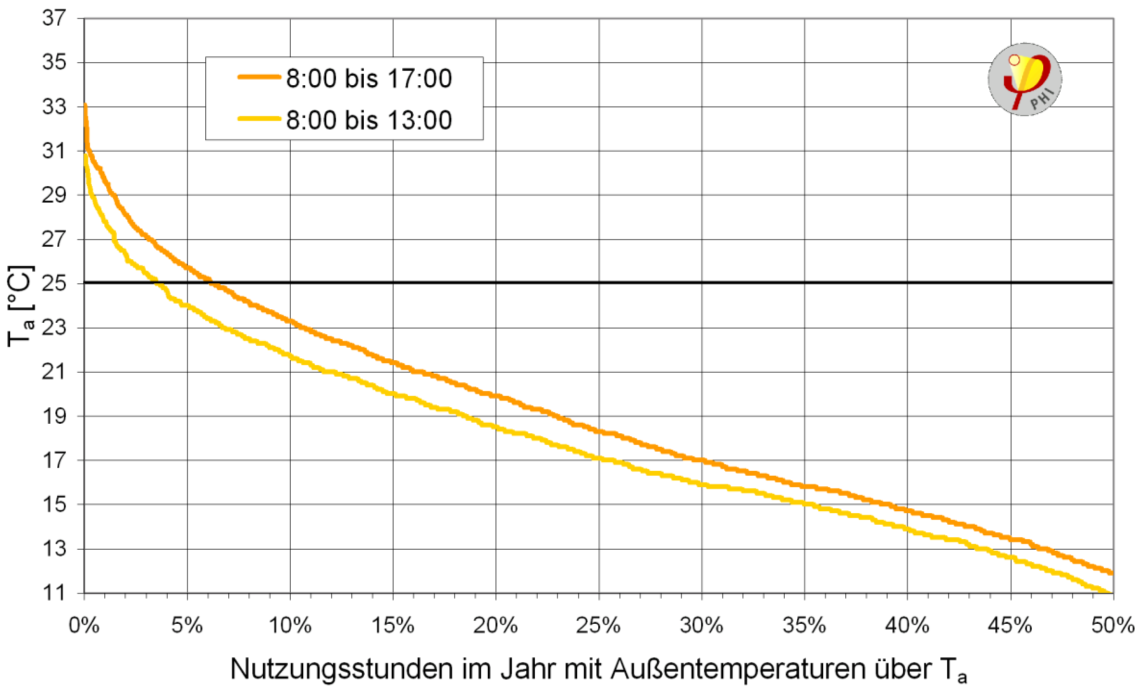


Fig. 95: **Cumulative frequency of the outdoor air temperature for Frankfurt / M. Weather data set for an average summer (dataset from German weather service). The percentage of annual hours of use with outdoor temperatures above the value T_a given on the ordinate. The outdoor air in Germany offers a considerable cooling potential during most hours in the year. Summer holidays have not been taken into account in this diagram *(Source: PHI)*.**
Nutzungsstunden…=hours of use in the year with outdoor temperatures above Ta,

Fig. 96 shows typical daily totals of the entered heat output for the studied uses. With the studied uses, a good standard of sun protection is essential for summer comfort on account of the high percentage of window areas that are related to building use. If only interior sun shading is present, the daily total amount of solar and internal gains may increase threefold in the summer.

In sports halls and in primary schools the internal and solar loads are much less critical than in classrooms of secondary schools or in group rooms of children's day-care centres. In order to provide a view towards the outside for the smaller children, the window areas in children's day-care centres are often almost room high. A good solar protection solution is accordingly decisive especially with this use.

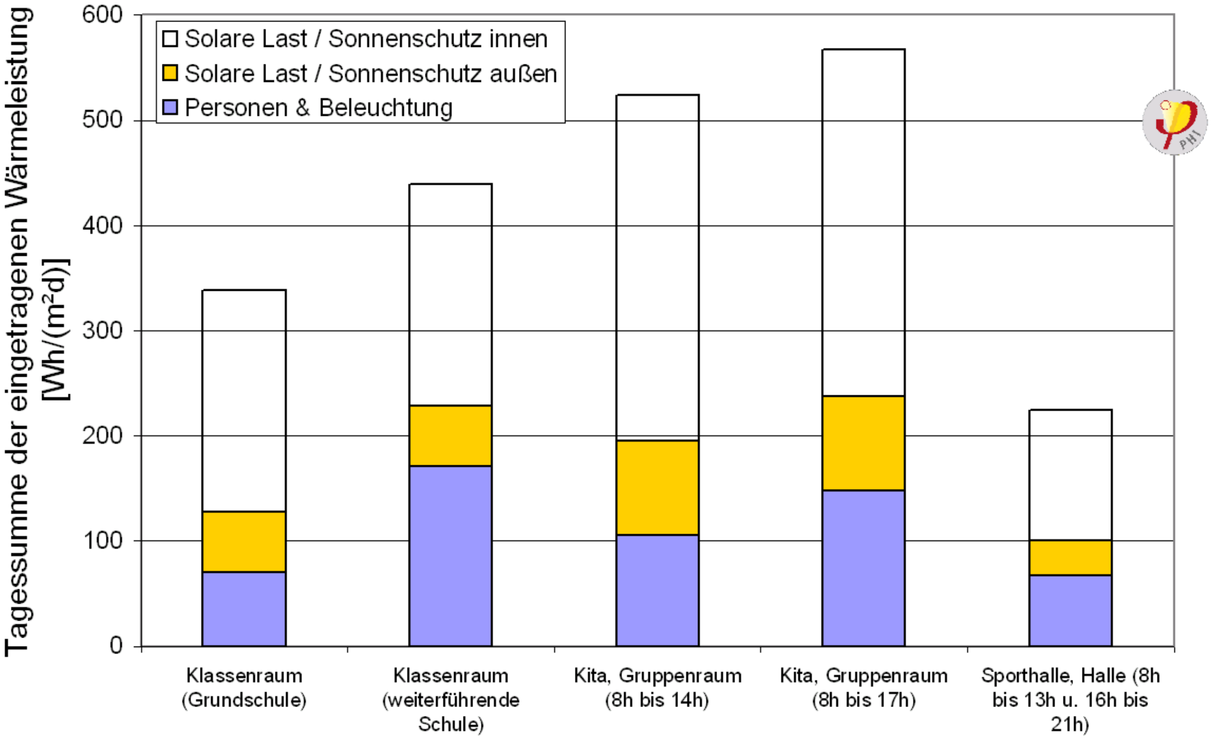


Fig. 96: **The daily totals of the entered heat output for the studied uses in summer are shown here. A good standard of solar protection is decisive for all building uses. (*Source: PHI*)**
Tagessumme der …=daily total of the entered heat output, Klassenraum…=classroom (primary school), classroom (secondary school), day-care centre group room (8 am till 14 pm), day-care centre group room (8am till 17pm), sports hall, hall (8am till 13pm, and 16pm till 21pm)
Assumed:
Window percentage (reference to base area): classroom 19 %, children's day-care centre 30 %, sports hall 11 % (+ 11 % facing north) / occupancy rate: primary school 22 persons, secondary school 30 persons, children's day-care centre 22 persons, sports hall 30 persons / usage time in school according to the timetable applicable in Hesse (25 and 34 hours a week), in children's day-care centres it was assumed that children mostly stay in the group room. The actual internal loads are probably less in summer due to outdoor activities on the premises.

In order to ascertain the influence of the excellent level of thermal protection on summer comfort, systematic simulation calculations based on the example of a secondary school (see [Kah 2006]) were carried out in the context of the Research Group for Cost-effective Passive Houses on the topic of "Passive House Schools" (see [AkkP 33]). It was demonstrated that a school building with conventional (according to EnEV 2004) and with a highly insulated standard of thermal protection behave almost identically provided that the standard of solar protection is good and a night-time ventilation strategy is foreseen. Mechanical ventilation at night was assumed during hot weather periods for both variants, which does usually form part of the building services concept in conventional school buildings.

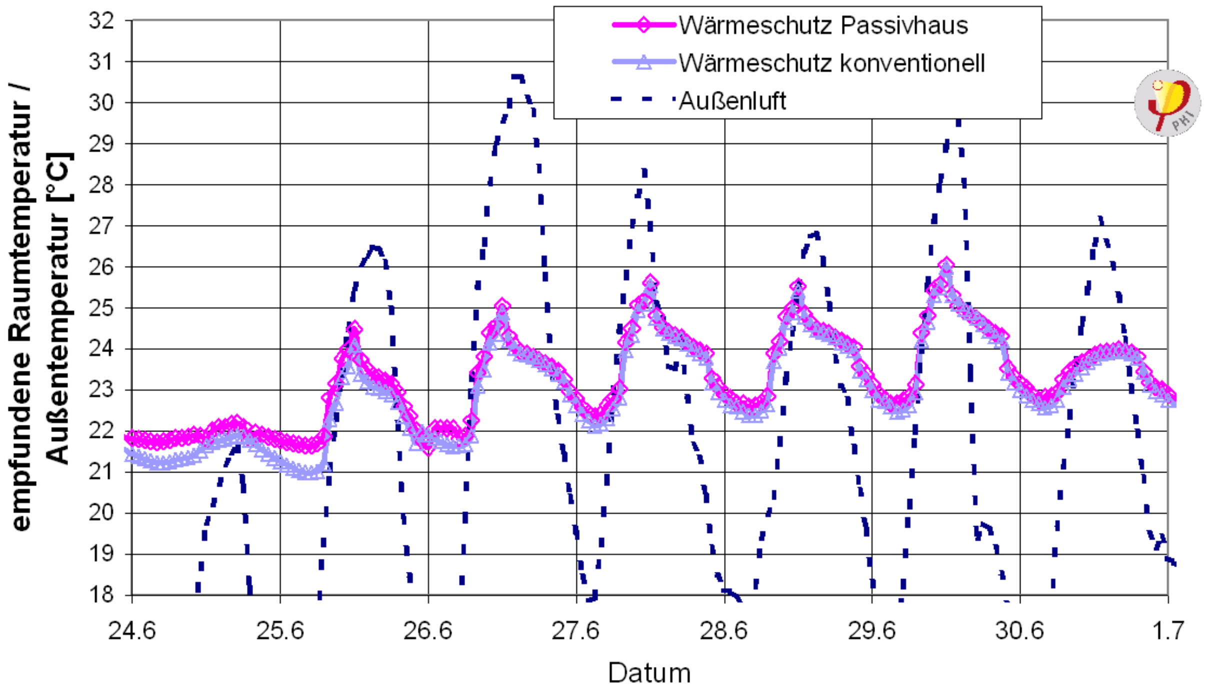


Fig. 97: **Temperature progression during a hot week. The temperature progression for both thermal protection standards is almost identical. In both variants, the indoor temperatures do not exceed 26 °C *(Source: [Kah 2006] in [AkkP 33])*.**
Wärmeschutz PH=PH thermal protection, Wärmeschutz konventionell=conventional thermal protection, Außenluft=outdoor air, empfundene…= perceived indoor temperature/outdoor temperature, Datum=date

The influence of the thermal storage capacity on the indoor temperature behaviour in summer is shown in Fig. 98. Adequate thermal capacity of the building structure is a prerequisite for the night-time cooling strategy of the building. At the same time, adequate available thermal storage mass buffers the daytime temperature peaks. The maximum daytime temperatures in the purely lightweight construction variant at the end of the hot weather period are about 2 K higher than in the solid or mixed construction variants.

The overall effective area-specific thermal storage capacity of the space enclosing building components should be c_{eff} > 150 Wh/(m²K) (based on the base area of the classroom). This recommendation is met e.g. through the use of solid building components for the inner structures of the building.

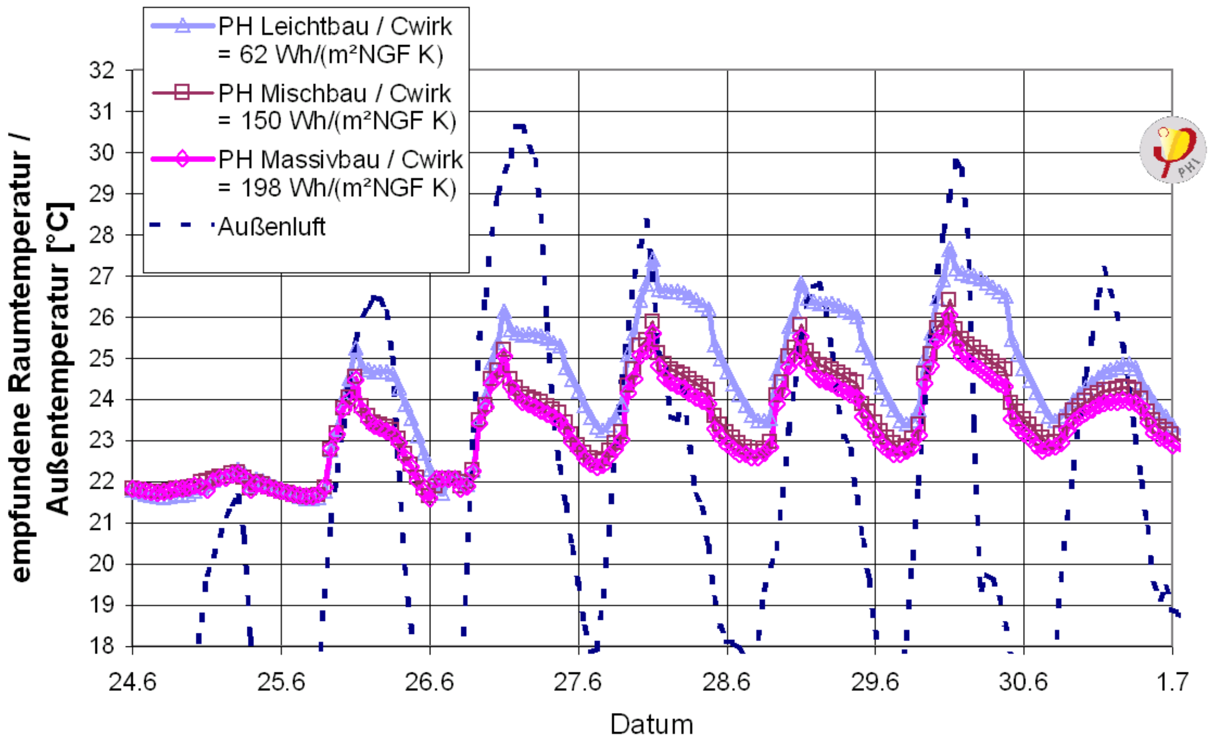


Fig. 98: **Variation in temperature for the Passive House construction method for the school building. With the lightweight construction, the daily temperature amplitudes are greater. The daily temperature peaks are 1 to 2 K higher with the lightweight design during the week under consideration** ***(Source: [Kah 2006] in [AkkP 33])*****.**

PH-Leichtbau…= PH lightweight construction/C_{eff}, PH mixed construction/C_{eff}, PH solid construction/C_{eff}, Außenluft=outdoor air, empfundene…= perceived indoor temperature/outdoor temperature, Datum=date

Although highly insulated constructions reduce heat input through the opaque building components during hot periods, cooling through the building envelope barely takes place at night. It is therefore imperative to provide a night-time ventilation strategy in well-insulated buildings for educational use. Controlled ventilation (with summer bypass operation) offers the possibility of mechanical ventilation at night. Air exchange via controlled ventilation is usually sufficient. Further improvements are possible with concepts for natural ventilation at night with higher outdoor air quantities. Constructional implementation of natural night-time ventilation should therefore be considered (see also Section 8.4). At the same time, it has proved decisive that the night-time ventilation strategy begins as early as possible. The building can then enter a hot period with moderate temperatures.

Fig. 99 shows the influence of night-time ventilation using the example of a classroom. As already discussed above, effective shading for protection against solar incidence through the glazing is indispensable (see Fig. 100).

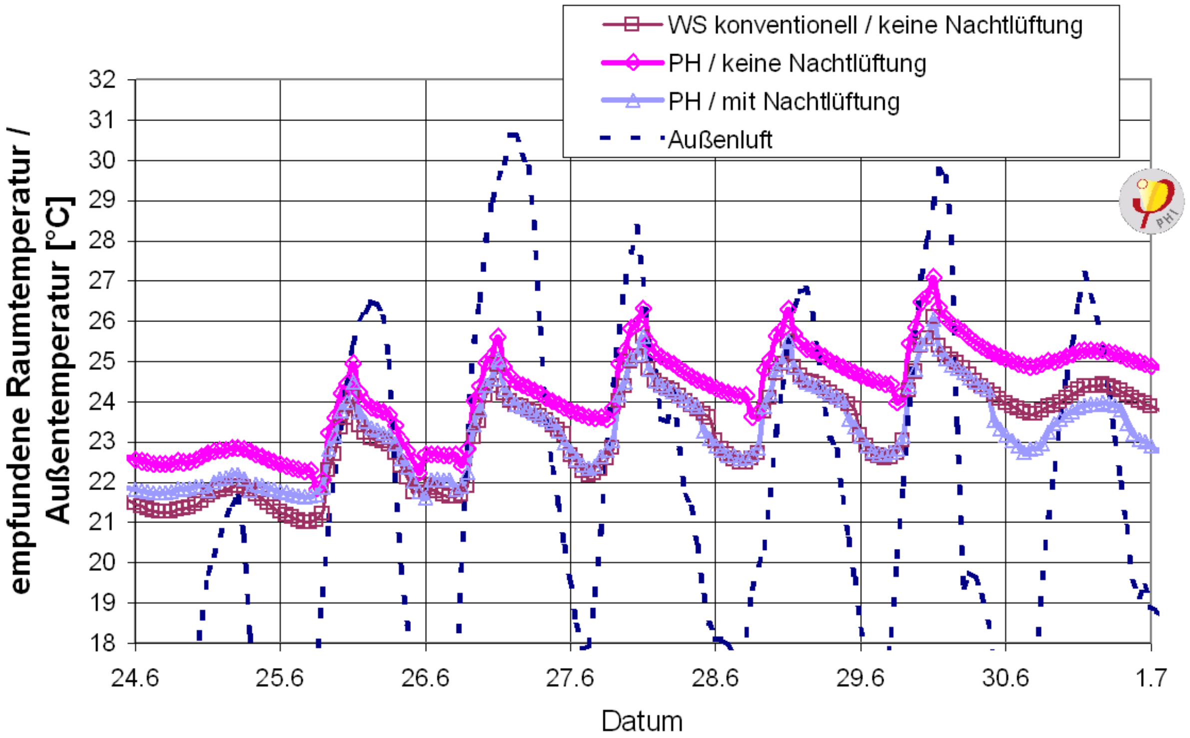


Fig. 99: **Influence of night-time ventilation. Night-time ventilation is crucial in a Passive House school building *(Source: [Kah 2006] in [AkkP 33])*.**
WS konventionell /keine Nachtlüftung…=conventional thermal protection/without night-time ventilation, PH/without night-time ventilation, PH/ with night-time ventilation, Außenluft=outdoor air, empfundene…= perceived indoor temperature/outdoor temperature, Datum=date

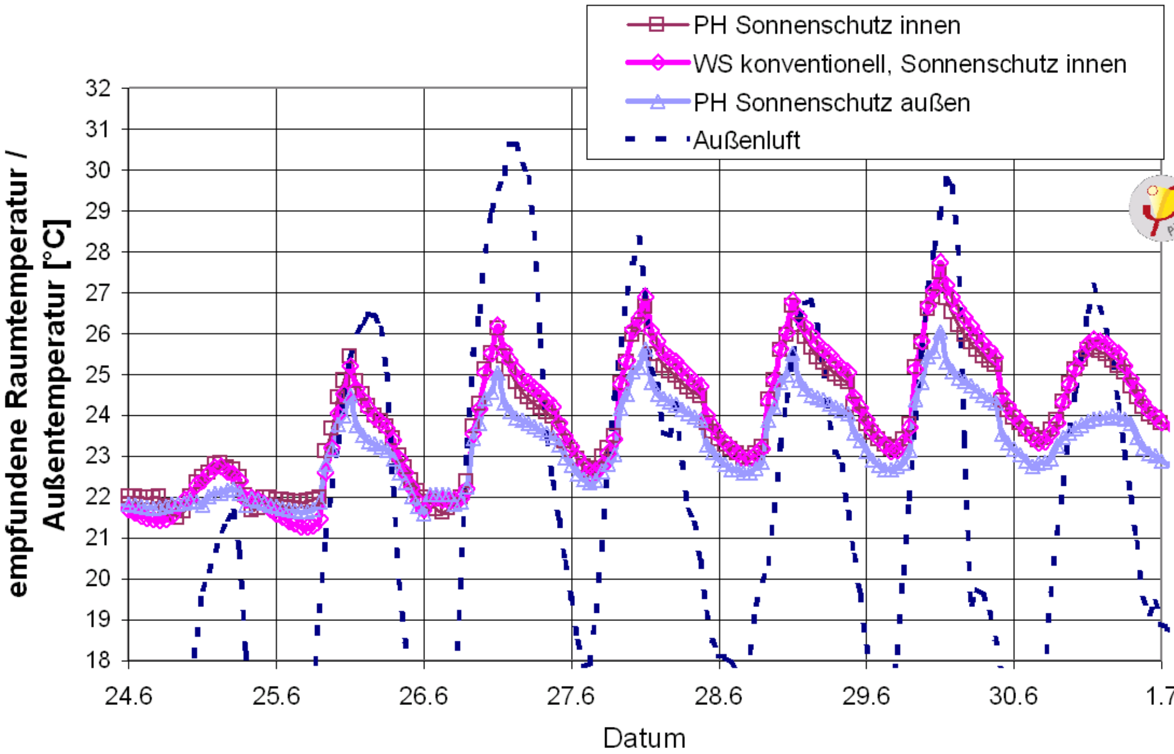


Fig. 100: **Implementation of solar protection. Sun shades on the inside are less effective. Compared with solar protection on the outside, the additional solar loads lead to continual heating up during this week of hot weather. *(Source: [Kah 2006] in [AkkP 33])*.**
PH Sonnenschutz innen=PH solar protection on the inside, WS konventionell Sonnenschutz innen=conventional thermal protection solar protection on the inside, PH solar protection on the outside, Außenluft=outdoor air, empfundene…= perceived indoor temperature/outdoor temperature, Datum=date

By means of dynamic building simulations, the summer behaviour of Passive House sports halls was also examined. The conditions are similar. Here too, comfortable indoor temperatures were maintained in the summer through the measures "solar protection on the outside" and "night-time ventilation" (see Fig. 101).

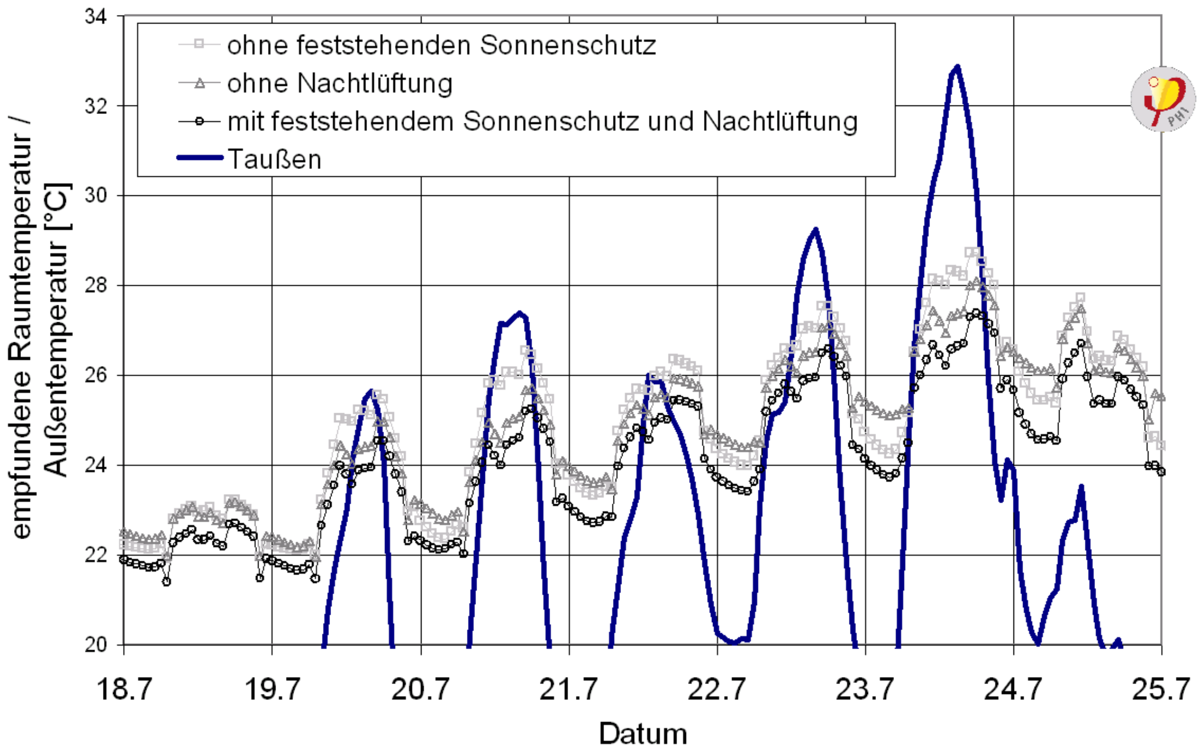


Fig. 101: **The summer characteristics of a Passive House sports hall are shown here. Except for the roof, the building is built as a solid construction. Night-time ventilation and solar protection improve thermal comfort in summer during this week of hot weather. A good standard of solar protection is decisive for this.** ***(Source: PHI)***

ohne feststehenden Sonnenschutz=Without fixed solar shading elements, ohne Nachtlüftung=without night-time ventilation, = mit feststehenden Sonnenschutz und Nachtlüftung =With fixed solar shading elements and night-time ventilation, T außen=outdoor temperature, empfundene…= perceived indoor temperature/outdoor temperature, Datum=date

In the case of sports halls, the construction method also has an influence on the summer behaviour. Solid building components in the hall area will buffer solar and internal peak loads (see Fig. 102). With lightweight constructions the daily indoor temperature peaks can be higher by 2 K compared to solid constructions. An extreme variant (Massivbau2) with additional solid execution of the roof (reinforced concrete ribbed ceiling) improves the summer behaviour even more, as anticipated. Such solutions should only be chosen if indicated by additional requirements (e.g. use of the roof as a parking area).

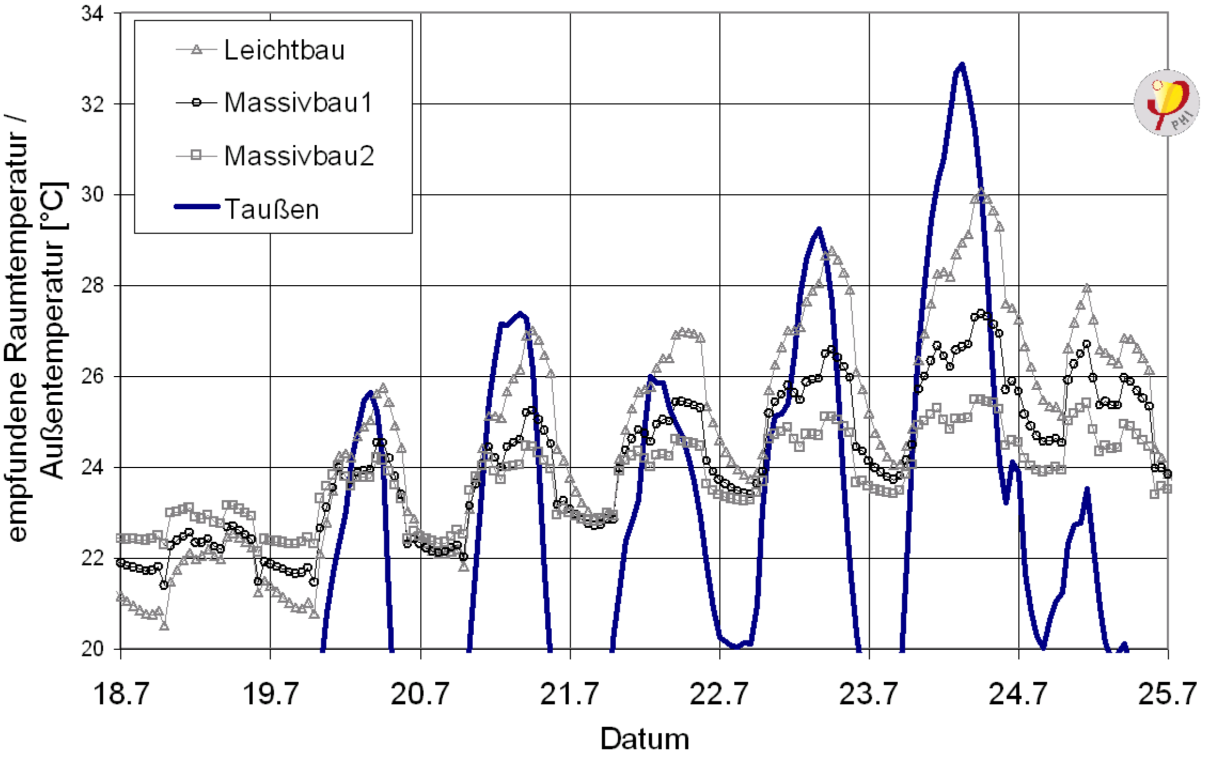


Fig. 102: **Indoor temperature progression during a week of hot weather in a Passive House sports hall. The behaviour of different construction types is shown. The variant Massivbau2 represents an extreme case: massive execution of the roof (concrete ribbed ceiling) has also been taken into account besides the interior and exterior walls. Sufficient storage mass also improves the summer characteristics of sports halls.** ***(Source: PHI)***

The recommended measures provide for adequate summer comfort during a typical summer in Germany. The dynamic building simulation led to a frequency of overheating (above 25°C) in the range between 2 % (primary school) and 6 % (secondary school) of the hours of use.

Measurements in a realised Passive House primary school confirm the results of the simulated calculations (see Fig. 103). In the three examined classrooms, only 2.7 % (summer 2005) and 3.6 % (summer 2006) of the average hours of use were above 25 °C (see [Peper et. al 2007]).

This summer behaviour is comparable to that of a reasonably operated conventional educational-use building. The cooling potential of the recommended measures is limited. In contrast to concepts with active air conditioning, high indoor temperatures during extreme summer conditions cannot be ruled out.

If the conditions are unfavourable for a building, or if the recommended measures for thermal protection in summer cannot be fully implemented, then a thermal building simulation is recommended in case of uncertainty.

Furthermore, in unfavourable climate zones it may be necessary to undertake measures for a good level of summer comfort (see Section 8.6).

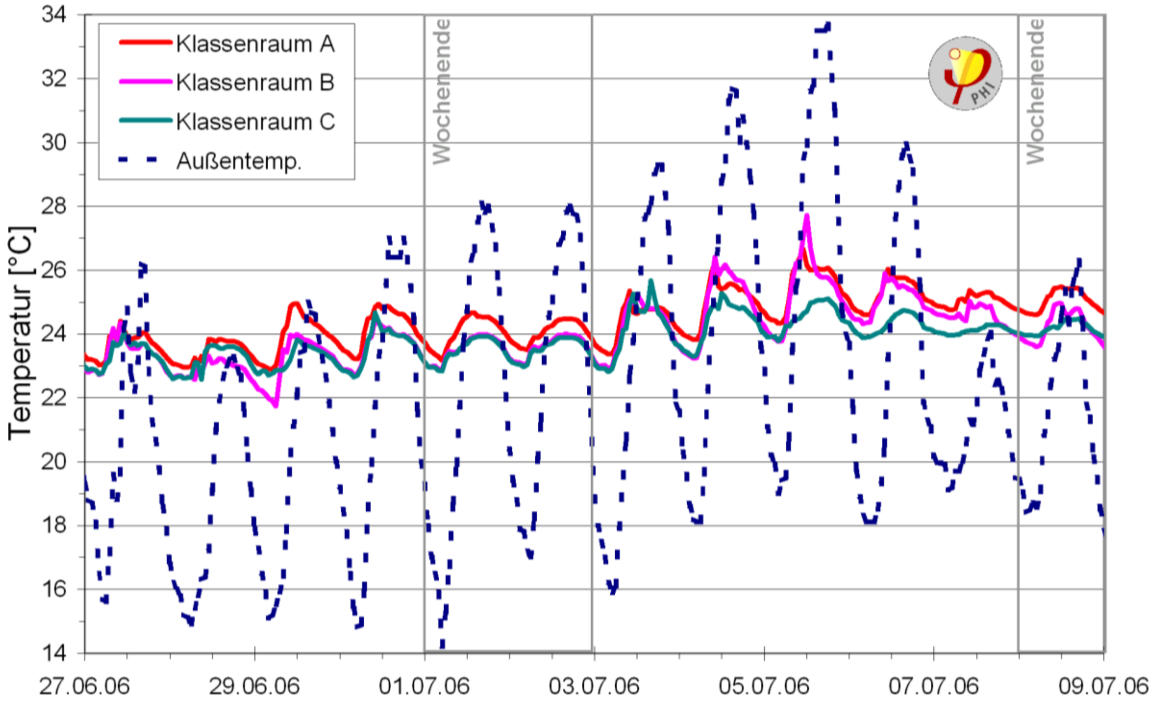


Fig. 103: **Temperatures in Passive House primary school in Frankfurt / M. during the course of a hot weather period *(data source: [Peper et al. 2007])*. With the aid of free night-time ventilation, the building is cooled down at night so that during the course of the hot weather period the indoor temperature (air temperature) increases only moderately. In Summer 2006, on average the three classrooms had a temperature above 25 °C only during 3.6 % of the hours of use, and in the rather moderate summer of 2005 this was the case only during 2.7 % of the hours of use.**

8.2 Ventilation in summer

Because of the structural conditions it must be possible to ventilate the occupied rooms of educational-use buildings independently of the ventilation system during the summer months. For one thing, operation of the mechanical ventilation system outside of the heating period does not make sense from the energy efficiency point of view; even with efficient fans (< 0.45 Wh/m³) the electricity demand of the system will be significant for the primary energy demand of the building. For another thing, experience has shown that users wish to ventilate rooms via sufficiently large window areas in the summer, and did not accept closed windows or few or very small opening casements.

In contrast to cold winter months the windows can often be opened in the summer without impairing comfort. The openable window cross-sections must be dimensioned so that sufficient outdoor air can flow into a classroom, group room of a day-care centre or sports hall when fully occupied. At the same time, the choice and positioning of the opening casements in schools and children's day-care centres should be in accordance with accident prevention regulations (see Section 5.2, [GUV-V S1]).

Dimensioning of the opening cross-sections depends on the occupancy rate, but the type of ventilation is also relevant. The air exchange induced by cross-ventilation with identical cross-sectional areas is much higher compared to positioning of windows on one side of the building. The doors of the group rooms in children's day-care centres often remain open, so that as in sports halls, cross-ventilation is possible here as well if necessary (see Fig. 104).

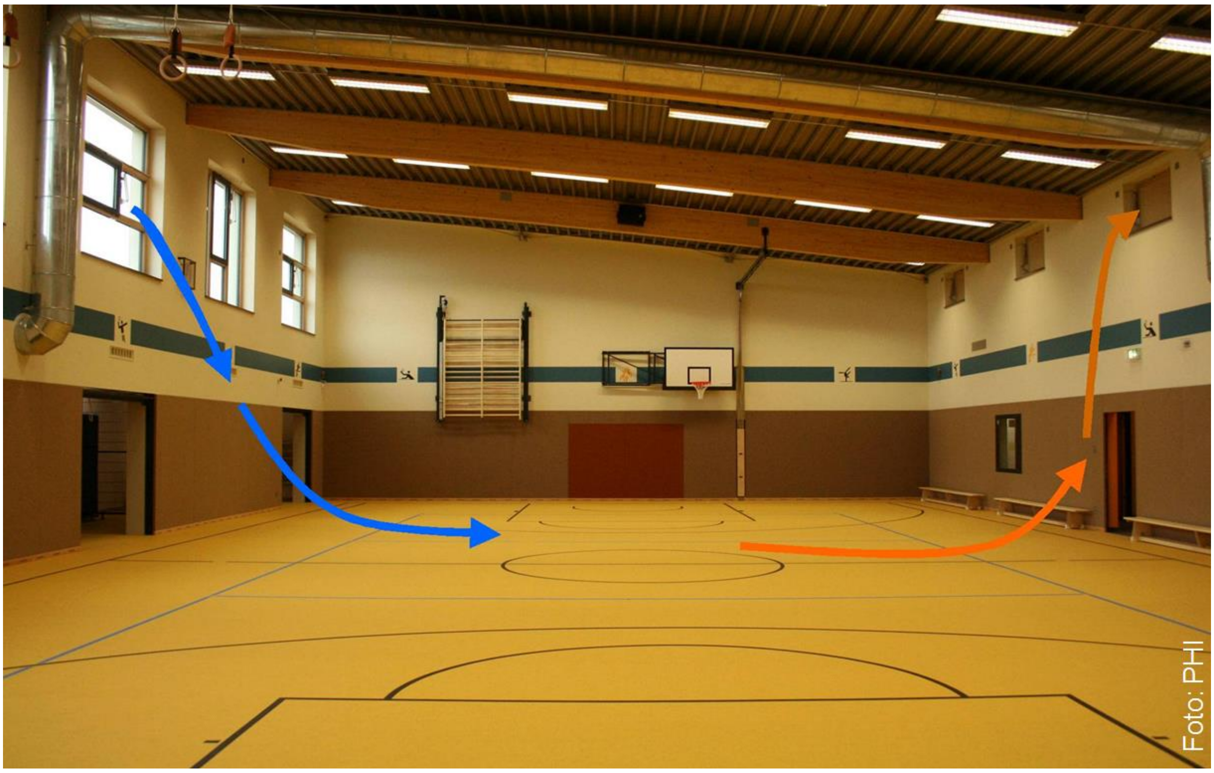


Fig. 104: **Natural ventilation a school sports hall (Reichelsheim) by means of cross-ventilation. / Architecture: In-house building management of the Wetteraukreis & a5 Planung, Bad Nauheim**

To ensure the air quality, at least 20 m³/(h*person) should be achievable through natural ventilation, with a larger amount dimensioned for the summer (30 m³/(h*person)). Besides covering the hygienically necessary air demand, a significant part of the heat loads in summer can be removed through daytime ventilation (50 to 90 % of the heat given off by persons on a typical day in the summer if dimensioned adequately).

A method for estimating the window cross-sections for natural ventilation is available in the download section of the Passive House Institute website (www.passivehouse.com, calculation tool "SommLuft"). This method is also included in the latest version of the Passive House Planning Package [PHPP] ("SommLuft" worksheet).

The city of Frankfurt recommends a clear opening area of 0.3 m³/person for classrooms with one-sided ventilation [Linder 2009]. In group rooms and classrooms the opening areas usually are not adequate in case of ventilation solely through windows with tilting casements. On the other hand, sufficient air exchange can already be achieved with two French windows with side-hung casements. However, the use of side-hung casements is not easily possible everywhere, and as already mentioned above, must conform to the requirements in the accident prevention regulations.

8.3 Solar protection

Large glass façades facing south, west and east make a valuable contribution to the reduction of the heating demand in the winter, but these solar heat gains are undesirable in the summer. In the case of south-facing glazing, a roof overhang can help shade most of the summer sun at its highest.

East and west facing glazing are problematic if they are not equipped with variable sunshading elements, because significant heat loads enter the building when the sun is low in the morning and evening. This is especially underestimated in the case of east-facing façades because when the windows are open the fresh morning air conveys cooling and masks critical heating up due to solar incidence. If it becomes too warm in the room during the course of the morning, by then it is usually too late to deploy the shading elements. For this reason, manual control of the shading elements is not recommended. It is more effective to use variable shading elements especially if their operation is controlled based either on time or temperature, or irradiance. In order to ensure the acceptance of automatically controlled shading elements, the user should always have the option of overriding. With automatic control, solar protection can also be assured at the weekends and in the summer holidays.

Fig. 105: **Weather station for control of solar protection. Solar protection systems must be controlled by means of a weather station. The variable solar protection elements should be designed for wind speeds of at least 13 m/s [Linder 2009].**

An additional measure for external solar protection is e.g. natural shading by deciduous trees and shrubs. Permanent shading elements are unsuitable here because these would restrict solar gains also during the heating period. This is especially true of solar control glazing which has an especially low total solar transmittance (g value) and reduces the solar heat gains both in summer and in winter, and lessens the utilisation of daylight. Compared to external blinds, this allows significantly more solar energy into the building so that its contribution towards summer thermal protection is smaller. Triple low-e glazing has g-values of around 50%, solar control glazing has a g-value of about 30 % and external blinds with a reduction factor of 0.1 reduce the g-value of the glazing by 90 %, i.e. to 5 %.

Table 10: **Reduction factors for typical temporary shading elements if triple low-e glazing is used (according to DIN 18599-2)**

Type of shading	external	internal
Blinds, vertical slats	0.06	0.7
Blinds, slats at 45°	0.10	0.75
Window shade/awning, white	0.24	0.6
Window shade/awning, grey	0.12	0.8
Film	--	0.6

The solar protection should allow for adequate daylight utilisation even in the closed state. Possible solutions include external venetian blinds with divided sections for controlling daylight, or a "light shelf" in the upper part of the window.

Considerable solar loads can also enter the building through roof windows. Solar protection at roof windows is usually more complicated (see Fig. 107). A solar protection element should also be foreseen at glazed external doors of group rooms in children's day-care centres and at glazed doors of emergency exits. Fig. 106 shows a solution with a roof overhang and awning.

External solar protection elements of room-high windows are particularly at risk in the foot area. Accessible façades with room-high glazing in schools should be equipped with vandalism-proof solar protection concepts (e.g. fixed exterior louvres).

Fig. 106: **Solar protection of the south-facing children's day-care centre was assured by means of a roof overhang. On account of the room-high windows an awning is additionally necessary for shading. Due to the positioning of the awning on the outside, the solar protection can also cover the door area of the group room. However, the building cannot be fully shaded during the transitional period.**
Children' day care centre in Frankfurt Schwanheim / Architecture: sdks, Darmstadt

Fig. 107: Solar protection of skylights on the roof of a Passive House school in Marburg (Martin-Luther-Schule). Architekten Hess/Talhof/Kusmierz, Munich. (Picture: Passivhaus Dienstleistung GmbH)

8.4 Night-time ventilation

In the climate in Germany, night-time temperatures are often below 20 °C even in high summer, so this air is ideal for cooling down buildings (see Fig. 108). This means that the peak loads occurring during the daytime can be removed during the cooler night hours.

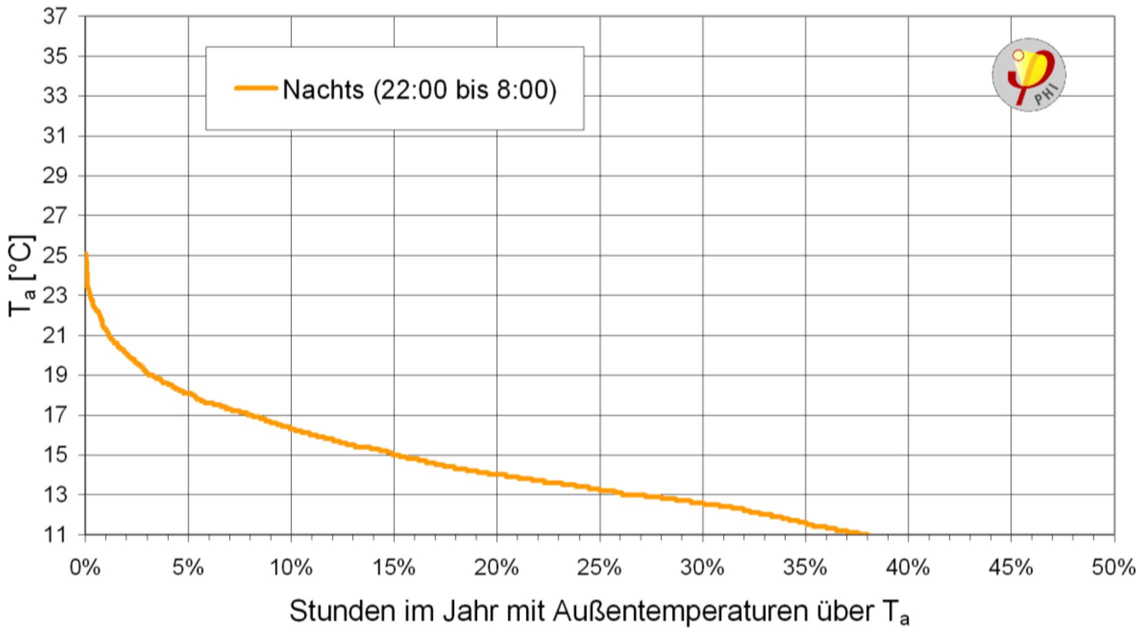


Fig. 108: **Cumulative frequency of the outdoor air temperature for Frankfurt / M. Weather data set for an average summer (data set from German weather service). The percentages of annual hours with external temperatures higher than the value T_a given on the ordinate are shown here. The outdoor air in Germany during most of the night hours offers a considerable night-time cooling potential *(source: PHI).***

Stunden im Jahr…= hours in the year with outdoor temperatures above Ta, Nachts=night-time

For effective heat dissipation from the building the nightly air exchange as well as the temperature difference between the outside and indoor air must be sufficiently high.

Air changes between two and four times the indoor air volume at a temperature difference of at least 2 K have proved to be effective (see [AkkP 22]). A two-fold air change rate is hygienically necessary in schools and children's day-care centres so usually controlled ventilation can also be utilised for effective night-time ventilation. With mechanical night ventilation, the minimum temperature differences should be rather higher (4 K) due to the temperature swing caused by the fan waste heat. Detailed information about strategies for "passive cooling" can be found in [Zimmermann 1999].

Natural cooling down at night is energy efficient and more effective as a rule (with more than twice the air changes per hour). The city of Frankfurt for example stipulates this for its new municipal building projects (see [Linder 2009]). For this purpose, suitable motor-driven, temperature-controlled opening casements must be foreseen in order to ensure effective regulation of night-time cooling. As with daytime ventilation (see Section 5.2), the opening area necessary for this depends largely on whether room-by-room ventilation or cross-ventilation is possible. The latter requires the possibility of air transfer from the classrooms or groups rooms into the rooms situated on the opposite side. Night-time ventilation can be utilised even more effectively if the openings in the façade are positioned at different levels. The opening cross-sections can be smaller due to the thermal buoyancy effect.

The possibility of air transfer into other zones is significantly influenced by the fire safety concept. The night-time ventilation concept should therefore be seen as a planning task which can be realised economically and effectively provided that is taken into account as early on as possible. As already mentioned above, the resulting volumetric flow can be estimated using the "SommLuft" tool. The planner can thus obtain information about the achievable night-time air exchange.

Night-time ventilation flaps can be implemented as a partial area within the glazing or also as a separate opaque flap. In both cases, attention should be given to effective protection against break-ins and insects as well as prevention of rainwater from entering. Outwards opening flaps are especially suitable here, but caution is needed as the protection against break-ins and insects will usually reduce the actual free cross-section for ventilation. The multiple use of smoke and heat extraction vents that are required anyway is quite possible and is economical.

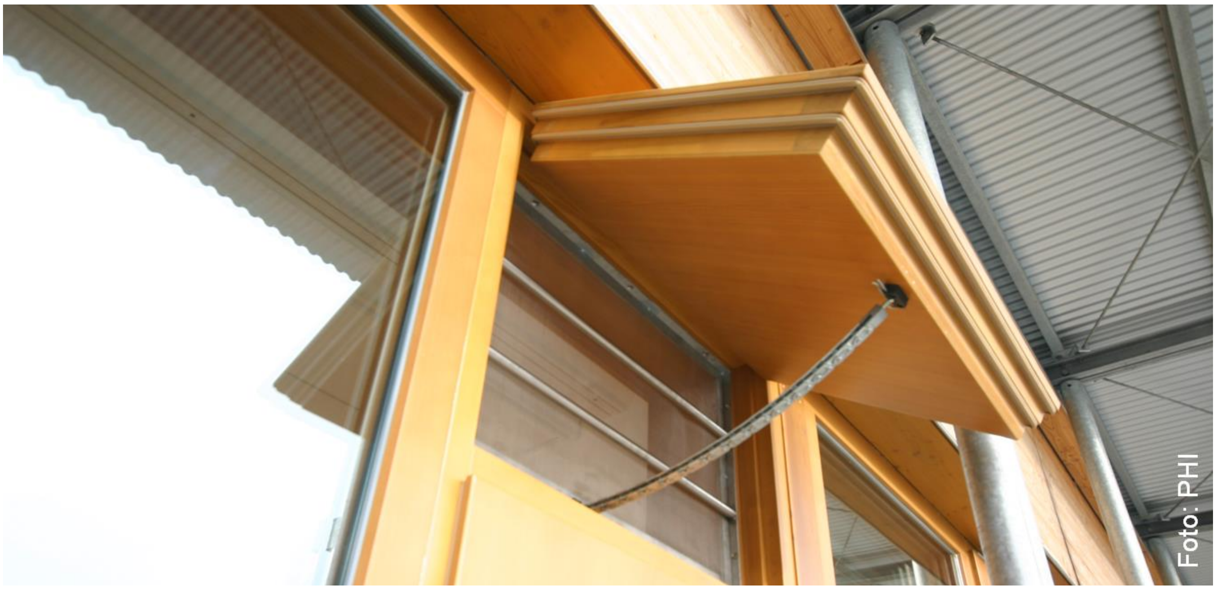


Fig. 109: **Night-time ventilation flap in a children's day-care centre. The chain drive enables a large opening angle. The outwards opening flap prevents the entry of rain, the bars are an effective protection against break-ins and the net behind these ensures protection against insects.**
Children's day-care centre in Frankfurt Schwanheim / Architecture: sdks, Darmstadt

Fig. 110: **Detail of a ventilation flap. Glass slats and wire mesh protect against break-ins and insects.**
Children's day-care centre Goldstein (Frankfurt), Architecture: AS&P, Frankfurt

Night-time cooling in two Passive House schools is operated particularly effectively by utilising thermal buoyancy forces (see Fig. 111 and Fig. 112). For this purpose, opening flaps at different heights in the building and open connections between the respective zones were provided.

In the Martin-Luther-Schule in Marburg the smoke and heat extraction vents in the roof lantern and the ventilation flaps in the classrooms are opened for night-time ventilation. Air flows from occupied areas through doors which stay open at night (door holders, these close automatically in case of fire) into the central stairwell. Thermal buoyancy intensifies the natural driving forces due to the difference in height of the openings (see Fig. 112).

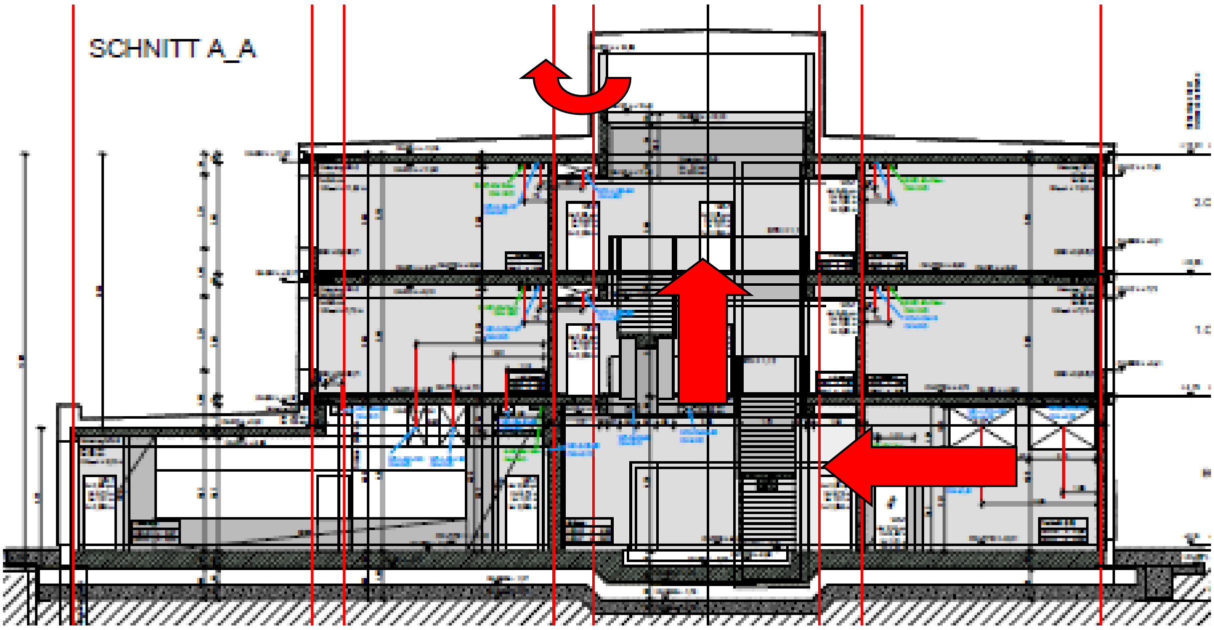


Fig. 111: **Night-time ventilation in the atrium of a school. For cooling down at night the ventilation flaps on the ground floor and the smoke and heat extraction vents in the roof lantern that are necessary anyway are opened at night. Ziehenschule Frankfurt, architect: Marcus Schmitt, Frankfurt)**

Fig. 112: **Free night-time ventilation in a school using the stack effect. The ventilation flaps in the relevant occupied rooms open at night. The doors to the central stairwell can be kept open by means of door holders. The night air that is heated up in the occupied rooms can leave the building via the open smoke and heat extraction vents in the roof lantern.**
Passive House school in Marburg (Martin-Luther-Schule). Architekten Hess/Talhof/Kusmierz, Munich. (Pictures: Passivhaus Dienstleistung GmbH)

8.5 Limiting internal loads

In particular people, lighting and technical equipment (computer systems) count among the important internal heat loads in school buildings. While the former type are unavoidable, it is possible to considerably reduce the heat dissipation from artificial lighting and IT devices. Between 20 and 30 % of the internal loads in classrooms can be reduced by means of efficient electrical applications (see Fig. 113).

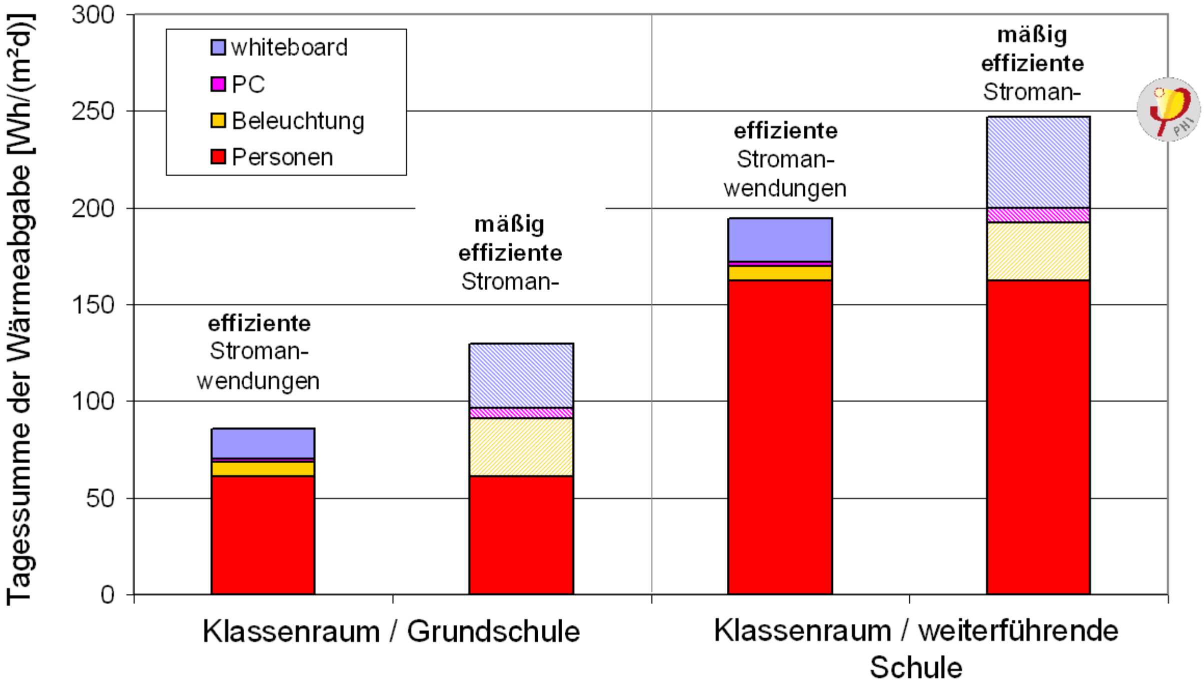


Fig. 113: **Influence of electrical applications on the internal loads in a classroom. Efficient electrical applications do not only save energy, in schools they can also reduce the internal loads significantly (columns on the left).** ***(Source: PHI)***
Assumed: Primary school: use of a PC for 45 minutes/school day
Secondary school: use of a PC for 2x45 minutes/school day
Whiteboard: system consisting of a PC and beamer
Tagessumme der Wärmeabgabe=daily total heat dissipation, Klassenraum=classroom, Grundschule=primary school, weiterführende Schule=secondary school, effiziente =efficient, Stromanwendungen= electrical applications, mäßig=moderate, Beleuchtung=lighting, Personen=persons

A largely reduced electricity demand for artificial lighting and minimised heat dissipation associated with this is ensured firstly through the minimisation of operating times of the lights and secondly through efficient lamps (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). Specification of the limit and target values for the specific installed capacity of the artificial lighting appears to be of central importance here (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

As already mentioned previously, adequate supply of daylight should be possible even with activated solar protection measures. As a rule, natural lighting is associated with much less heat input compared to switching on artificial lights. Possible solutions are offered by external Venetian blinds with daylight control or so-called "light shelves" in the upper area of the window. The natural light and simultaneous shading are more critical in the case of west and east facing façades on account of the low sun.

Besides lighting, IT equipment also dissipates heat on a considerable scale. Teaching methods supported by information technology are now standard in classrooms so that there is at least one computer and a beamer in each classroom. Whiteboards are increasingly being used as an alternative to the blackboard or as an additional teaching aid. These systems consist of a PC and a beamer.

Modern technology offers energy efficient solutions in this respect too. The following databases provide a good overview of energy efficient IT devices: www.ecotopten.de, www.office-topten.org, www.eu-energystar.org.

8.6 Additional summer cooling strategies

Furthermore, it may be necessary to undertake further measures for a good level of summer comfort in unfavourable climate zones or urban heat islands in addition.

A simple and efficient method for buildings with controlled ventilation is to condition the supply air. Cooling coils in the supply air section can be recooled e.g. by means of a geothermal probe.

The additional effort for indirect adiabatic cooling of the supply air is also small. Here, cooling is generated through air humidification and evaporative cooling of the extract air. The cooling capacity with this concept is limited and depends on the extract air humidity. Cooling can be generated without any additional energy expenditure. This concept is being successfully used e.g. in a vocational training college in Waldshut, Germany (see [Weiß 2006]).

Another alternative is structural component temperature control. Compared to the previously mentioned solutions the effort for this is higher. Here too, a field of geothermal probes are used as a source. This solution is of particular interest if the geothermal probes are incorporated into the heat supply system by means of a heat pump also in the winter.

The spatial arrangement of the space utilisations also has an influence on the way in which heat loads are dealt with. Rooms with particularly high internal loads (server room, IT room) should be located on the northern side. The adjoining outdoor air is cooler and solar gains can be greatly reduced.

8.7 Summer operation in brief

Special attention must be given to summer thermal protection in schools and children's day-care centres. The main findings relating to summer comfort are briefly summarised below. If individual aspects of summer thermal protection turn out to be unfavourable for a specific project, it may become necessary to undertake further measures for a good level of summer comfort. A thermal building simulation is recommended in case of uncertainty.

- Effective solar protection on the usual window areas on the eastern, southern and western façades of educational-use buildings is decisive.
- Due to the high temporary internal loads in school buildings and children's day-care centres, the construction must provide adequate thermally accessible storage mass. The area-specific thermal storage capacity should be at least 150 Wh/(m²K).
- A night-time ventilation strategy must be provided for hot periods. This can be achieved by means of controlled ventilation (without heat recovery) or even more effectively through natural ventilation via motorised flaps.
- In contrast to winter, ventilation in the summer should take place mostly via windows. This saves operating energy for the controlled ventilation system that would otherwise be necessary, and is usually also desired by users.
- During a typical summer the outdoor air in Germany provides adequate cooling potential during most hours. In schools and children's day-care centres the outdoor temperature is above 25°C only for 30 to 120 hours of use. In summer, intensive ventilation via windows should therefore be provided except for heat periods.

A simple and efficient additional measure is pre-conditioning of the supply air by means of a brine circuit. In addition, adiabatic cooling offers a further cooling potential with little additional effort.

9 Electrical applications

9.1 Artificial lighting

In schools and children's day-care centres the requirements stipulate 300 lx for illuminance (see [EN 12464-1]). During the daytime, appropriate lighting can be achieved through daylight. As explained in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**, the use of daylight in the depth of the room is particularly crucial in classrooms and group rooms. Preferably high arrangement of windows without lintels and a bright interior design will improve use of natural daylight. Transparent parapet areas in contrast have only a small influence on the amount of daylight.

In schools with evening classes, higher illuminances (500 lx/m²) should be foreseen for evening operation. Lighting in this case should be switchable with two output levels for use in the daytime and in the evening (300 / 500 lx/m²).

The requirements for illuminance in school sports areas also foresee 300 lx/m². Much higher illuminance levels may be required to some extent for club sports in the evening and particularly for competitive sports. If higher illuminances are required for use by sports clubs then it should be possible to switch on artificial lights at different illuminance levels. The switching stages with the higher illuminances should be enabled only when required using separate key-operated switches (e.g. for competitions on weekends).

Artificial light is necessary only when rooms are occupied and daylight is inadequate. With sufficient natural illuminance, the additional artificial lights are barely perceived, which is why it is often forgotten to switch these off. Further savings potentials can be utilised by means of lighting control. For example, presence detectors can be used in sanitary facilities in schools so that the use of artificial lighting is limited to usage times.

In Frankfurt, switching off the lights in classrooms during breaks has proved successful (see [Bretzke 2006]). After the breaks, the users must decide again whether artificial lighting is needed additionally. The lighting must be centrally controlled for this purpose (assignment to the building bus). In group rooms of children's day-care centres and classrooms, daylight-dependent control can reduce the electricity demand by switching off when sufficient illuminance is reached.. In sports halls, daylight dependent control is especially interesting and strongly recommended because the additional effort for this is smaller: many lights can be simultaneously supplied by means of a control unit.

When planning artificial lighting, significant savings potentials result by optimising the selection of lights and their positioning. The installed capacity for artificial lighting and therefore also the electricity demand can be often be reduced by 25 % in this way (see [SIA 380/4], [LEE]).

Fig. 114 illustrates the savings potential of optimised planning based on the example of a single-court sports hall. With adjusted luminaire sizes and positioning, the specific installed capacity can be reduced by 30 % – with the same level of illuminance.

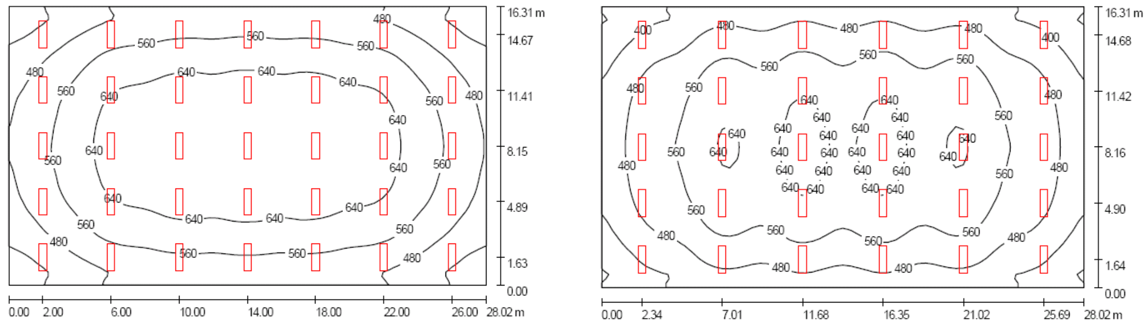


Fig. 114: Positioning of luminaires in a sports hall with a higher illuminance requirement. With the variant with optimised luminaires and positioning (left) the necessary installed lamp output could be reduced by around 30 % with more uniform illuminance. The specific connected load reaches an excellent value of 2.2 W/(100 lx m²). Single-court sports hall in Reichelsheim. Electrical planning: Ing.-Arbeitskreis Stefan, Friedberg.

For making use of this potential during lighting design, it is recommended that the target and limit values for artificial lighting are agreed with the planner at an early stage (see Table 11). As experience with school projects has shown, in practice the values may even be below the specified values (see [Bretzke 2006]). The city of Frankfurt accordingly stipulates more stringent values for municipal buildings (2.0 to 2.5 W/(100 lx m²) (see [Linder 2009]).

Table 11: Planning recommendations for the specific installed capacity of lighting

	Recommendation for limit value with 300lx	Recommendation for target value with 300lx
SIA 380/4, electrical energy in buildings [SIA 380/4]	9 W/m²	6.5 W/m²
Handbook of electrical energy in buildings [LEE]	9.8 W/m²	7.2 W/m²

9.2 Other electrical applications

Frequently, efforts for saving electricity end with the lighting. However, it may also be worthwhile to look for optimisation possibilities in other areas as well. For example, many IT applications have been adopted in schools; classrooms often have one or two computer workstations for doing research and other work. Furthermore, "whiteboards" are increasingly being used as an alternative to or in addition to the blackboard for lessons, and in some pilot projects entire classes work on laptops.

Fig. 115 shows typical values for the electricity demand for electrical applications in a classroom. The whole spectrum from efficient applications to moderate efficiency is shown. The electricity demand of the whiteboards is surprising. If operation during school time is assumed, then the electricity demand for this application is higher than for artificial lighting. If whiteboards are used, the projectors should be as efficient as possible (and preferably quiet: the noise level should be less than 30 dB).

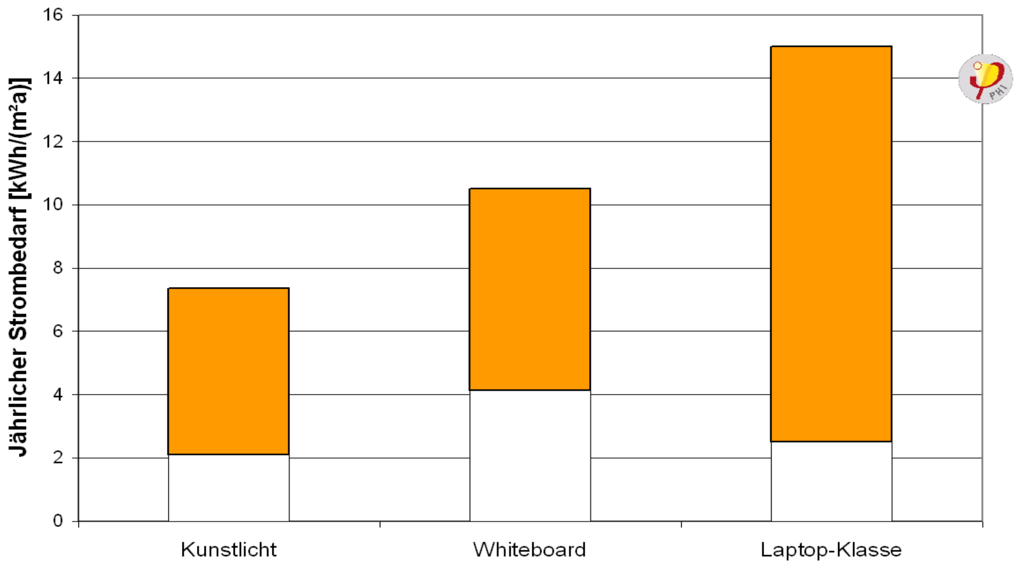


Fig. 115: Electricity demand for typical electrical applications in a classroom. A realistic range of power consumptions and operating hours typical for schools were assumed for the calculation. The lowest values apply for efficient solutions. Assuming good daylight utilisation and an efficient artificial lighting solution, it may be surprising that the operation of whiteboards leads to higher electricity consumption. Selecting efficient devices for the IT equipment is also worthwhile. *(Source: PHI)*

Furthermore, the following databases provide a good overview of energy efficient IT devices: e.g. www.ecotopten.de, www.office-topten.org, www.eu-energystar.org.

10 Energy balance

It is necessary to use reliable and practicable methods for project planning of energy efficient buildings. The building characteristics and the later energy demand can be precisely pre-calculated using dynamic simulations. The dimensioning recommendations relating to energy efficient Passive House educational-use buildings were determined on the basis of systematic dynamic simulation calculations. These tools are too time-consuming for daily planning in practice and cannot be recommended on account of their complexity. Instead, steady-state energy balancing methods should be used as these also deliver sufficiently accurate results.

The heat balance of a building is the key planning aid for energy efficient buildings. This should accompany planning right from the first draft and must be detailed according to the planning progress. The Passive House Planning Package (see [PHPP]) is a tried and tested planning aid for energy efficient buildings.

With reference to the windows, the specific characteristic values should be completed by the detail planning stage at the latest, because the window areas are known by then, the installation details are or will be sketched in and different products must then be compared with one another (U_f values, Ψ values of frame and U_g values and g values of the glazing and installation Ψ values). Detailed consideration of these product characteristics and the actual shading situation is possible with the Passive House Planning Package.

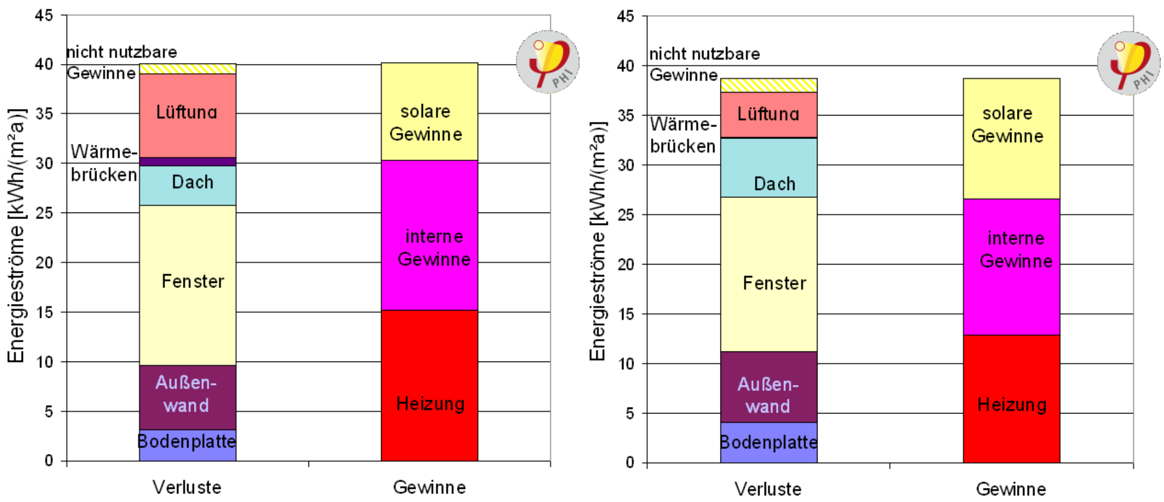


Fig. 116: Annual heating energy balance calculation according to EN 832 for an example school (left) and a single-court sports hall (right) with the Passive House Standard. Internal heat gains and solar gains cover over 60 % of the heat losses. *(Source: PHI)*

Energieströme=energy flows, Verluste=losses, Gewinne=gains, nicht nutzbare Gewinne=non-usable gains, Wärmebrücken=thermal bridges, Lüftung=ventilation, Dach=roof, Fenster=windows, Außenwand=exterior wall, Bodenplatte=floor slab, solare Gewinne=solar gains, interne Gewinne=internal gains, Heizung=heating

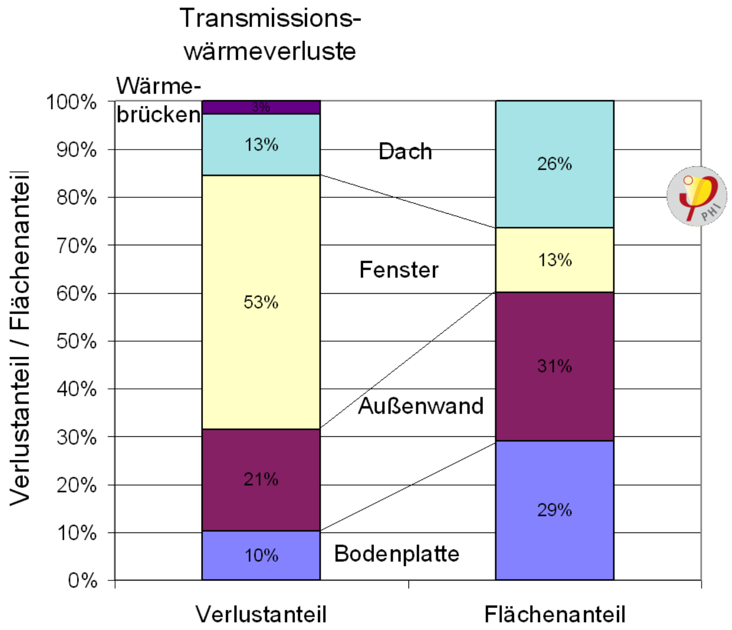


Fig. 117: Transmission heat losses through the individual building components in comparison to their area percentage based on an example of a Passive House school.
In spite of the good insulation values of the Passive House suitable windows ($U_W \leq$ 0.8 W/(m²K)), their share of losses compared to opaque building components (U-values 0.10...0.15 W/(m²K)) is still much higher. For the example school, 13 % of the building component area account for 53 % of the heat losses. *(Source: PHI)*
Transmissionswärmeverluste=transmission heat losses, Wärmebrücken=thermal bridges, Verlustanteil=share of losses, Flächenanteil=area percentage, Bodenplatte=floor slab, Außenwand=exterior wall, Dach=roof, Fenster=windows

For project planning of Passive House educational-use buildings, boundary conditions were determined for the Passive House planning tool [PHPP 2007] using systematic simulation calculations (see **Fehler! Verweisquelle konnte nicht gefunden werden.** and Table 12). While high internal loads (up to 50 W/m²) occur in classrooms and group rooms of children's day-care centres, the temporal and mean values of 2.8 W/m² (see also [Kah 2006]) averaged over the building are not very far from the values measured in residential use buildings (ca. 2.1 W/m²).

On account of the time-limited building use, temperature setback operation should be foreseen in educational-use buildings. Table 13 gives correction terms for the indoor temperature as a function of the operating time for schools and children's day-care centres. In contrast, typical temperature setback times and indoor temperatures have already been taken into account in Table 12 for sports halls. The depicted boundary conditions (indoor temperature and internal gains) for energy balance calculation are average values for the heating period and for an entire building. In the sports hall area a setpoint temperature of 18 °C is assumed, which corresponds to the customary mode of operation (recommendation is 17 °C according to [AMEV 2001] and 20 °C according to standards for sports facilities [DIN 18032-1]). A setpoint temperature of 22 °C is assumed in the showers and changing areas (see also [AMEV 2001], [DIN 18032-1]).

Table 12: boundary conditions and criteria for planning of Passive House sports halls using the [PHPP 2007] TFA: treated floor area according to [PHPP 2007]

Boundary conditions:	Schools / children's day-care centres
Indoor temperature:	20°C
Internal gains:	2.8 W/(m² TFA)
Passive House criteria	
Specific value of heating energy	max. 15 kWh/(m²TFA a)
Pressure test air change rate n50	max. 0.6 h^{-1}
Specific value of total primary energy	max. 120 kWh/(m²TFA a) inc. all electrical applications

Table 12: Boundary conditions and criteria for project planning of Passive House sports halls with the [PHPP 2007]
Treated floor area according to [PHPP 2007]

Boundary conditions:	Sports halls
Indoor temperature:	18°C
Internal gains:	2.8 W/(m² TFA)
Passive House criteria	
Specific value of heating energy	max. 15 kWh/(m²TFA a)
Pressure test air change rate n50	max. 0.6 h^{-1}
Specific value of total primary energy	max. 120 kWh/(m²TFA a) inc. all electrical applications

Temperature setback operation in educational-use buildings is reflected by a lower average room temperature compared to the setpoint temperature. Setback operation can be taken into account in the planning with a temperature deduction. The deductions were calculated with the aid of dynamic building simulations in the main heating period. Similar correction terms result for lightweight and solid constructions.

Table 13: Determination of the average room temperature for schools and children's day-care centres for energy balance calculation using the [PHPP].
$T_{average} = T_{setpoint} + \Delta\theta$

Operating times on workdays	7:00 till 14:00	7:00 till 16:00	7:00 till 18:00
Temperature correction term $\Delta\theta$	-1.0 K	-0.8 K	-0.6 K

11 Appendix

11.1 Measurement survey on pollution by particulate matter in a primary school

Pollution by particulate matter has increasingly been in the focus of public interest in recent years. One reason for this was the implementation of the EU Directive 96/62/EG on pollution by particulate matter in outdoor air, as a result of which more measurements were carried in indoor spaces and particularly in schools. Due to the different sources of the particulate matter on the inside and outside, their effects are not directly comparable. The specific danger from particulate matter in indoor spaces is still under debate, with the UBA commission for air hygiene in indoor spaces stating that "…increased concentrations of particulate matter in indoor spaces is undesirable in terms of hygiene… A reduction in the dust concentrations in the air thus serves to prevent avoidable pollution."

Particulate matter is a collective term for airborne particles from diverse sources. The specific risk potential results from the composition as well as the size of the particles. Fine particles are only partially retained by the mucous membranes in the nose and throat and thus reach the respiratory tract, the finest particles as far as the alveoli.

On account of the high level of pollution by particulate matter in schools in Frankfurt, cleaning was carried out at shorter intervals in all schools in the city, with a noticeable impact on the city's budget.

In the context of this handbook, a six-week measurement survey on indoor air pollution was carried out in two classrooms of a primary school in an inner city location. With the objective of examining various ventilation strategies, manual ventilation took place in one classroom while another classroom was ventilated by means of a ventilation system. A school that had a controlled ventilation system was chosen for this, and one classroom was prepared for the survey by taping over the ventilation valves.

During this time period, the teachers in the prepared classroom were requested to ventilate the room conventionally via windows. In the second classroom the ventilation system remained in operation; only the outdoor air volume flow was specifically varied.

For this purpose, the concentration of particulate matter in the two classrooms was continually determined. The particulate matter monitors used for this purpose measure the number of particles using light scattering (see Section 11.1.2). Conversion to mass concentrations took place according to the monitor manufacturer's instructions.

The main focus of the test for particulate matter was on the influence of controlled ventilation on the resulting concentrations of particulate matter. Studies in residential buildings indicate that the use of ventilation systems has a positive effect. Basically there are two mechanisms which influence the concentrations of particulate matter in indoor spaces:

- For one thing, the particulate matter contained in the outdoor air is carried into the room with the exchanged air. This applies especially to finer particle fractions ($PM_{2.5}$) because their sources are largely in the outside area. With mechanical ventilation the outdoor air filter in front reduces the entry of dust from outside. This is a clear advantage over window ventilation. For residential spaces [Riley et al. 2002] showed that only when ventilation systems are used can a very low proportion of external particles in indoor air pollution be expected.
- For another thing, a high indoor concentration of particulate matter can be diluted with outdoor air through ventilation provided that the outdoor concentrations are lower. This is the case with the larger particle fractions. [Gabrio/Volland] found that adequate ventilation has a significant influence on pollution by particulate matter in classrooms. Because the outdoor air exchange is always higher with mechanical ventilation compared to ventilation via windows in practice, it is expected that a ventilation system will be advantageous here as well.

11.1.1 Measured results

During lessons the concentration of particulates with a mass fraction of PM10 increases and reaches values significantly higher than the outdoor concentration. The PM_{10} median values determined on school days over the measurement period ranged between 30.6 and 182.1 µg/m³ (median 80.5 µg/m³). For the mass fraction $PM_{2.5}$ daily median values between 4.5 and 36.5 µg/m³ result, with a median of 15.5 µg/m³. The measured values are comparable to results from other measurement surveys. [Fromme et al. 2006] determined PM_{10} daily medians between 16.3 and 313 µg/m³ (median 91.5 µg/m³) in a primary school, and 2.5 to 79.1 µg/m³ (median 26.5 µg/m³) for the mass fraction $PM_{2.5}$. [Heudorf 2006] ascertained PM_{10} daily medians between 35 and 150 µg/m³ in schools in Frankfurt.

During the measured time period, the daily medians of the particulate matter concentrations in outdoor air ranged between 2.7 and 47.4 µg/m³ (median 26.1 µg/m³) for the mass fraction PM_{10} and between 1.6 and 47.4 µg/m³ (median 23.1 µg/m³) for the fraction $PM_{2.5}$.

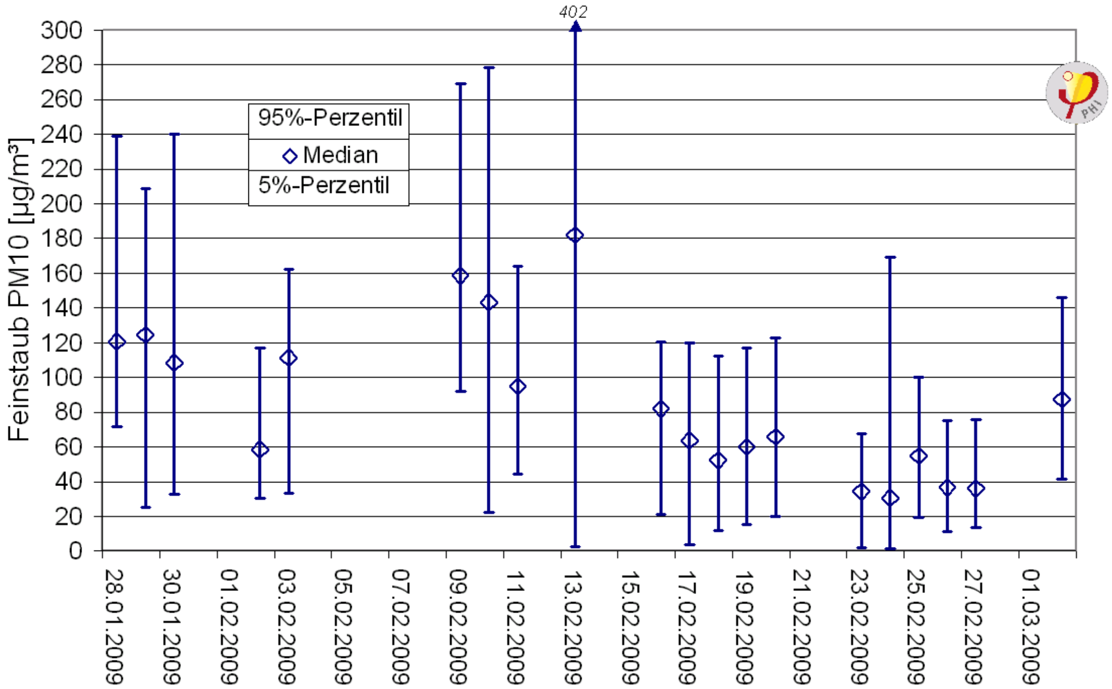


Fig. 118: **Measured values for the mass fraction PM_{10} in Classroom A. The controlled ventilation system was switched off until 16.2. *(Source: PHI)***
Feinstaub=particulates, Perzentil=*percentile*

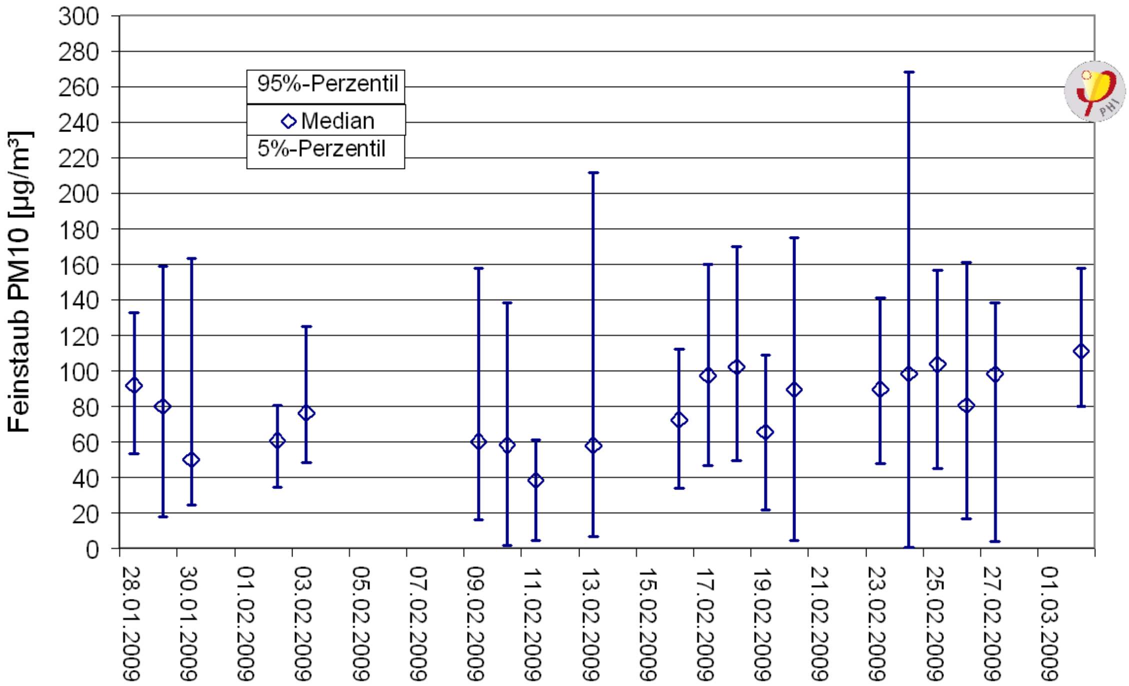


Fig. 119: **Measured values for the mass fraction PM_{10} in Classroom B. The controlled ventilation system was switched off from 16.2. onwards. *(Source: PHI)***

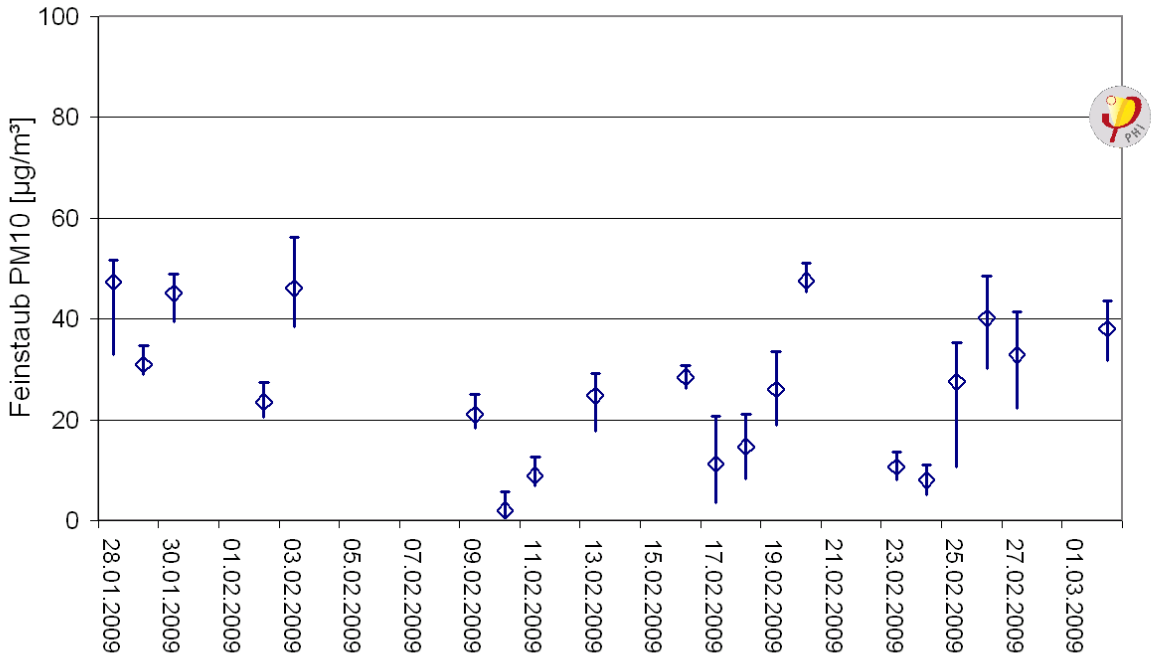


Fig. 120: Measured values for the mass fraction PM_{10} in outdoor air during the measurement period *(Source: PHI)*

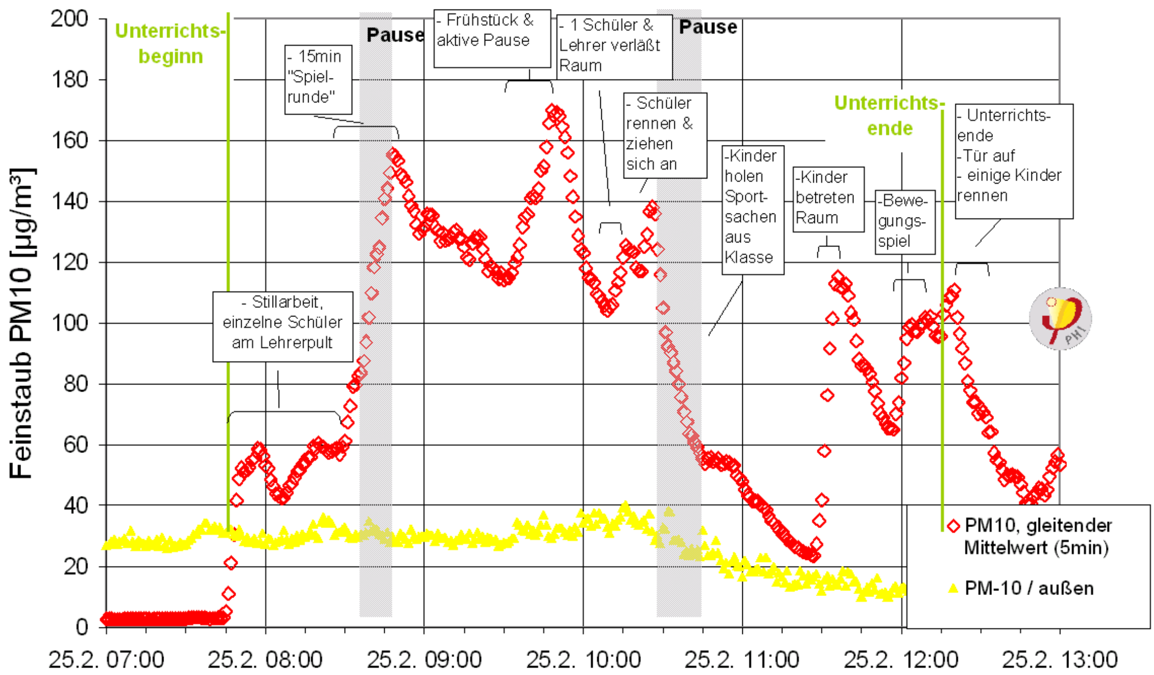


Fig. 121: Progression of the mass fraction PM_{10} in a classroom. The mass fraction correlated with the activities of the schoolchildren. *(Source: PHI)*

Unterrichtsbeginn=start of lessons, Spielrunde=playtime, Stillarbeit…= quiet work, single pupils at the teacher's desk, Frühstück…=breakfast and active breaks, 1 Schüler und Lehrer verlässt Klassenraum= 1 pupil and teacher leave the classrooom, Schüler rennen und ziehen sich an=schoolchildren run about and change clothes, Kinder holen Sportsachen aus Klasse= children fetch sports equipment from classroom, Kinder betreten Klassenraum =children enter classroom, Bewegungsspiel=active game, Unterrichtsende…=end of lessons, open door, some children are running, gleitender mittelwert= floating mean, außen=outside

Mass fraction PM_{10}

To examine the influence of the ventilation strategy on the concentration of particulate matter, the data was evaluated according to time periods with controlled ventilation and with ventilation via windows. It became apparent that the amount and progression of particulate concentrations in the classroom correlated to a high degree with the activity of the schoolchildren (see Fig. 121). Active games that are typical for primary schools led to significant peaks in concentrations of the mass fraction PM_{10}.

As with [Gabrio/Volland] and [Fromme et al. 2006], the measured results indicate a significant influence of the ventilation strategy and intensity of ventilation on the mass fraction PM_{10} in the classrooms. Furthermore, the influence of various ventilation strategies could also be studied within the context of this study. The average particulate matter content (PM_{10} median values) in the periods of time with controlled ventilation are between 30 and 50 % below the values with ventilation via windows (see Fig. 122 and Fig. 123). A correlation analysis confirms the suspected relationship between particulate concentrations and air exchange. For this purpose, the air exchange for times with window ventilation was estimated on the basis of the window opening times and configuration. The correlation between the volume flow and average particulate content (PM_{10}) is also significant (R^2 = 49%; see Fig. 123)

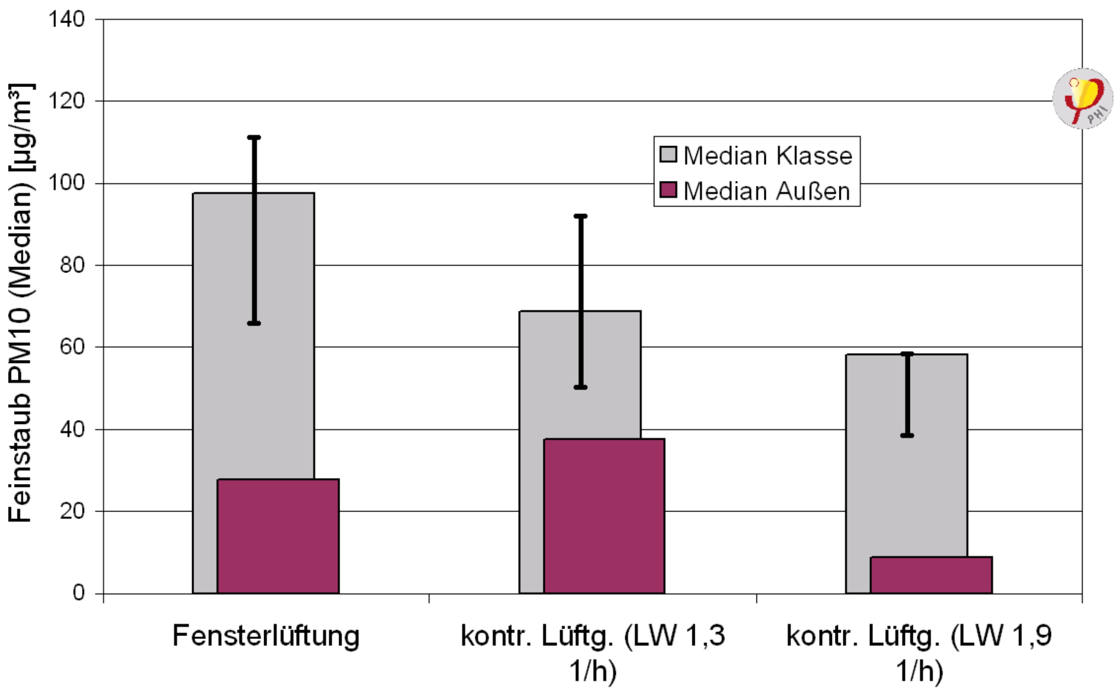


Fig. 122: **Daily medians of pollution by particulate matter indicate a significant influence of the ventilation strategy on pollution by particulate matter. With controlled ventilation the average daily medians in Classroom A are 30 % (air change rate**

approximately 1.3 h^{-1}) and 40 % (air change rate approximately 1.9 h^{-1}) below the average daily median with ventilation via windows. *(Source: PHI)*

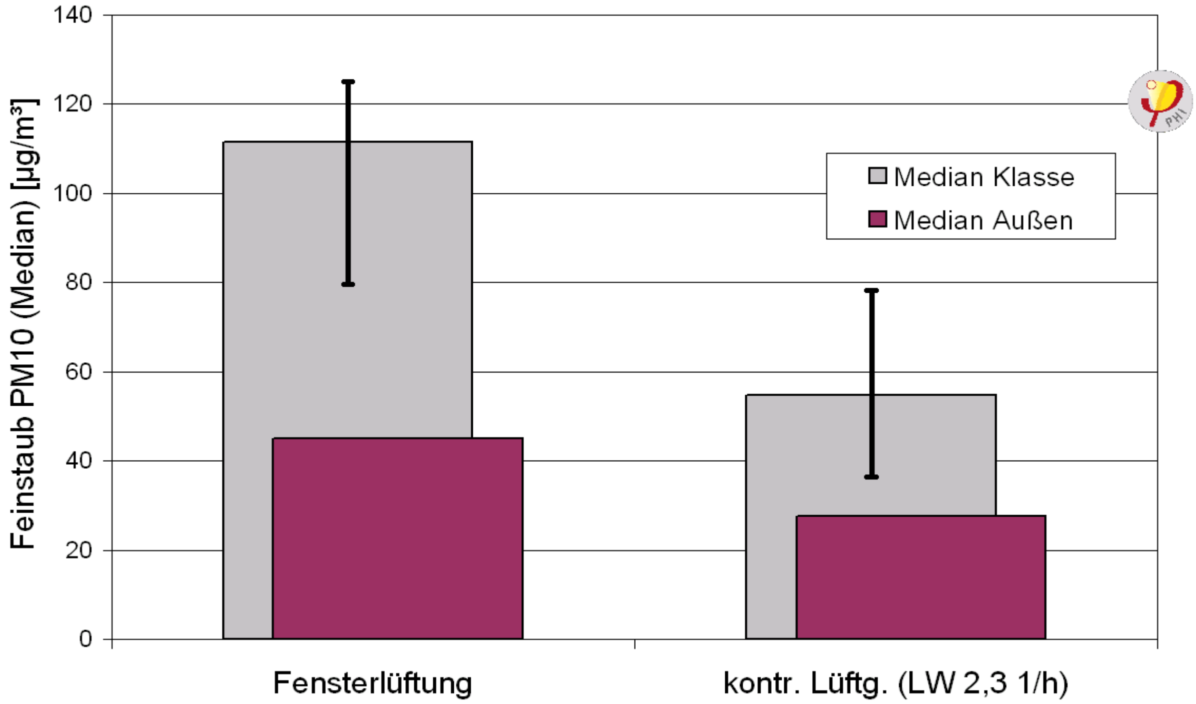


Fig. 123: **Daily medians of pollution by particulate matter. Significantly reduced pollution by particulate matter on average results also in Classroom B with controlled ventilation. Compared to the period with ventilation via windows the average daily medians are even reduced by 50 % with controlled ventilation (air change rate approximately 2.3 1/h). *(Source: PHI)***

Feinstaub=particulate matter, Fensterlüftung=window ventilation, kontr. Lüftung=controlled ventilation, Median Klasse=median classroom, Median Außen=median outside

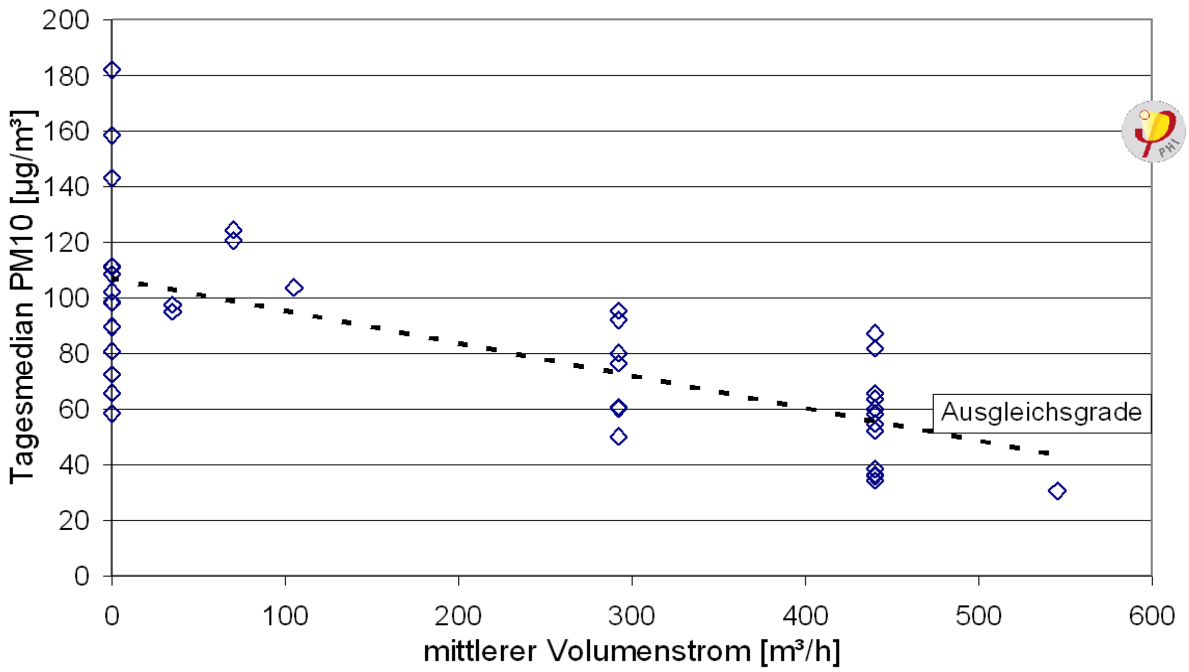


Fig. 124: **Influence of the outdoor air exchange on pollution by particulate matter in indoor space. The measured results indicate that an adequate outdoor air change rate reduces pollution by particulate matter in indoor space (R^2 = 49%). Average volume flows between 0 and 100 m³/(h classroom) are assignable to ventilation via windows, 290 and 440 m³/h were delivered during times with controlled ventilation.** ***(Source: PHI)***
Tagesmedian=daily median, mittlerer Volumenstrom=average volume flow, Ausgleichsgerade= line of best fit,

The mass fraction PM_{10} during lessons is probably determined largely by the activity of the schoolchildren. For a closer examination of the sink effect of ventilation on the particulate matter content, the decline in the particle concentrations after the end of school was studied in addition. In this way, the number of influencing factors can be minimised. As an evaluation of the decay curves of the PM10 mass fraction shows, the fine dust concentration decreases significantly faster during ventilation system operation (see Fig. 125). The results indicate that ventilation for the PM10 mass fraction is the main sink process in the classes investigated. The time constant of the exponential concentration drop is reduced by about 70 % compared to the case with blocked controlled ventilation and sedimentation as a significant sink. The acceleration of the concentration drop is in good agreement with a mass balance approach, which takes into account a dilution of the indoor air by outdoor air.

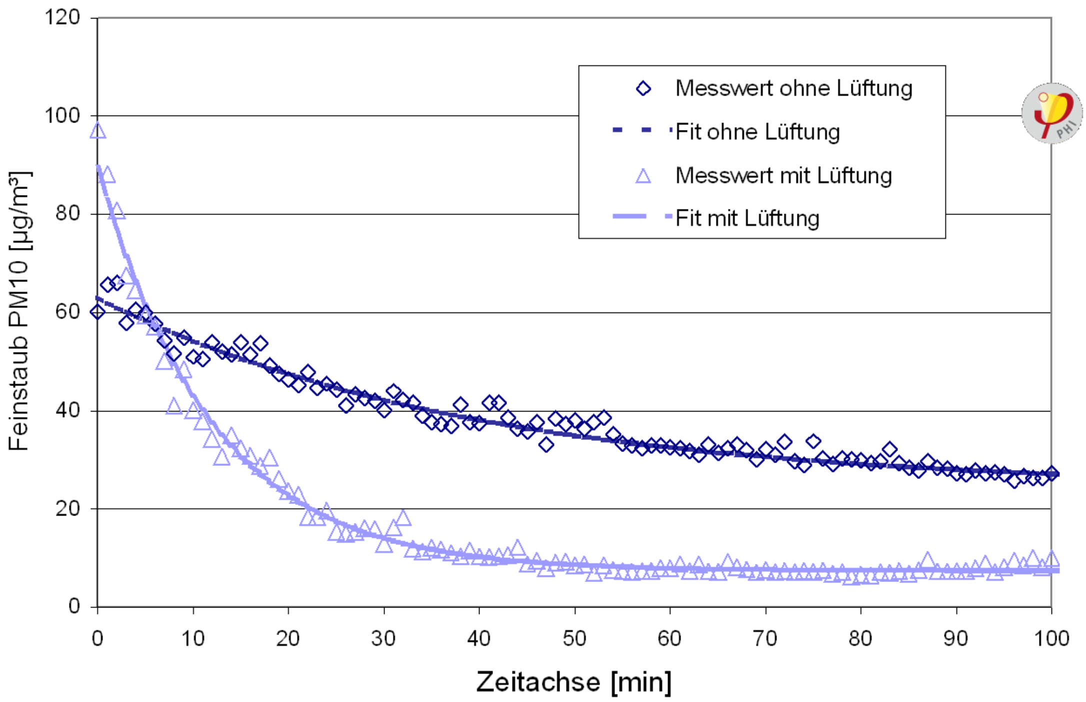


Fig. 125: **Decline in the mass fraction PM_{10} after the end of school with and without ventilation. Two typical concentration curves are shown. The decline in concentration (PM_{10}) is significantly accelerated with controlled ventilation. The time constant of the decline curve is reduced by 70 %.** ***(Source: PHI)***

Mass fraction $PM_{2.5}$

For particles with the mass fraction $PM_{2.5}$ the results indicate that these are greatly determined by the outdoor content. The correlation analysis points to a significant correlation (R^2 = 64%; see Fig. 126). Moreover, in general the measurements in the examined classrooms substantiate lower indoor concentrations of this mass fraction than outdoor concentrations. This is also in line with expectations, because the main source of fine particles is presumed to be in the outdoor area.

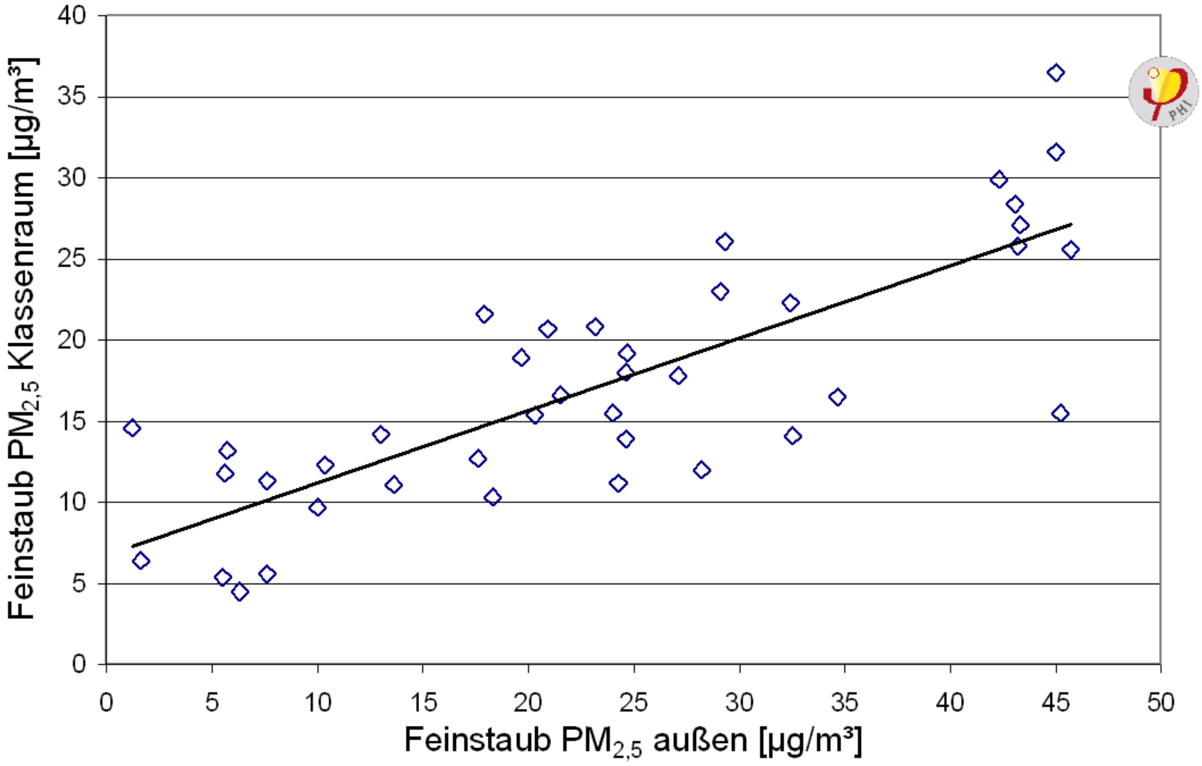


Fig. 126: Correlation analysis between the indoor and outdoor concentrations of the mass fraction $PM_{2.5}$. With R^2 = 64%, this correlation is significant. (*Source: PHI)*
Feinstaub=particulate matter, Klassenraum=classroom

The assumed influence of controlled ventilation on the particulate matter content ($PM_{2.5}$) compared to window ventilation could not be clearly established on the basis of the measured indoor concentration. A reduction in the amount of fine particles takes place in the ventilation system due to the filtering system; however, much less outdoor air is exchanged during periods with ventilation via windows. Estimation of air exchange with ventilation via windows on the basis of window opening durations and configurations leads to outdoor air volume flows which are over 70 % lower than with controlled ventilation.

In an additional measurement, the particulate matter content in the supply air and in the outdoor air were directly measured. These examinations support the assumption that the ventilation system also has a noticeable filtering effect with regard to the outdoor particulate concentration. In the case of particles with diameters smaller than 2 µm, a reduction of about 50 % in the particle concentration was observed in the supply air in comparison to the outdoor air.

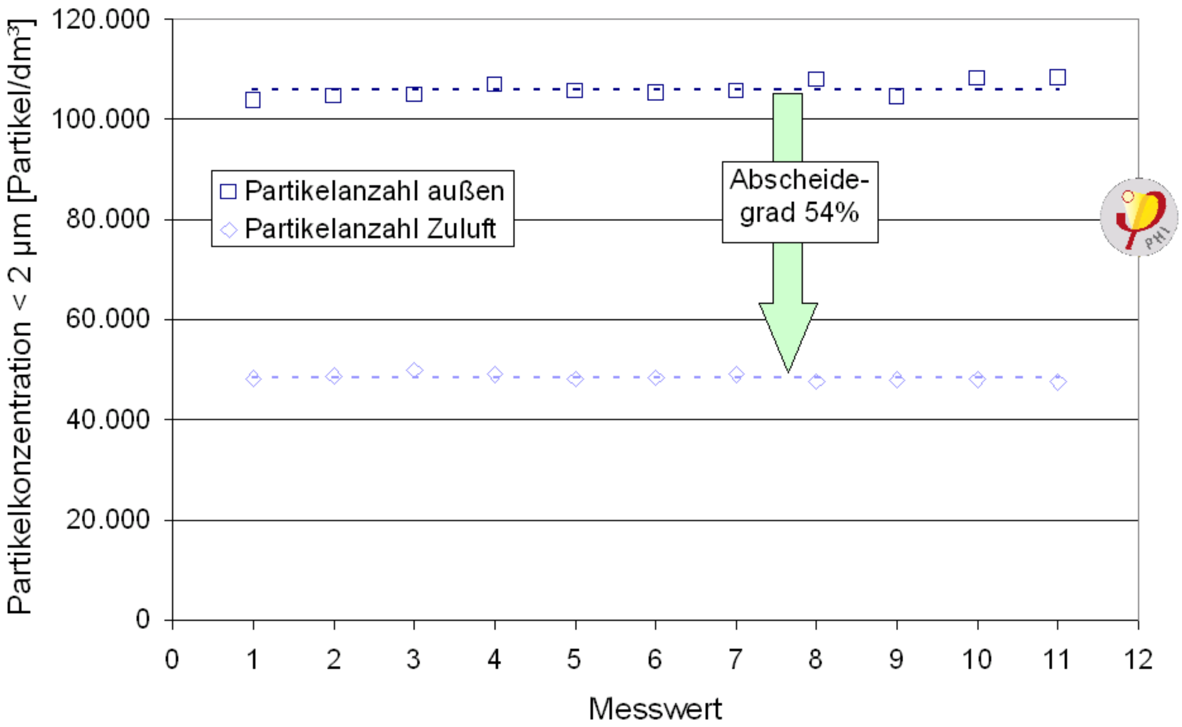


Fig. 127: **Investigation of the filtering effect of the ventilation system. The reduced particle concentration in the supply air compared to the outdoor air indicates a filtration efficiency of about 50 %. *(Source: PHI)***
Messwert=measured value, Partikelkonzentration=particulate concentration, Partikelanzahl=number of particles, außen=outdoor, Zuluft=supply air, Abscheidegrad=filtration efficiency

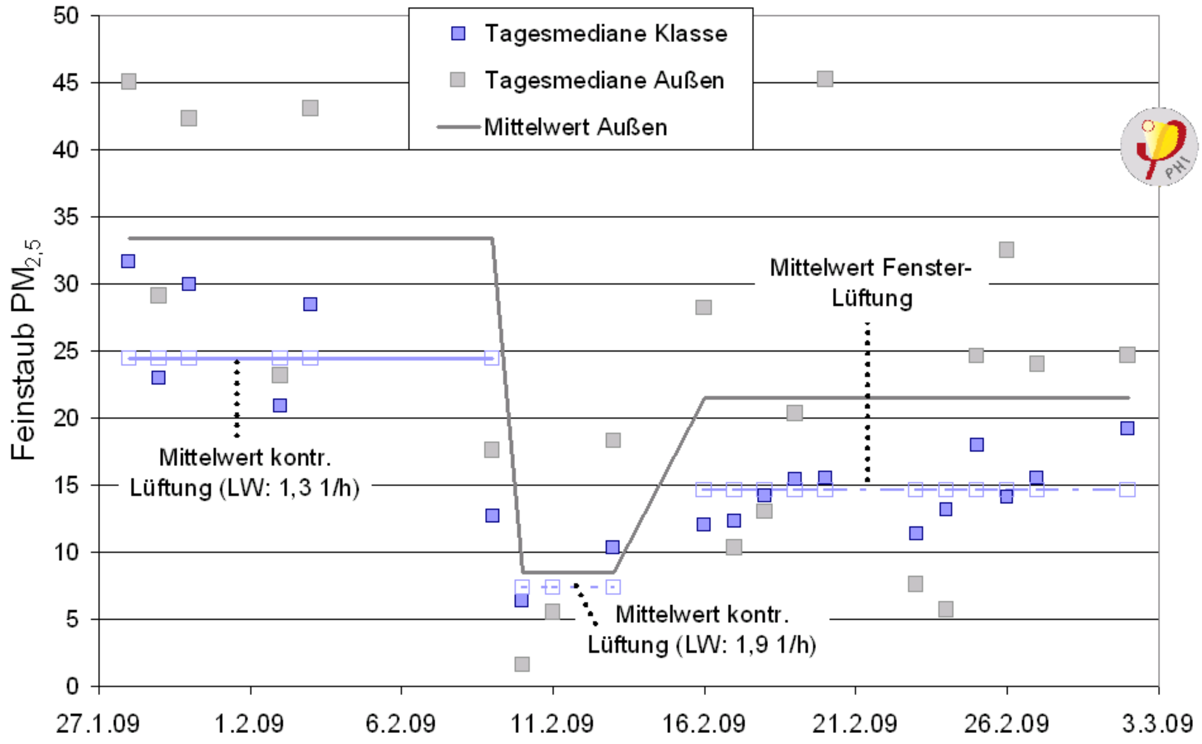


Fig. 128: **Progression of the mass fractions $PM_{2.5}$ in Classroom A and outside. For all ventilation strategies, the pollution on the inside is less than it is outside. The main source of the fine particles are also presumed to be in the outdoor area. Depending on the ventilation strategy, the indoor pollution is 13 %, 28 % and 42 % lower than the average outdoor pollution. Initially, it may be surprising that with ventilation via windows most of all the indoor pollution levels with 42 % are less than those on the outside. This can be explained by the extremely low outdoor air exchange during this time period. The outdoor air exchange estimated with the help of the window opening durations is lower by over 70 % compared to the mechanical outdoor air exchange.** ***(Source: PHI)***
Feinstaub=particulate matter, Mittelwert=average value, kontr. Lüftung=controlled ventilation, Fensterlüftung=window ventilation, Außen=outdoor, Tagesmediane=daily median, Klasse=classroom

Searching for the sources

The measurement results suggest that the schoolchildren themselves significantly influence pollution by particulate matter with the mass fraction PM_{10} (see Fig. 121). [Gabrio/Volland] also assume that the schoolchildren contribute substantially to pollution by particulate matter. Essentially, two processes may be responsible for this: the schoolchildren themselves carry particulate matter into the building (e.g. dander, paper dust from books etc.), and the activity of the schoolchildren causes resuspension (stirring up) of already sedimented particles in the school building. In order to clarify whether a major contribution enters indoor air due to resuspension, the indoor air was intensively stirred up by means of a blower fan outside of the lesson times. It turned out that even a twelve-fold air change rate in the classroom had only a minor influence on the particle concentration in the classroom (see Fig. 129). The experiments that were carried out indicate that pollution by particulate matter is largely due to individuals themselves. Further examinations should clarify the exact associations.

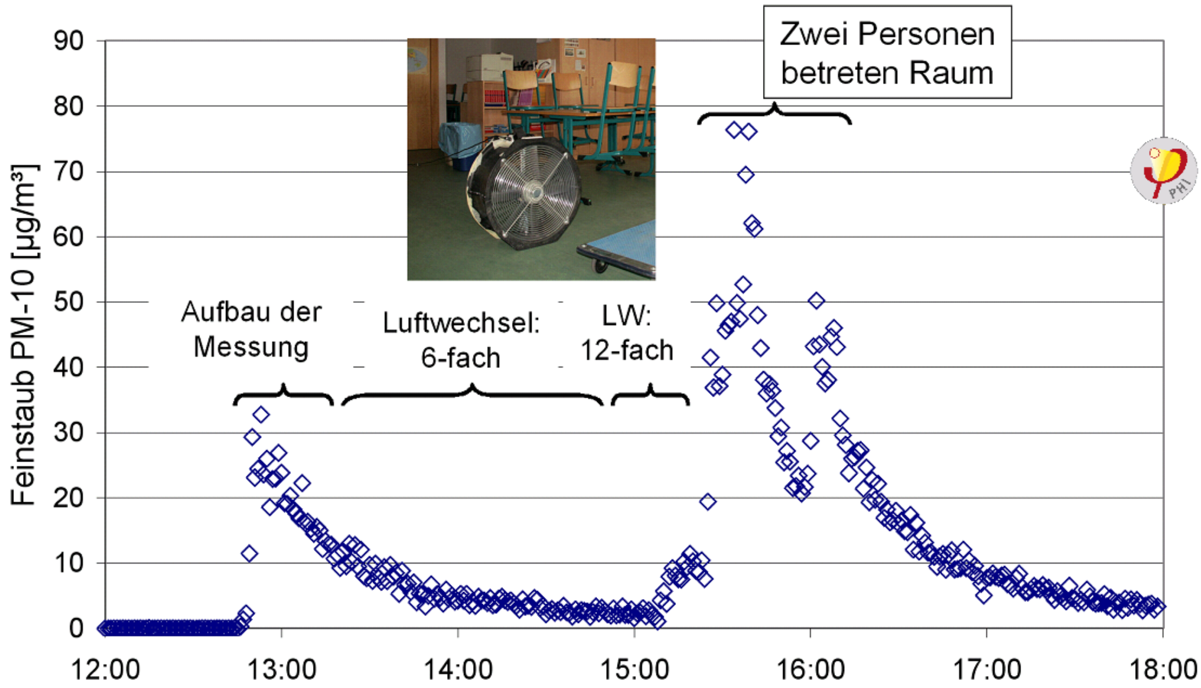


Fig. 129: **Influence of resuspension of sedimented particles in a classroom. To check for the influence of resuspension, the indoor air was stirred up six-fold or twelve-fold by means of a blower fan. This experiment demonstrates that in the tested classroom the contribution of resuspension is rather small. In contrast, the entry of two persons increased the concentration of particulate matter significantly.** ***(Source: PHI)***

Aufbau der Messung=measurement setup, Luftwechsel=air change rate, Feinstaub=particulate matter, zwei Personen betreten Raum=two persons enter the room

11.1.2 Particulate matter monitor

The measurement of particulate matter in air were carried out using the particulate and dust measuring device 1.108 supplied by the company Grimm. The measurement principle is based on laser light scattering.

Conversion of the measured data to mass concentrations took place according to the manufacturer's procedure.

Count rate:	up to 2 000 000 P/l
Dust mass range [µg/m³]:	0.1…> 100 000
Reproducibility:	5 % for the whole area
Size range [µm]:	0.3…> 20
Size channels [µm]:	15 / number of particles (0.23)/0.3/0.4/0.5/0.65/0.8/1/1.6/ 2/3/4/5/7.5/10/15/20 µm

11.2 Derivation of Passive House criterion for school sports halls

Like many non-residential buildings, sports halls are used only temporarily. Operation of the ventilation system should be based on the usage times, whereas continuous operation may double the primary energy demand relating to ventilation - in contrast with residential buildings (energy demand for meeting the ventilation heat losses and for operating the controlled ventilation system). For space heating via post-heating of the supply air, this means that the heating system is also linked to the times of use. The thermal protection for a Passive House sports hall should be of such a high standard that post-heating of the hygienically necessary air quantities is sufficient for space heating (in contrast to convection heating, which is often used in conventional sports halls). This condition is easily fulfilled during utilisation. A heat output of up to 33 W/m² can be introduced into the hall area with an air change rate of about 0.7 h^{-1} in the hall that is necessary for indoor air hygiene, and potential heating of the supply air up to 50 °C. In contrast, reheating after a night-time temperature setback is more critical. An approximately two-fold replacement of the air volume should take place before the start of use (see [EN 15251]). This pre-ventilation phase is necessary for reasons of hygiene and should be sufficient for reheating the building after a night-time temperature setback. The functional definition of a Passive House criterion for sports halls similar to that for school buildings can be derived from this (see [Kah 2006, Kah 2006b]):

The thermal protection of a Passive House sports hall should be such that space heating and reheating is possible by means of post-heating of the supply air using the air quantities required for hygiene reasons (including the pre-ventilation phase).

The hall area is decisive for deriving the Passive House criterion, because heatability via the supply air is much more critical here than it is for the changing areas and showers. For comparison: 5 to 10 times the air change rate is necessary in the changing areas/showers during use so that in these areas much higher heat outputs that can be transferred via the supply air are available. A setpoint temperature of 18 °C is assumed in the sports hall area. This setpoint corresponds with the conventional mode of operation and ranges between the recommendations given in standards for sports facilities with 20 °C (see [DIN 18032-1]) and those of the AMEV (see [AMEV 2001]) with 17°C. As Fig. 130 shows, with the Passive House quality of the sports hall, the setpoint temperature is achieved at the start of utilisation; the already necessary pre-ventilation phase is sufficient for reheating after the night-time setback. With a lower standard of thermal protection and therefore higher heating demand values, the setpoint temperature cannot always be achieved at the start of operation using the supply air heating (see Fig. 131).

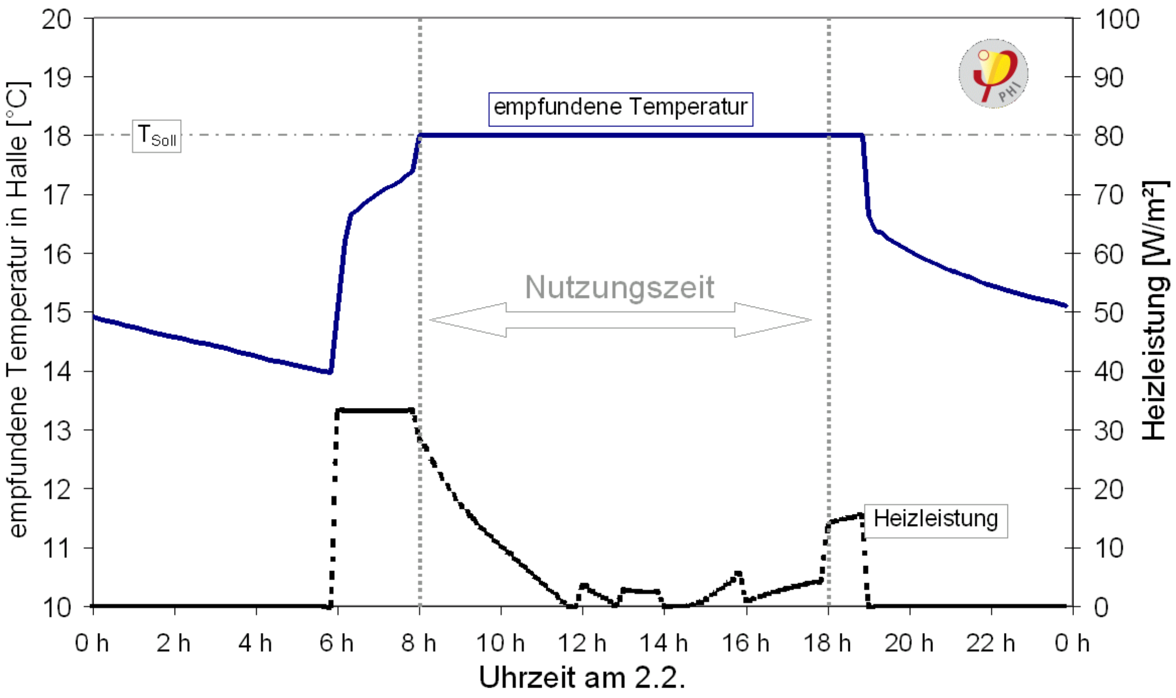


Fig. 130: **Progression of the indoor temperature during heat up for typical use of a Passive House sports hall. (Source: PHI)**

Uhrzeit am 2.2=time on 2.2, empfundene temperatur=perceived temperature, Nutzungszeit=usage time, Heizleistung=heat output

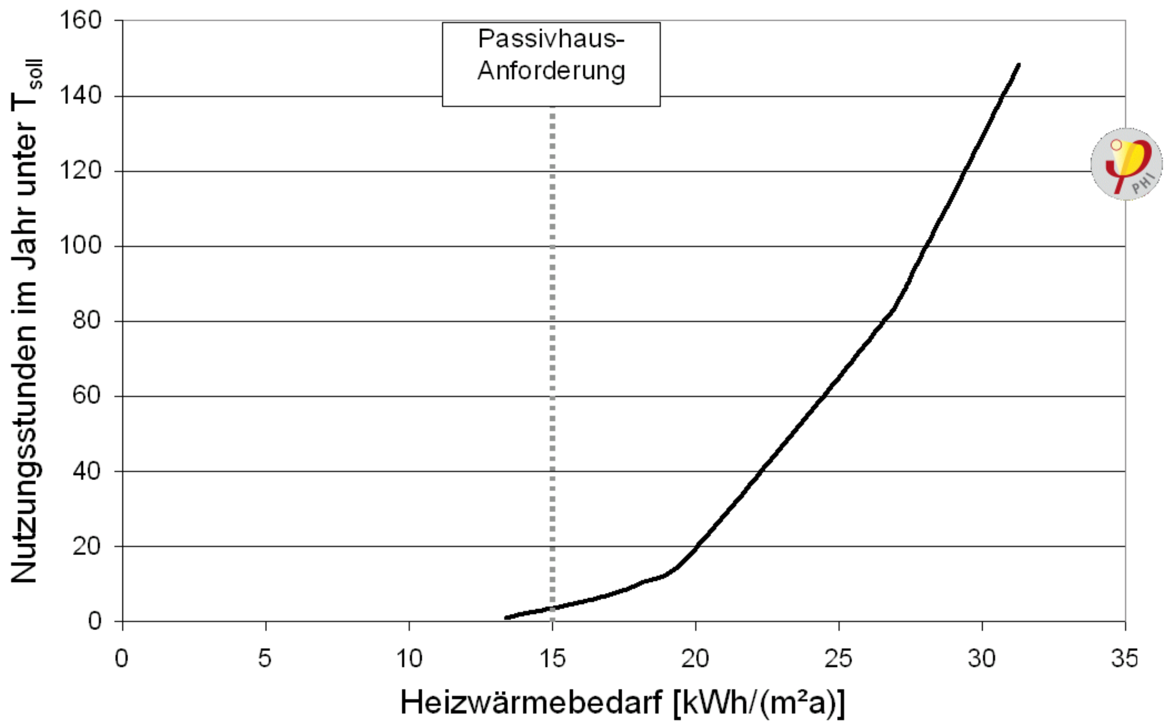


Fig. 131: **This shows the increase in the hours of use with excessively low room temperatures for increasing heating energy values. (Source: PHI)**

The Passive House concept aims for simplification of the heating system, which is made possible by an excellent standard of thermal protection. Consequently, space heating using the ventilation system implied in the Passive House Standard was therefore considered. Heating with other transfer systems such as radiators will not be the subject of discussion here, but technically is also always possible.

Table 14: Boundary conditions

Setpoint temperature in the hall area during use	18°C
Duration of pre-ventilation phase	2-fold air exchange / 2 h pre-ventilation duration
Supply air flow in a single-court sports hall (30 sportspersons)	30 x 60 m^3/h = 1800 m^3/h
Maximum temperature difference ΔT / max. heat output	30 K / ca. 33 W/(m^2 hall area)

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