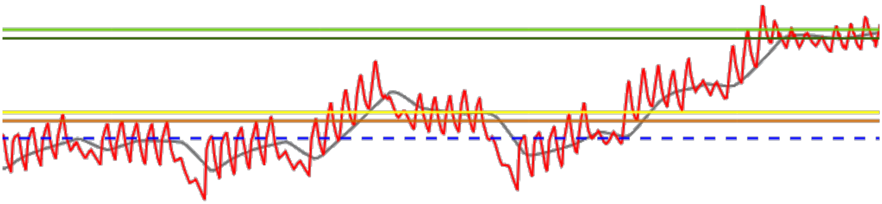

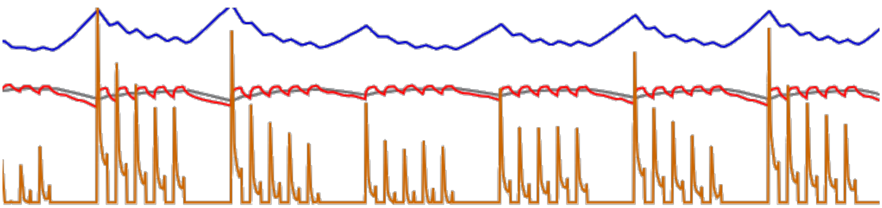

Instrumentation and Controls for Buildings in Passive House Standard

Preface by Assoz. Prof. Dr. Rainer Pfluger

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Acknowledgements

The AchieVE ZEB project received support from the Life Programme of the European Union, grant number 101167494.

"Funded by the European Union. Views and opinions expressed are, however, those of the author(s) only and not necessarily reflect those of the European Union or CINEA.
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Motivation

Highly energy efficient buildings in Passive House standard and the corresponding deep retrofits to EnerPHit standard are steadily gaining traction. Particularly owners with long-term perspectives like municipalities see the benefits like cost-certainty, attractive life-cycle cost and resilience in the event of power outages. The construction method itself provides an appropriate response to the challenges posed by advancing global warming and the so-called energy transition.

The author was able to be part of various such projects in different roles; consulting the design team, as certifier or assisting in commissioning and performance-optimisation- in many instances also as part of a multi-year performance monitoring scheme. Some repeated observations first prompted closer investigation within the 59^{th} session of the Working Group on Cost-Effective Passive Houses. Also from the 45^{th} and 52^{th} sessions some important aspects could be borrowed. We would like to express our sincere thanks to the German State of Hesse for their generous support. The Protokollband (in German) published on the findings remains valid and is recommended for further study. This document hopes to develop some aspects further and compile the aspects relevant for practitioners.

Building on earlier findings more practical experience was gained additionally to evidence that reliable as-designed function and performance can be achieved if appropriate control concepts are implemented from the outset. Too often, however, suboptimal conditions are encountered. Changing control paradigms after commissioning and re-programming automation controllers in full operation is challenging and expensive.

This text aims to provide an overview of the particular properties of highly energy efficient buildings and the fundamental problems that arise with respect to conventional control strategies. At the same time a more appropriate alternative shall be suggested.

In this regard the last word is not spoken. Feedback and suggestions for improvement are welcome.
If this document contributes to a better understanding of highly energy efficient buildings and better accomodation of their special characteristics in building controls, and thereby assists in avoiding disappointing installations and kindling fruitful further discussion in the industry it has served its purpose.

Foreword

Within the EU-Directive on the energy performance of buildings (EPBD 2024, RL (EU) 2024/1275) the Zero Emmission Building (ZEB) is defined as the guiding principle for the future, replacing the nearly Zero Energy Buidling (nZEB). The new EPBD aims to implement the ZEB-standard for the entire EU building stock by 2050 (sec. 9 para. 2).

In new construction the Passive House standard, that has been introduced world-wide, today defines the foundation and has been applied successfully to nearly all building typologies (residential and non-residential buildings). For retrofits the EnerPHit standard has proven itself- for all climate zones and building categories- conforming to ZEB requirements.

Largely independent of their varied building services concepts these highly efficient buildings were demonstrated to achieve the expected energy savings in numerous monitoring campaigns. In Innsbruck/Austria alone in the scope of various research projects funded by different authorities (FFG, EU) many new-builds (e.g. Lodenareal, Campagene-Areal) and retrofits were studied (SINFONIA, outPHit, 3ENCULT) and analysed scientifically. Currently, the innovation lab INNERGY develops innovative concepts, technologies and solutions to manage 100 per-cent renewable energy in the heat sector and puts them to the test.

The cornerstone for the EU targets with a comprehensive transition to the ZEB standard is thus laid. Due to the high time constant of highly efficient buildings they are furthermore very well suited to act as *energy-flexible* buildings within a renewable energy system, since the time of day at which power is put in for space conditioning is largely irrelevant. Moreover, the low heating load facilitates renewable energy supply as the annual load duration curve is flattened. The problem of costly seasonal energy storage is mitigated, with a very positive effect on cost and ressource intensity of the energy transition.

Keeping in mind the above mentioned thermal characteristics of highly efficient buildings the imperssion arises that, in contrast to existing buildings, they are "docile" and easy to control within the energy system. While this is true in principle it should nonetheless be noted that such structures respond thermally in a slightly different way and hence call for adjusted or new control paradigms. These are in no way more complex or expensive, but differ in some points from decade-old practices. Applying the latter without consideration on highly efficient buildings not all efficiency and thermal comfort potentials may be realised.

This brochure, therefore, wants to point out and document differences and particularities of the controls for energy efficient buildings in a simple, comprehensible and concise form, in order to apply them successfully to new-build and retrofit projects. The path towards the energy transition and the zero emmission building is thus clear.

Assoz. Prof. Dr. Rainer Pfluger, Universität Innsbruck
Innsbruck, in the winter 2025/26

1. The Passive House and its Particular Characteristics

The Passive House standard is the only building standard comprehensively defined in terms of physics. In addition, since its introduction by Feist 1990, a large quantity of systematically investigated and documented operational experience has been accumulated.

Within the Passive House concept no new building components are introduced. Those required anyway are optimised stringently and integrated as part of a comprehensive system. The focus is on five main aspects, like the fingers of a hand:

1. Superior insulation. In the cool-temperate climate of central Europe typically e.g. 24 *cm* all around the building envelope.
2. Thermal bridge free construction. All insulation layers join without gap or offset. Penetrations are avoided, or their impact minimised by optimised design.
3. Passive House windows. With insulating frames, triple glazing and carefully designed connections to the opaque building envelope heat losses are minimised. In favourable conditions the solar gain can outweigh the transmission heat losses in the winter. As a result of the low heat loss the interior surface temperature remains high eliminating the need for a heater to ensure thermal comfort.
4. A highly airtight building envelope contains warm air and prevents draught or moisture-related damage in the building fabric. Furthermore it facilitates the targeted operation of ventilation systems.
5. A mechanical ventilation system with heat recovery (MVHR) ensures hygienic air replacement and retains the heat within the building during the cold season.

The thermal system, designed with consistent consideration of the five elements mentioned above, has very low energy requirements for heating and cooling. The energy requirements can also be met with low power, enabling economic advantages possible due to the correspondingly small capacity of the building services systems and protecting the power grid from peak loads.

To effectively control the building, it is important to appreciate that the thermal system of the building is characterised by high thermal resistance of the building envelope and a considerable heat capacity. In a first approximation it could be modeled as a linear time-invariant first-order system with a time constant of usually five to fifteen days. When the building is equipped with building services designed for low loads, such a system behaves sluggishly resulting in stable and predictable control behaviour. At the same time, it exhibits pronounced low-pass behaviour, in that short-term stimuli from the weather or usage do not cause any significant change in the system state. As long as the ventilation with heat recovery works as intended and windows are not opened excessively, the thermal resistance of the envelope can be considered practically constant and the system state is reflected in the temperature of the heat capacity.

Most of the heat loss in a Passive House building is covered by *free heat*. This consists of passive solar heat gain through the windows, as well as heat emitted by appliances and occupants. The exact proportion varies slightly for each building, but as a rule of thumb, it can be estimated at $\frac{2}{3}$; Figure 1.1 shows an example of the annual energy balance graph for an administrative building calculated using the Passive House-Planning-Package (PHPP). The usage-related internal heat sources in residential buildings, offices, schools and similar structures amount to no more than 2...4 $\frac{W}{m^2}$ on a daily average.

The enormously high proportion of free heat makes it clear that particularly careful management of heat from solar radiation, as well as appliances and users is crucial within the Passive House concept. In no way it should be considered merely a *disturbance factor*.

During the cold season, this requires that the room temperatures be allowed to fluctuate within a comfortable range (typically $20 \ldots 23.5\ ^\circ C$) without reducing the ventilation heat recovery or even cooling. While the sole purpose of the heating system is to guarantee a lower limit on the room temperature, the room temperature can *and must* rise temporarily due to solar radiation or usage-related internal heat gains, in order to be able to transfer heat to the structural mass of the building for later use. Control concepts geared towards a *constant* room temperature are thus unsuited for buildings in Passive House standard.
With a balanced radiation climate within the room, minimal radiation temperature asymmetry and air movement, very high thermal comfort in accordance with category A, ISO 7730 is achieved.

During the warm season, it must be possible to lower the room temperature by removing heat, for example through night ventilation or cooling, in order to use the storage masses to buffer the heat loads of the day. For normal cases, $20 \ldots 25\ ^\circ C$ is considered an acceptable range.

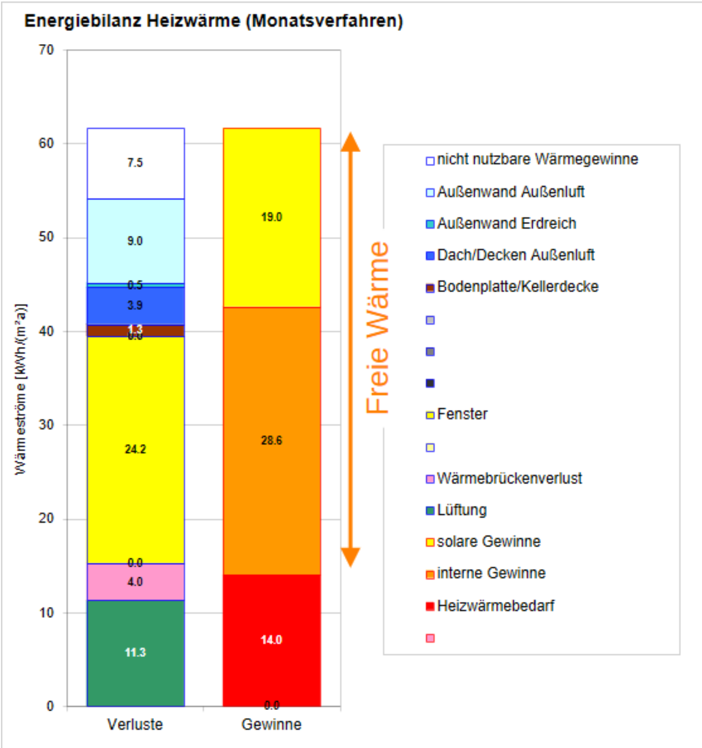

Figure 1.1.: Energy balance of an office building in PASSIVE HOUSE standard. Clearly apparent is the critical contribution from free heat (orange arrow)

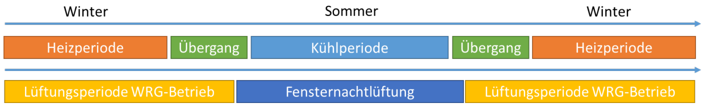

Figure 1.2.: Diagrammatic representation of seasonal operating modes

Due to the large time constant on the one hand and the outstanding importance of free heat on the other, there is usually no useful correlation between the control tasks and the outside temperature (ϑ_{ext}). Conventional approaches to controlling and regulating building services systems based on the outside temperature therefore give rise to a variety of problems in Passive Houses and prove to be of little help.

There are also significant seasonal differences:
While additional heating is required during the short core winter period, during the longer transitional periods, the proper management of the free heat can cover all heat losses. The heating period is therefore much shorter than in conventional buildings. For this reason, the operating time of the ventilation system with heat recovery begins *before* the heating period and ends *after* the heating period, as illustrated in figure 1.2.

With the onset of the warm season, a point is reached at which further heat input is no longer beneficial.
In the summer, as in all buildings, excess heat often has to be dissipated.

The transition from the heating period to the cooling period is never abrupt, due to the thermal inertia of the building, so there is no need to manage rapid changes between the two modes in terms of controls. There is also no need to worry about increased energy consumption due to rapid changes between heating and cooling if proper control measures are implemented.

A control concept suitable for buildings to the Passive House standard must respond to these different requirements with appropriate seasonal adjustments to the control system.

Another significant feature results from the good thermal insulation of the building fabric: heat losses are so low that they are compensated for by heat radiation alone, even with minimal temperature differences. A quick calculation may illustrate this:

An exterior wall with a heat transfer coefficient $U = 0.15 \frac{W}{m^2 K}$ in steady-state at 20 K temperature difference dissipates heat power of 3 $\frac{W}{m^2}$. At room temperature, however, a good 5 $\frac{W}{m^2 K}$ are exchanged between interior surfaces by thermal radiation alone; As a result the surface temperatures of walls, ceiling and floor hardly differ. This is also known as a 'thermal short-circuit'.

The method and location, but also the point in time of heat input are of secondary importance: the heat from the floor warmed by solar radiation spreads evenly in a short time as well as the heat from a ceiling in the case of concrete core activation or heated supply air, that is diffused via a nozzle using the COANDĂ-effect. A *winter compensation*, this is an increased set point for the room temperature at very low outdoor temperatures, is unnecessary and would only increase the space heating demand.

A very balanced radiation climate promotes high thermal comfort and clearly shows how strongly the indoor conditions depend on the temperature of the surrounding thermal masses. Knowing this temperature is the key to developing an effective control strategy.

The above description emphasises that a PASSIVE HOUSE building is an integrated thermal system whose function extends beyond the conventional trade boundaries. For example, seasonally adjusted operation of sun protection systems is only possible when indoor temperatures are taken into account. A uniform, cross-trade and manufacturer-neutral building automation system is recommended.

2. The Thermal Condition of a Building

The Thermal Condition (ThC) of a building corresponds to the temperature of its internal heat capacity. The latter is usually largely bound to the load-bearing structure of the building, although finishing elements also play a role.

The deep layers of massive structural components are only marginally affected by daily temperature fluctuations. They are, therefore, a good indicator of the long-term trend, as they reflect the overall effect of all heat gains and losses. The core temperature of massive components is a suitable measure of the charge status of the thermal capacity and thus of the Thermal Condition of a building. The Thermal Condition is determined in a number of selected control rooms.

2.1. Determining the Core Temperature by Measurement

With high grade thermometers [1] the core temperature of massive structural members may directly be measured within boreholes. In practice, it is important to ensure that the diameter of the borehole matches the diameter of the sensor, that the sensor is mechanically secured at the bottom of the borehole, and that the sensor cable outlet is sealed airtight. Thermal influence on the measuring spot due to a continuous metal sensor sleeve or excessively large cross-sections of the connecting cables must be avoided. Under these conditions, embedding in thermal paste or similar is unnecessary. The drilling depth is 125 mm.

This approach was used in a well-documented school project [2] by Kuckelkorn and proved successful there; the measured values for individual rooms were averaged and also subjected to running mean calculation over a daily period. This means that the computing effort required to process the measured values is low;

[1] Resolving to 0.01 K, Measuring uncertainty of the entire measuring chain $\leq \pm 0.3$ K

[2] DBU-Abschlussbericht-AZ-26170_02.pdf, in German

however, the approach requires dedicated instrumentation and the associated costs for installation, operation and maintenance.

2.2. Determining the Core Temperature via a Thermal Model

If room temperatures are monitored continuously, it is possible to calculate the temperature of the building's structural core with sufficient accuracy for typical reinforced concrete buildings without incurring significant costs. In buildings with continuous ventilation, i.e. residential buildings, it may also be possible, after consideration of the individual case, to use extract air temperature as a representation of the average building temperature and the input to the process. The procedure shall be explained in more detail below.

First, the room temperature value should be available with sufficient resolution of 0.01 K to minimise rounding effects in the calculation process. Preferably, the value should also have low measurement uncertainty — the total uncertainty of the entire measuring chain should not exceed $\pm 0.3\ K$.

This is beyond the $\pm 0.5 ... 1\ K$ currently standard in building automation. [3] Since reliable room temperatures are increasingly required for operating data evaluation and technical monitoring, it is desirable that the standards for temperature measurements in building automation be improved. At a minimum, four-wire platinum temperature sensors of class AA / DIN EN 60751:2009-05 should be used. In addition, automation controllers should include ratiometric temperature measurement for resistance thermometers with more than 14-bit digitisation depth. [4] Alternatively, fully integrated electronic temperature sensors can provide high-quality digitised measurement results with low measurement uncertainty. With a measurement uncertainty of $\pm 0.2\ K$, they are currently available for around €1. However, the cost of a microprocessor and fieldbus connection must also be taken into account.

The measured room temperature is fed into the thermal model of a solid concrete component. According to Beuken, this is formulated as an electrical analogy of resistances and capacitances in five layers. Figure 2.1 shows a schematic representation of the model.

[3] e.g. for two-wire-Ni1000 RTD with only an approximate calibration of the wiring resistance and the digitising tolerances of a common building automation controller ca. $\pm 0.7\ K$

[4] An example for a commercially available temperature measurement would the the Modbus module Seneca Z-4RTD2-SI based on the AD7124 circuit.

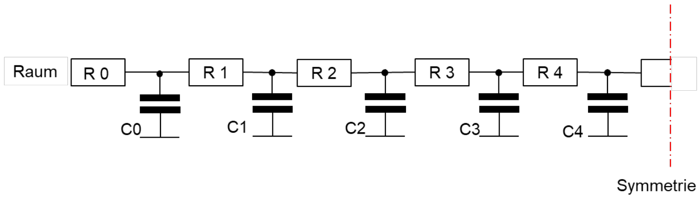

Figure 2.1.: Electrical analogy model of a building member with five layers

The layer thickness for discretising the concrete component is 25 mm; thermal symmetry or an adiabatic boundary is assumed at the deepest layer. This simulates the situation when measuring in a borehole through half the component thickness.

If L_i describe the conductances of the layers, t_r the room temperature, t_i the temperatures of the respective layers, C_i the heat capacities of the layers and q_i the heat flows at the layer boundaries, and DT the time step, the core algorithm of the model can be simply formulated as:

$$q_1 = L_0 \cdot (t_r - t_1) + L_1 \cdot (t_2 - t_1)$$
$$q_2 = L_1 \cdot (t_1 - t_2) + L_2 \cdot (t_3 - t_2)$$
$$q_3 = L_2 \cdot (t_2 - t_3) + L_3 \cdot (t_4 - t_3)$$
$$q_4 = L_3 \cdot (t_3 - t_4) + L_4 \cdot (t_5 - t_4)$$
$$q_5 = L_4 \cdot (t_4 - t_5)$$

$$t_1 = t_1 + (\frac{q_1}{C_1} \cdot DT)$$
$$t_2 = t_2 + (\frac{q_2}{C_2} \cdot DT)$$
$$t_3 = t_3 + (\frac{q_3}{C_3} \cdot DT)$$
$$t_4 = t_4 + (\frac{q_4}{C_4} \cdot DT)$$
$$t_5 = t_5 + (\frac{q_5}{C_5} \cdot DT)$$

Temperature t_5 thus represents the desired core temperature.

The model is run with a time step of one minute ($DT = 60\ sec$); longer intervals lead to numerical instability with the simple forward difference approach. However, it is not a problem to run the model several times in succession with the same input value, i.e. to provide a measured value every 10 minutes and to iterate the model ten times in a loop with this value, or 30 times for half-hourly values. Appendix A provides a code example.

The model is normalised to 1 m^2 and uses typical material properties for concrete: bulk density $\varrho = 2400\ \frac{kg}{m^3}$, specific heat capacity $c = 1080\ \frac{Ws}{kg \cdot K}$ and thermal conductivity $\lambda = 2.1\ \frac{W}{m \cdot K}$.
A step response of the model is shown in Figure 2.2; the time constant is approximately 17 hours.

On start-up, the model must be initialised with a starting temperature; it is sufficient to select the same temperature for all nodes in the model. However, no starting value is known during initial commissioning. There are various options for determining the temperature value, which are listed here in ascending order of complexity:

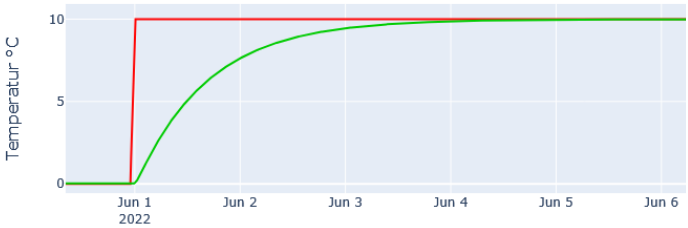

Figure 2.2.: Step response of the thermal model of a concrete component (green). Time constant $\tau \approx 17\ h$

1. Initialisation with a fixed value in the neutral range, e.g. $22.5\ °C$. The advantage of simplicity is offset by the disadvantage that, depending on the actual thermal situation in the room, the model may take up to 10 days to tune.
2. Use of the first measured value to initialise the model. Provided that the room in question is largely in thermal equilibrium, i.e. there is no peak in free heat generation and no short-term cooling (e.g. from opening windows) at the moment in question, this can provide a useful starting value, resulting in a correspondingly shortened tuning time in the range of a few days.
3. Determination of a starting value by aggregating the measured values during a lead time of $24\ h$. Provided that the room is not subject to extreme fluctuations, such a daily value can provide a very good basis for initialising the model, reliably reducing the tuning time to around one day. The aggregation itself can be implemented as an arithmetic mean, which then requires a large memory array for the individual values, or, on limited hardware, via a convolution of the type $t_{m,new} = k \cdot t + (1-k) \cdot t_{m,old}$, where k is the reciprocal of the number of measurements available during a day. For 10-minute values, this results in 144 individual values per day, corresponding to $k = \frac{1}{144}$ or $0.0069\overline{4}$.

In order to avoid these tuning times when restarting the system after shutdown or power failure and to continue operation practically seamlessly, it is advisable to store the respective core temperature in non-volatile memory. It can then be used for initialisation when restarting. Since the core temperature changes very slowly, such a backup is usually sufficient once a day, but can also be performed more frequently. For the same reason, downtimes of up to one day can be bridged almost seamlessly. Only in the event of a longer outage can relevant tuning times

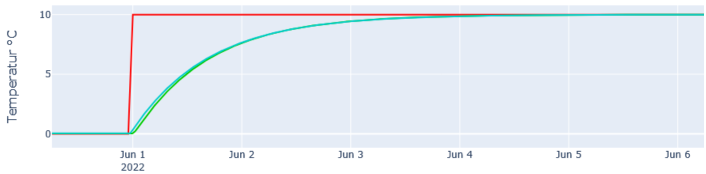

Figure 2.3.: Step response of the thermal model of a concrete member (green) and the result of a convolution over the period of the time constant of 17 *h* (light blue) for comparison.

occur again.

2.3. Approximation of the Core Temperature via Convolution

A particularly easy approximate solution for determining the core temperature can be achieved by convolving the measured values over a period corresponding to the thermal time constant of the simulated concrete component of 17 *h*. (cf Figure 2.2.)
This condition, however, must be strictly adhered to in order for the results to correspond closely to those of the thermal model presented above. The calculation approach using convolution is therefore less robust and flexible with regard to changes in the frequency of the input values. Wherever possible, calculation by thermal model should be preferred.

If the convolution factor is well adjusted, the system behaviour can be reproduced with little deviation, as shown in Figure 2.3.

The convolution is performed as $t_{core,new} = k \cdot t + (1 - k) \cdot t_{core,old}$, where k is the reciprocal of the number of measured values within a 17 h-period.

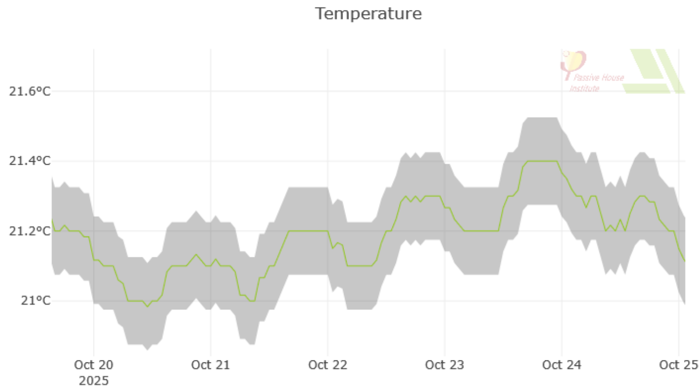

Figure 2.4.: Measured core temperature of a concrete ceiling slab

For 10-minute values (6 values per hour), this results in $17 \cdot 6 = 102$ individual values within the time constant of 17 h, corresponding to $k = \frac{1}{102}$ or 0.009804.

If measured values are available every minute then $17 \cdot 60 = 1020$ individual values are included in the convolution over the time constant and $k = \frac{1}{1020}$ or 0.0009804.

2.4. Refining the Core Temperature to the Thermal Condition

The component core temperature still exhibits slight daily fluctuations in the order of a few tenths of a Kelvin, regardless of whether it is determined by measurement in a borehole or by computation. As Figure 2.4 shows, this amplitude is not large, but it is already in the order of magnitude of a meaningful hysteresis during the transition between operating modes (see Section 2.5). It is therefore necessary to subject the core temperature to further smoothing or low-pass filtering over a daily period. As explained above, a moving arithmetic mean or a convolution approach can be used here, in the same way as described for initialisation.

The smoothed core temperature represents the Thermal Condition of a building as is used for further control purposes.

If several room temperatures are available, in the simplest case, the arithmetic mean of the measured values can be used to feed *one* thermal model and thus calculate a Thermal Condition.
However, if the hardware performance allows it, it is more informative to calculate and display the Thermal Condition for each room individually and only then calculate the mean value for control purposes.
For large buildings with a complex layout or those with very different uses, the Thermal Condition can be determined for each wing and used for control purposes, but in most cases a (weighted) average value may already be sufficient for overall control.

Room temperature and Thermal Condition should always be recorded in order to facilitate systematic operation monitoring.

2.5. From Thermal Condition to Seasonal Mode of Operation

The Thermal Condition has a temperature unit and fluctuates by 5...8 K over the course of the year. This amount is not very large, so the evaluation must be carried out with high resolution.
In the school project mentioned above, three operating modes were derived from the Thermal Condition and used successfully. However, a slightly finer differentiation was already deemed desirable there and is also recommended here. Table 2.1 summarises the recommended modes and the corresponding switching values for the Thermal Condition.

For buildings with typical uses, such as residential, educational and administrative buildings, these values represent a realistic approximation and allow for satisfactory building function. The range of comfortable room temperatures is assumed to be 20...25 $°C$, and deviations from this should only be made in justified cases. The switching values should be easily editable as part of operational optimisation in order to take account of the circumstances of each individual case. The hysteresis should only be set to greater than 0.1...0.2 K in justified exceptional cases. It ensures that no short-term changing classifications are issued even in the threshold range between two operating modes.

Mode	**Thermal Condition** ϑ_{ThC} $[^{\circ}C]$ $(Hysteresis)$
0, Stand-by (Vacation)	$\leq 17.2\,(17.4)$ Heating enable, MVHR off , Shading open
1, Heating	$\leq 20.4\,(20.6)$ Heating enable, MVHR operating, Shading open
2, Neutral Cool	≥ 20.6 Shading open, MVHR operating
3, Neutral Warm	$\geq 22.5\,(22.3)$ Shading closed at $\geq 150\ \frac{W}{m^2}$, MVHR bypass at $\vartheta_{ODA} < \vartheta_{ETA}$
4, Passive Cooling	$\geq 23.5\,(23.3)$ Night ventilation enable, Shading closed at $\geq 150\ \frac{W}{m^2}$, MVHR bypass at $\vartheta_{ODA} < \vartheta_{ETA}$
5, Active Cooling	$\geq 24.5\,(24.4)$ Cooling enable, Shading closed at $\geq 150\ \frac{W}{m^2}$, MVHR bypass at $\vartheta_{ODA} < \vartheta_{ETA}$

Table 2.1.: Modes of operation and exemplary Thermal Condition thresholds

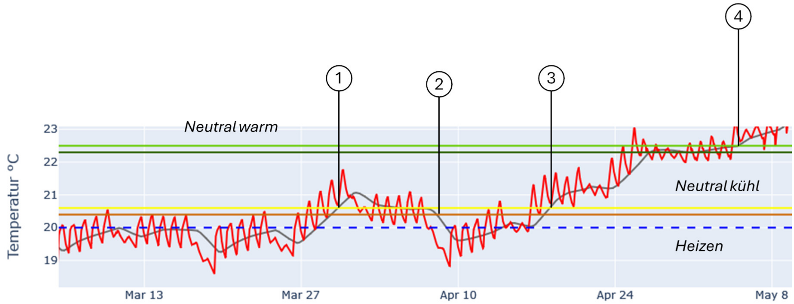

Figure 2.5.: Room temperature (red), Thermal Condition (grey) switching thresholds of operation modes with hystereses (coloured horozontal lines); Set point of the room temperature during office hours (blue, dashed line)

Figure 2.5 illustrates the development of the Thermal Condition (grey) in relation to the switching values for seasonal operating modes with their respective hystereses, compared to the room temperature (red). The example is taken from an office building built to the Passive House standard with regular usage times during working hours on five working days, interrupted by two days at the weekend. These setback phases are clearly visible, but *0, Stand-by* operation is not yet necessary given the shortness of the interruptions. Operating mode *1, Heating*, is abandoned at the end of March in favour of *2, Neutral Cool* (1), but a cold snap causes the building's capacity to cool down, reactivating operating mode *1, Heating* (2). In the second half of April, *2, Neutral cool* is reached again (3). About two weeks later, at the beginning of May, the operating mode changes to *3, Neutral warm* (4).

3. Control Tasks

The availability of measured and calculated values, such as room temperatures and Thermal Conditions across all building automation sectors, including sun protection control, must be ensured in all cases so that seasonally adjusted operation can be achieved easily and reliably. This is usually easy to ensure within cross-trade automation. If a gateway is required for communication between separate systems, a planned emergency function must be activated in the event of device failure to avoid undefined operating states.

Under this condition, the Thermal Condition can enable closed-loop control with reference to the target variable for a number of individual tasks. These and other aspects that are important for buildings constructed to the Passive House standard are summarised below for key control tasks.

3.1. Control Tasks in MVHR systems

MVHR and its seasonally adapted operation are of **vital** importance in a Passive House building. The related control tasks, therefore, are front and centre.

3.1.1. Balanced Operation

Permanently balanced air flows enable high energy savings in the long term through heat recovery. This issue is independent of the Thermal Condition of the building, but is so fundamental to satisfactory building function that it should nevertheless be addressed here first.
Of utmost importance is the balance at the point of passage through the building envelope, which is usually on the outdoor- and exhaust air side. The practically unavoidable deviation from the ideal state must not exceed 10 % imbalance. Due to the similar temperatures of the air flows, a volumetric flow balance is a sufficient approximation to the mass flow balance for practical purposes.
In multi-storey residential construction, attention should also be paid to the balance within the individual residential units. These do not have an effective air connection between them, and local excess supply air cannot therefore be balanced by a neighbouring unit with excess exhaust air, but leads to exfiltration via leaks in the fabric. This can result in moisture-related structural damage and discomfort.
The ventilation unit itself must ensure constant volume flow operation of the fans

based on a suitable measurement. Balanced operation of the ventilation system can then be ensured with the aid of a configuration in which the exhaust air volume flow follows the supply air flow. For operational monitoring, the measured values of the volumetric flows must always be available and recorded. Constant pressure operation of the supply air and exhaust air ducts is not sufficient, as the downstream volume flow limiters do not offer sufficient accuracy and their individual deviations can also add up.

3.1.2. Heat Recovery

The heat recovery function within the ventilation unit with an effective heat recovery rate $\eta_{eff} \geq 75$ % [1] constitutes the key element in thermal protection of the ventilation system and can be regarded as a virtual part of the thermal building envelope. The PASSIVE HOUSE concept assumes, that the heat recovery is continuously active to its full extent during the cold season. The use of the heat recovery precedes the beginning of the heating season and ends a long while after heating has last been put in.

Under normal circumstances, reducing the heat recovery by controlling a bypass damper in plate heat exchangers, regulating the speed of thermal wheels or adjusting the cycle time in storage blocks is expressly *not* a control function for stabilising the room temperature or the supply or exhaust air temperature in a PASSIVE HOUSE. Due to the high thermal inertia of the PASSIVE HOUSE, there is no need for fast control elements of this type. Furthermore, fluctuating room temperatures are necessary in order to utilise free heat: if the use of free heat is continuously reduced by limiting heat recovery, this has a significant impact on the building's energy consumption.

Control of Heat Recovery by Thermal Condition of a Building as the Preferred Method

If the Thermal Condition of a building is known, all conceivable operating conditions can be easily translated into the necessary control instructions for heat recovery.

As long as the Thermal Condition indicates operating modes *1, Heating* and *2, Neutral cool*, heat recovery remains at 100 %. When switching to *3, Neutral warm*, heat recovery can be completely dispensed with from an energy perspective; it then serves only to ensure a minimum supply air temperature of, for example, 16.5 $°C$, if weather conditions require it.

[1] An overview of the requirements for PASSIVE HOUSE-suitable MVHR units can be found in the Certification Criteria

The planning and design prerequisite for such operation, which is based on the energy balance of the building, is draught-free supply air introduction even at temperatures slightly below room temperature, outside the occupied area, i.e. a mixed ventilation concept. Displacement ventilation concepts are usually unfavourable and should be avoided. In PASSIVE HOUSE buildings, high-quality heat recovery of effectively ≥ 75 %, and in most cases today ≥ 80 %, is always used. The difference between the supply air temperature and the room air temperature is therefore regularly only small due to heat recovery alone, and heating of the air is not necessary. However, the supply air distribution still requires careful planning, especially in densely occupied rooms (classrooms, meeting rooms).
Heating the supply air for comfort reasons is only an option with regenerative heat exchangers and very low outside temperatures, and should only be done if the minimum supply air temperature of 16.5 $°C$ can no longer be achieved by the heat recovery alone.

As a rule, the supply air is conveniently blown in above head height and distributed across the ceiling surface by means of the COANDĂ effect. This causes it to mix with the room air and warm up through contact with the ceiling surface. To ensure that the air velocity is dissipated almost completely outside the occupied area , a sufficiently long distance is required, for example a slot outlet across the width of the room and a free flow along the depth of the room. There must be no steps in the ceiling soffit, no perforations and flow obstacles such as transverse luminaires and the like must be avoided. An integrated planning approach is therefore necessary.
Alternatively, supply air can be introduced at minimum local velocity via a textile hose or perforated duct and thus distributed over large areas.

In normal cases, it can be assumed that the air in the room is completely mixed ($\epsilon = 1$), and displacement ventilation is neither possible nor necessary. [2]

Whether further reheating of the supply air for thermostatically controlled room heating is required depends on the building's heating concept. If other heat transfer systems are available, these should generally be used as a priority, as they usually require lower flow temperatures. This applies in particular to radiant heating systems and heat supply via heat pumps.

If the exterior temperature exceeds the room or exhaust air temperature during the warm season (operating modes *3, Neutral Warm* and higher), heat recovery

[2] Rainer Pfluger: „Hocheffiziente Klassenraumlüftung für Passivhaus-Schulgebäude – Lessons learnt“, Protokollband, 26. IPHC, Wiesbaden, 2023, in German

should be fully reactivated in order to reduce the heat load from ventilation.

The logic for heat recovery control based on the requirements described above is illustrated in Appendix B.

Control of Heat Recovery by Centrally Measurable Quantities as an Option for Approximation

If the Thermal Condition of a building cannot be determined, it is not possible to achieve ideal heat recovery control for all situations with certainty. If only centrally measurable quantities are available as input variables for control at the ventilation unit, an approximate solution can be implemented as described below.

1. While the extract air temperature remains below 23 $^{\circ}C$ *and* the 24-hour mean outdoor temperature [3] is lower than 16.5 $^{\circ}C$, the heat recovery operates at 100 %.
2. If one of the conditions is no longer met heat recovery is controlled to maintain a minumum supply air temperature of 16.5 $^{\circ}C$.
3. If the outdoor temperature is greater than the extract air temperature during the warm season the heat recovery comes back at 100 %.

All listed temperature setpoints should be easily editable for optimisation if necessary. A code example for the stated logic is found in Appendix C.

3.1.3. Frost Protection in the Heat Recovery

The issue of frost protection in ventilation units is independent of the Thermal Condition of a building. In regenerative systems, e.g. thermal wheels, it is also mostly negligible in the cool, temperate climate of Central Europe. However, the energy required for frost protection can be relevant for plate heat exchangers without moisture transfer, especially if inadequate controls and control parameters are used. Therefore, this issue will also be briefly addressed here.

For targeted control, it is first and foremost essential to measure the conditions with low measurement uncertainty. Here, too, the long-term goal is to improve standards with $\pm 0.3\ K$ measurement uncertainty for the entire measurement chain. To prevent harmful freezing of the heat exchanger, the outside air is usually preheated. It is in the nature of things that freezing is only physically possible at outside air temperatures below 0 $^{\circ}C$. Preheating of the outside air should also be

[3] For this purpose the outdoor air temperature from an intermittently operating MVHR unit must not be used as it is only valid during operating hours.

adjusted to the critical temperature of the respective heat exchanger. This is usually $\vartheta_{limit} \leq -3\ ^\circ C$, only slightly closer to freezing point in the case of very high heat recovery rates above 85 %. It makes sense to enable preheating only below this limit value in order to keep energy consumption to a minimum and limit the effects of malfunctions in the downstream frost protection control system. Other parameters, such as the current dew point temperature of the extract air, can be incorporated into the control system, but are subject to the non-negligible measurement uncertainties of conventional capacitive humidity sensors. More complex and long-term stable measurement technology, such as measurement via a dew point mirror, is available for the HVAC sector and is an option worth considering for larger systems. If the data from such a sensor is used solely for frost protection control, its operation can be linked to the higher-level activation of frost protection mode, thereby extending its technical service life.

Less commonly, frost protection is provided by a partial bypass on the supply air side, which causes an excess of warm extract air in the heat exchanger, but maintains the overall balance. In this operating state, the supply air must be heated accordingly in order to maintain the minimum supply air temperature. The above applies to the higher-level enabling; the exact control of the outside air bypass damper is otherwise manufacturer-specific.

Unilateral changes in volume flow that lead to an imbalance in the entire ventilation system, for example by throttling the supply air fan, are unsuitable. These increase the heating load of the building and lead to forced infiltration of cold outside air. If the supply air is used to supply heating, this operating mode would also result in increased heat demand coupled with reduced heat distribution capacity.

3.1.4. Intermittent Operation

In most non-residential buildings, such as schools, offices or administrative buildings, the ventilation system is operated intermittently. Air pollution accumulated during the overnight shutdown phase is removed during a pre-flushing time before the start of operation. This usually lasts one hour and can be easily scheduled in advance.

To ensure long term hygienic cleanliness, a filter drying procedure should be carried out before switching off the system in the evening. This involves closing the outside air damper and circulating dry, and if necessary additionally heated, indoor air through the filter. Once the filter is completely dry, the ventilation system can be turned off.

If the selected ventilation unit does not have internal devices for reversing the air flow for filter drying, this must be taken into account in the design by arranging appropriate ducts and dampers.

3.1.5. Air Heaters

In Passive House buildings, high performance heat recovery systems are always used, with most achieving ≥ 80 % efficiency. As a result, the difference between the supply air temperature and the room air temperature is usually minimal due to heat recovery alone, making additional air heating unnecessary. This presents and opportunity to save the costs, pressure loss and control requirements of an air heater altogether.
The operation of an air heater often even has a negative effect, as the unregulated heat input relative to the room temperature leads to overheating of the rooms. Particularly in rooms with a high occupancy (classrooms, meeting rooms), the body heat of the users themselves generates a considerable amount of heat when the rooms are in use, which can be supplemented by significant solar gains, especially on clear, cold winter days.

Heating the supply air for comfort reasons is therefore only an option with regenerative heat exchangers and very low outside temperatures. Operation of the air heater should only be enabled if the heat recovery system is operating at 100 % capacity and a minimum supply air temperature of 16.5 $°C$ can no longer be achieved by heat recovery alone. The power and annual energy consumption required for this very limited purpose are very low.

An air heater is required if the building is to be heated using supply air. In Passive House buildings, this can completely replace other heat distribution systems and, in such cases, represents a particularly cost-effective solution. However, even then, control is purely thermostatic with reference to the room temperature.

3.2. Control Tasks in Heating Systems

3.2.1. Heating Enable

The Thermal Condition of a building is ideal for triggering the activation of the heating system in operating mode *1, Heating*, and deactivating it again once the specified hysteresis has been exceeded. The operation of the corresponding systems can thus be restricted to a narrow time window in which actual heat demand is likely. An advantage is that late cold spells or unexpected usage patterns are also reflected in the Thermal Condition, so that reactivation can occur, e.g. in late spring, without any user intervention being necessary (i.e. a closed-loop control). Due to the thermal inertia of the Passive House, the heating system can – and should – be switched off completely outside of operating mode *1, Heating.* Sudden heat demand is not to be expected.

The heat distribution in the rooms is regulated by thermostats. Conventional thermostats on the flow side can be used, but return temperature limiters (RTL) are an interesting alternative.

3.2.2. Stand-by Mode

In residential buildings, night-time temperature set-back in PASSIVE HOUSES is virtually ineffective due to the large thermal time constant and can be omitted during normal operation. In houses, setting the thermostat lower can reduce the temperature during longer periods of absence (holidays).

In non-residential buildings, a mode *0, Stand-by* of the heating system should ensure a minimum indoor temperature or Thermal Condition of 17 $^{\circ}C$ outside operating hours. A more pronounced set-back could achieve marginally greater energy savings in certain situations; However, in order to ensure sufficiently fast reheating, an uneconomically powerful heating system design is then required. [4]
A cooling rate of $\leq 1\ \frac{K}{d}$ can usually be expected, as illustrated in Figure 2.5; therefore, stand-by mode is generally only relevant during longer interruptions in operation, such as long weekends or holidays.

3.2.3. Power Setting of the Heating System

Conventional outdoor temperature controlled regulation of the heating flow temperature is not advisable in PASSIVE HOUSES, as free heat contributes significantly to offsetting heat losses and the correlation between heat demand and outdoor temperature is very weak.

A much more effective and equally simple approach is to regulate the system temperature according to the building's Thermal Condition. This indicates the order of magnitude of a possible power demand. The concept of the temperature-dependent control curve can be adapted from the outside temperature control, with the Thermal Condition serving as the reference variable instead. The characteristics of the heat transfer system can be taken into account using radiator exponents, and adjustment via slope (factor) and parallel shift (summand) allows

[4] For buildings that meet the Passive House standard, a limit of 20...30W/m^2 for the installed heat generator output has proven effective in intermittent operation. One example are the *Leitlinien zum wirtschaftlichen Bauen* der Stadt Frankfurt, in German and an empirical study from BAHNSTADT in Heidelberg, in German

for easy readjustment to optimise operation. The design case for non-residential buildings is to be expected when the building is reheated after stand-by mode, i.e. at a Thermal Condition of 17 $^{\circ}C$. When the limit temperature for operating mode *1, Heating* is reached, the system temperature reaches its minimum. The logic is demonstrated in Appendix D for a classic control curve with heater exponent.

A control system based on the power consumed would be most aligned to the ideal solution, but is more challenging to implement. Depending on the size and complexity of the building, however, an interesting approximation can be achieved by means of a return temperature control in conjunction with the integration of the mass flow delivered by the controllable heating circuit pump. The installation of a central heat meter is valuable for operational monitoring; it also provides continuous flow, forward/return temperatures and differential as well as power, which can be leveraged for effective control.

3.2.4. Radiant Heating

In buildings constructed to the Passive House standard, radiant heating systems can be an excellent solution for heat distribution at very low flow temperatures, provided they can be installed at a reasonable cost [5] . Under such circumstances, operation with air source heat pumps can still be carried out with high coefficients of performance even in the depths of winter. At the same time, heat can be effectively extracted during the warm season at a flow temperature of 20 $^{\circ}C$ or more without any risk of falling below the dew point. However, two aspects must be taken into account here.

The widespread expectation that underfloor heating will be as noticeably warm as in conventional buildings with poor thermal insulation, will not be met in the same way in highly insulated buildings:
The heating load in a Passive House is approximately 10 $\frac{W}{m^2}$ in the design case, and most of the time significantly less. Under the simplifying assumption that heat transfer to the room occurs purely by radiation and that the entire surface area of the floor is covered by the heating system, an excess temperature of less than 2 K is required for this.
In fact, the area is somewhat less ideally covered by the heat-conducting pipes, but additional heat is transferred by convection— in any case, users do not immediately perceive the heated floor as *warm*. This should be clarified at an early stage.

[5] High investment costs for a heat distribution system are difficult to justify given the low heat demand.

For building services planning, this also means that the flow temperature for such systems can be close to the room temperature.
Local control via return temperature limiters can be a simple and elegant solution.

When radiant heating is provided by concrete core activation, this can usually serve as the primary heat transfer system for winter and summer operation. Direct access to the ceiling's storage mass allows temperature control to be managed independently of the building usage, which may even be advisable. In unfavourably located corner rooms, an additional wall heating system connected to the same heating circuit can be used to cover a slightly higher local heating demand.

If a minimum temperature difference between the flow and return is to be used as a switch-off criterion (e.g. 1 K), high-quality measurement technology is essential. Without it uncertainty ranges of both measurements will overlap preventing a reliable result. High-precision resistance temperature sensors or a bridge circuit connecting both sensors to determine the *temperature difference* alone can be possible solutions here. Alternatively a return temperature control system can be employed that shuts down the pump at marginal mass flow.

In any case, it is far better to be able to measure the charge state of the concrete core using a temperature sensor located between the rows of pipes directly in the centre of the respective control zone and to regulate the heat input (or heat extraction in summer) accordingly. For this purpose, a plastic conduit can be installed horizontally in the ceiling, which makes it possible to insert the sensor during the finishing phase from a corridor zone with a dropped ceiling and to service it at a later date.

Provided that there are no particularly high internal heat loads [6] a simple control strategy in non-residential buildings built to the PASSIVE HOUSE standard for winter and summer can consist of tempering the concrete core, starting at 10 p.m., until the core temperature reaches 22 $°C$. In winter, the heat introduced penetrates the room until the morning hours and ensures a room temperature of 20 $°C$ at the start of operation; as the day progresses, the heat flow from the concrete core decreases, while the free heat covers the heat losses.
In summer, heat is extracted from the concrete overnight, regenerating the storage capacity of the concrete ceiling; this can then absorb the heat loads generated during the day and limit the temperature rise within a comfortable temperature range.

A Thermal Condition can also be calculated from measured room temperatures in the case of concrete core activation of the ceiling and used to control building

[6] Less than 4 $\frac{W}{m^2}$ on a daily average, as is typical for office and administrative buildings and also for educational buildings.

functions. It then indicates the behaviour of a non-activated component under the prevailing conditions.

3.2.5. Heat Pumps

When planning heat pump systems, care should always be taken to ensure that the sink temperature is only differing from the source temperature as far as absolutely necessary at all times, in all operating conditions and for all applications.

The power demand in heating systems fluctuates regularly, and this also applies to buildings that meet the PASSIVE HOUSE standard. In non-residential buildings with intermittent operation, the highest power demands occur briefly during the reheating phase before operation begins.

For economic reasons, output should generally be limited to 20...25 $\frac{W}{m^2}$. The achievable coefficient of performance (COP) depends on the temperature difference of the heat pump process; high system temperatures are required to cover peak loads. Thus each individual case must be assessed to determine whether and under what conditions set-back operation is still advantageous for the total energy requirement. Continuous heating with lower system temperatures and a higher COP is possible in PASSIVE HOUSE buildings without increased total energy consumption, as long as operation interruptions are brief. Night-time set-back is therefore not recommended; only extended periods of inactivity justify a moderate set-back mode. It should be noted that for continuous operation, the installed capacity can be designed for the steady-state condition which can reduce the investment in the heat pump by roughly half.

In order to achieve a thermodynamically favourable heat supply with minimal temperature difference at the heat pump, buffer storage tanks with increased temperature levels should be avoided. If the water content of the heating system is insufficient and they are required as an additional reservoir for defrosting outdoor air heat exchangers, a minimal size is still sufficient. They are not necessary for heating operation, as the building system is inert and thus acts as a storage capacity itself. Short-term, highly fluctuating power demand is not to be expected in PASSIVE HOUSE buildings, and longer response times can be tolerated.

The maximum *stationary* heating load in buildings to the PASSIVE HOUSE standard is approximately 10 $\frac{W}{m^2}$ - but this maximum scenario is rare. Over extended periods, significantly less power is required, as heat loss from the building is largely covered by free heat and active heating is only used to supplement this when necessary.

A heat pump system therefore requires a wide modulation range to avoid cycling, which systematically reduces the achievable COP and causes wear and tear on the equipment. Compressors with inverters can be throttled down to approx. 25 % of their rated output, but this is not always sufficient for low outputs in normal operation. For larger buildings, it is therefore advisable to couple several smaller machines. Commercially available heat pumps usually already have a corresponding control system.

In cases where only two devices are required, it can be advantageous to use an asymmetrical distribution of the total power; a ratio of $\frac{1}{3}$ to $\frac{2}{3}$ is suitable; for example, a total power of 30 kW can be provided by two devices rated 10 kW and 20 kW. In conjunction with a modulation capability of between 100...25 % in each case, any output from 2.5 kW to 30 kW can be achieved without cycling operation. This corresponds to an effective modulation range of 12:1, compared to 8:1 with symmetrical distribution. Switching between the devices requires an appropriate control system, the logic of which is illustrated in Appendix E.

3.3. Control Tasks in Systems for Heat Removal

3.3.1. Cooling of the Thermal Mass via Night Ventilation

The Thermal Condition provides reliable information about the state of the thermal storage masses, which can be used to precisely control heat removal systems. In contrast to control methods based on room temperature, there is no risk of premature heat removal termination or unintended switching to intermittent operation. For example, when cool outside air causes the room air temperature to drop rapidly and significantly, although the building mass has not yet cooled sufficiently. Ventilation openings, window drives or even special exhaust fans are used on the basis of the thermal condition in operating mode *4, Passive Cooling* for as long as is actually necessary for heat dissipation.

If the ventilation system is set up for night-time ventilation to remove heat, its activation first requires a sufficiently large temperature difference between the interior of the building and the outside air. Since the operation of fans introduces heat into the air flow and a more than marginal effect is to be achieved that justifies the energy used to move the air, this temperature difference must be $\vartheta_{thZ} - \vartheta_{AU} \geq 3\ K$, or better still $\geq 5\ K$. Operation takes place, of course, without heat recovery.

A Minimum Supply Air Temperature by Partial Heat Recovery is sometimes required, when heat is to be removed at low outdoor temperatures with the intention to prevent possible dew point issues on the (uninsulated) duct surfaces.

In fact, typical non-residential buildings such as schools and administrative buildings have only minor internal sources of moisture, which are continuously removed by ventilation. In addition, with a high air exchange rate for night-time cooling, the dew point of the indoor air is practically the same as that of the outdoor air. Assuming a heat transfer coefficient of $U = 5.8 \frac{W}{m^2 K}$ for a simple sheet metal duct provides a good approximation of the radiation exchange at a temperature difference of 1 K. Night cooling is only activated if the thermal condition and, with it, the radiation temperature in the room are correspondingly high. This means that the temperature of the duct surface cannot be significantly lower than the room temperature and, at most, a small amount of condensate may occur briefly during start-up. Immediate reheating of the duct surfaces after night ventilation has ended is also ensured. In normal building operation, this issue typically does not pose a problem.

3.3.2. Heat Removal by Active Cooling

If passive measures are insufficient for heat dissipation, or if high outside air temperatures at night (tropical nights) make this impossible, the Thermal Condition may indicate operating mode *5, Active Cooling*. This activates cooling systems that can operate independently of the outside temperature, i.e. chillers or radiant cooling systems connected to groundwater or ground probes. The annual capacity of the latter systems is often limited and can therefore be concentrated on the necessary core period.
A performance adjustment via the flow temperature provided by compression refrigeration systems can be tied to the Thermal Condition similar to the heating control using a control curve, as demonstrated with a simple linear relationship in Appendix D.

3.3.3. IT-Cooling

Smaller server rooms and floor distribution rooms are provided in many non-residential buildings. These rooms generate increased heat loads in relation to their floor space.
In the simplest case, the room can be designed as an extract air room with high air change, overflowing from the adjacent circulation area.
If the heat output is too high for this, recirculating air coolers are required. If there are other relevant cooling requirements in the building, it may be advisable to install a separate hydronic network with the appropriate temperature (e.g. 12 $°C$), but this incurs high distribution losses and costs. In addition, a special drip tray is usually provided in case of leaks in the water circuit, which requires appropriate

drainage.

The room temperature in actively cooled IT-spaces should be set to 26 $^{\circ}C$, which minimises heat load transferred to adjacent rooms in the summer, does not pose a threat to electronic components and allows for some passive heat transfer to the surroundings in the winter.

Alternatively, racks with integrated compression cooling may be used. The condenser can release heat directly to the outdoors or transfer it to the extract air flow of a ventilation system. In this arrangement they can be useful in other parts of the building during the cold season, via heat recovery. In some instances a hydronic heat exchanger may be useful to connect to the return flow of a concrete core activation system.
Larger server plants do require dedicated special planning. The heat released there quickly exceeds any possible heat demand in a Passive House building.

3.4. Control Tasks for Shading Systems

For highly efficient non-residential buildings an expedient operation of the sun protection systems must always be ensured without user intervention and also outside of usage times.
A seasonal adjustment of operating behaviour between winter settings (passive-solar heat gains maximised) and summer settings (solar heat loads minimized) is necessary. As the internal temperatures of a building are critical, shading controls must take these into account.

The Thermal Condition of a building reliably indicates whether further passive-solar heat gain via windows and glazing is desirable or detrimental. In the winter the building is mostly in the modes *1, Heating* or *2, Neutral Cool* and solar gain is welcome. In this situation controls should ensure that all shading devices remain inactive in order to use the solar potential. Only in the event of explicit user intervention a deviation is forced for a limited period of time. A reset to the automatic control must be devised, a period of 1...3 h has proven useful. The exact value is very important for user satisfaction and must be set with regard to the builing's usage, for example the timetable of a school.

Once the mode *3, Neutral Warm* is reached, the requirement is reversed. The shading is closed automatically if $\geq 150\ \frac{W}{m^2}$ ($\approx 15\ kLux$, set value) on the affected facade is exceeded. Again a temporal user override is possible and automatic control should resume after a specified period.

It can be helpful to divide the control zones for the shading devices not only by orientation but also by floors, in order to consider shading effects by surrounding buildings. Users usually react sensitively to sun protection movements that do not appear to be immediately obvious.

For Passive House buildings, only external sun protection systems are sufficiently effective. The sun protection should be designed to operate at wind speeds of up to $\geq 10\ \frac{m}{s}$; the maximum permissible wind speed for each product must be fully utilised through wind monitoring. Wind speed should be measured in the plane of the relevant façade, as wind conditions on the roof are usually not a reliable indicators of the actual threat to the shading devices, and leading to frequent and unnecessary movements. In addition to reducing the effectiveness of sun protection, this often leads to conflicts with users and accelerated wear on the devices.

For non-residential buildings, daylight utilisation should remain possible with activated shading by means of a divided blind. For the utilisation of solar heat in winter, an internal glare protection system that can be activated manually is recommended for non-residential buildings with screen work. Alternatively, a cutoff or retro position for the slats can be programmed. However, this impairs the possibility of solar heat gains and must be evaluated on a case-by-case basis.

4. Energy Efficiency of Building Automation Systems

Building automation no longer yields significant energy savings in Passive House buildings, but it is a functional necessity for building operation. The auxiliary energy requirement is very significant here, among other things because automation systems usually remain in operation permanently, even beyond the building's operation hours. Practical experience shows an electrical power demand of 1...2 $\frac{W}{m^2}$, which might seem low, but due to the size of the buildings and the long periods of time involved, this adds up to a similar amount as the electricity consumption of the actual building use. Energy-efficient operation of automation equipment is therefore important, and energy-saving automation controllers and actuators should be preferred. Discussions are underway to develop requirements within the framework of European ecodesign regulations, but so far (2026) without any operational results.

Energy-efficient, modern switching mode power supplies that are matched to actual loads and compliant with at least Level VI, or better still CoC Tier 2 requirements, should be a standard practice. A smaller number of powerful, well-utilised adapters are more efficient than individual adapters for each device.

However, automation controllers, room control units and sensors themselves are often not optimised in terms of their power consumption; it is worth comparing different devices and requesting precise information from the manufacturers. The decisive factor is not the rated power specified in data sheets for the design of the power supply, but the power consumption in practical operation. Table 4.1 provides guidance for evaluation. The values refer to each function for automation stations, I/O modules, sensors and the like in normal operation.

Assessment	**Power demand incl. power supply per measuring/switching/control function**
very good	0.03 W
good	0.10 W
satisfactory	0.25 W
inadequate	0.50 W
poor	≥ 1 W

Table 4.1.: Preliminary assessment of power consumption per functionality of automation equipment

The same applies to damper drives and other actuators. Their drive function is usually only required rarely and for short periods of time— the decisive factor is consumption in the holding and standby state; the values in Table 4.1 can also be used as a guide for this. Thermal actuators, which rely on a continuous supply of energy through electric heating to maintain their state, perform poorly in this respect. Particularly in the summer, this heat input is also detrimental to thermal comfort.

Conventional relays for switching larger electrical loads offer low electrical resistance on the load side, but they require continuous supply of electrical energy to maintain their switching state. If a load is switched by a relay, a continuous power of 150...1000 mW is used, which contributes to the heating of the control cabinet and increases power consumption. Many devices in building services plant, such as pumps, are in operation for long periods of time, and the holding power of the relay coils alone can add up to significant amounts.

An improvement can be achieved by connecting the relay coil to a capacitor and a resistor in such a way that the charging current of the capacitor is high enough to change the switching state, while only a significantly reduced holding current flows afterwards.

Alternatively, the relay coil can be controlled by a PWM [1] output, which supplies full power for a short time and then reduces it. The advantage of this is that the exact behaviour is defined in software and is therefore easy to adjust.
It is easier to using polarised relays, that feature a permanent magnet in the magnetic part. This reduces the magnetic force to required from the electromagnetic part, allowing a significantly smaller coil to be used with a lower current.
Latching relays require only a current pulse to change their switching state and remain in that state until an opposite pulse is received. No electrical holding power is required. However, in the event of a power failure, no defined state is established, which requires special precautions in safety-critical applications by means of an appropriate additional circuit.
Electronic solid state relays (SSR) can be switched with virtually no power consumption, but conventional silicon-based designs have a high power dissipation of around 3.5 % of the load, which rules them out for continuous applications. Developments in silicon carbide (SiC) semiconductors could bring significant improvements to a few $m\Omega$ in the near future.

Network components and bus systems, as well as repeaters and their power supplies, are also relevant in large buildings. Gateways for linking several different systems may allow separation by trade, thus contributing to clarity in warranty obligations. However, due to their own energy consumption and duplication of infrastructure, such an approach does not promote reliable and economical operation.

[1] *Pulse Width Modulation*

5. Monitoring

Accurate monitoring of building operations is essential for systematically detecting irregularities. Only by understanding the actual operating data can a well-founded assessment of room comfort be made, taking into account user feedback and systematic adjustments of the technical systems in the first years of operation. It is also cruicial for ongoing operational optimisation. Appropriate measuring and metering equipment must therefore be provided on the basis of a pre-defined level of detail for the investigation.

In order to carry out qualified operational monitoring, the collection and permanent storage of the relevant data must be ensured from the outset. Only on the basis of measured values can a malfunction be quickly and accurately detected and rectified.
Long-term data historisation over several years enables systematic comparisons, and the identification of correlations and patterns. Weather parameters, room temperatures and energy meter readings are of primary importance; temperatures and switching states in building services systems are also very helpful. For MVHR systems, air flows and air temperatures, as well as the degree of heat recovery, are significant. A sub-meter for electricity consumption is also easy to install and very helpful for evaluating operating behaviour. Electricity and heat meters must always be installed for heat pumps. It must be clearly documented whether pumps and controls are also included in the electrical sub-metering.

Data should be logged at intervals of 15 *mins*. This balances adequate tracking of dynamic processes with storage space requirements, which, thanks to inexpensive storage media, no longer represent a relevant bottleneck. However, it is important to have a mechanism for regular data backup. The values should be stored individually at regular intervals with time stamps and not only in the event of a change of value (COV). This approach ensures greater security in the event of malfunctions in the data acquisition process itself.
If an in-depth analysis is to be carried out, a simple export option in a CSV format is practical and widely used.

The weather during the period under consideration is an important boundary condition for the quantitative evaluation of energy consumption. It should be clarified at an early stage which source and by what means valid weather data, including global horizontal radiation, can be obtained for the building location. Ground-measured data from weather services should be preferred whenever possible. Otherwise, reanalysis data from weather models is available for any location and any time period, for example via Historical Weather API.

Alternatively, the parameters can be measured on site. However, in many cases, the increased measurement uncertainties should be taken into account, especially for global radiation measurement. Simple radiation sensors with silicon photodiodes are not always suitable for quantitative evaluation, and unlike weather stations, sensors on buildings are not regularly calibrated.

5.1. User Comfort

When a newly constructed building begins operation, there is often a desire for a trial run phase of approximately one month without occupancy. This is intended to facilitate the adjustment of the systems. However, in most cases, construction delays make this impossible, and high cost pressures require the building to be immediately. In this respect, the test run of the building usually takes place in the early phase of occupancy and in parallel with the move-in process. There are high expectations for the new building and its level of comfort and functionality.

Operational monitoring must therefore focus on user comfort in the early stages. As no values are available at the outset, the evaluation of energy consumption data can only begin at a later stage. For this very reason, however, the correct functioning of data collection and the completeness and consistency of the collected data must be checked as early as possible.

Provided that the building envelope has been planned and constructed to a high standard of quality, and the results of the airtightness test comply with the criteria and recommendations for Passive Houses, draughts are not to be expected. The focus of monitoring should therefore be on room air temperature, humidity, and, if necessary, air quality (usually based on the key parameter of CO_2 concentration). The room temperature is representative of thermal comfort, as radiation asymmetries and relevant air velocities do not usually exist. Room air humidity and CO_2 concentration provide valuable information about the functioning of the ventilation system and its adequate adjustment with regard to the number of users: low humidity and CO_2 concentration in winter indicate excessive air volumes, while permanently elevated values indicate insufficient air flow.
If feedback about draughts is nevertheless detected, this is usually due to faults in the ventilation system. In densely occupied rooms in particular (such as classrooms or meeting rooms), disturbances can occur due to the large air volume flows if the air flow has not been carefully planned or has been incorrectly implemented.

Especially in summer conditions, the function of shading devices has a major impact on indoor conditions. The control parameters may need to be adjusted here. However, the control settings should always be checked for plausibility on site before the warm season begins.

If confidence in the building's operating behaviour has already grown and more efficient monitoring is desired, it is helpful to statistically summarise the time series of the individual measured values. Aggregation in box plots with min / max / median / quartiles or presentation in the form of histograms is helpful for quickly reviewing longer data series. The observation periods should be easy and flexible to adjust.

If such monitoring and interpretation of the data is carried out competently and regularly, a well-founded picture of the current building behaviour emerges. User feedback can also be dealt with in a qualified and objective manner. Irregularities are detected at an early stage and their causes can be narrowed down (e.g. by correlation with other measured variables) – for example, if excessive room air temperatures always occur when global radiation is high, indicating that the shading devices are not functioning properly. It is even easier to interpret changes if empirical values from previous years are already available.

5.2. Energy Consumption

Quantitative monitoring of energy consumption requires not only the recording of room conditions and weather parameters, but also knowledge of the energy flows at the balance boundary (building envelope). Even if only existing utility meters are used, it is advisable to carefully consider the arrangement of these metering devices during the planning stage. Possible consumption outside the thermal building envelope of the building in question should be tracked by sub-meters, provided that it is of a relevant magnitude.

In order to interpret the data obtained correctly, additional information is helpful, not least a qualified description of the building services controls, which is updated during all optimisations, as well as the usage times and occupancy. A wiki on the BMS computer could be a pragmatic approach to document the current status in an easily accessible manner. Here, too, systematic data backup should be provided.

A key tool for quantitative evaluation is the energy balance calculation using the Passive House Planning Package (PHPP). This has several advantages:

- The PHPP calculation is already available from the planning stage for Passive Houses
- The PHPP calculation contains a comprehensive characterisation of the building and all energy flows in the balance
- The PHPP calculation provides detailed information about the energy flows to be expected under planning conditions for different energy applications
- The PHPP calculation distinguishes between useful energy and final energy

The completeness and correctness of the PHPP calculation should have been checked by an independent third party during the planning stage as part of a building certification process.

Based on this planning model, a calculation model adapted to the prevailing boundary conditions in the period under consideration allows reliable calculation of the expected energy use. A comparison of these parameters with actual consumption data then provides (within the limits of calculation and measurement accuracies) decisive information on the correspondence between calculated expectations and measured reality.

The influence of various parameters energy use varies depending on the individual building. Thus, targeted operational monitoring is only feasible with such a qualified benchmark. It also provides information on which consumption sectors may have a discrepancy between expectation and reality, how large this discrepancy is and where systematic troubleshooting or operational optimisation should therefore be applied.
Monthly balances, as used as standard in the PHPP, allow for updates at practical intervals.

To this end, the measured values must be preprocessed in order to obtain the necessary input data for the PHPP. At a minimum, the following auxiliary calculations are required:

- Determination of the average building temperature using an area-weighted average
- Creation of a weather data set from the available meteorological variables
- Adjustment of the operating time and occupancy of the building, if different from the planning
- Determination of actual internal heat gains from the presence of people and electricity consumption, taking into account evaporation and drainage losses

From version 10 onwards, the values can be prepared and processed largely directly in the MONI worksheet of the PHPP. A comparison of the calculated expected amounts with the measured consumption values is also carried out automatically and presented graphically. The effect of measurement uncertainties is taken into account by calculating the range of plausible values.

If such an analysis is carried out, at least in the initial period, and no discrepancies occur, it can be assumed with a high degree of certainty that the building is functioning as intended.

The Monitoring Platform of the Passive House Institute (PHI) includes visualisation, statistical pre-evaluation and classification of measured values, as well as automated processing and transfer to the PHPP and the creation of a report. Ideally, this type of evaluation should be integrated into building automation systems so that building operators always have access to up-to-date, reliable information once it has been set up.

6. Further Reading

- Fundamentals of the Passive House Concept
- Overview of Results from Arbeitskreises kostengünstige Passivhäuser Nr. 59, *Die Potentiale der Gebäudeautomation optimal nutzen.* In English
- Protokollband des Arbeitskreises kostengünstige Passivhäuser Nr. 59, *Die Potentiale der Gebäudeautomation optimal nutzen.* In German
- Protokollband des Arbeitskreises kostengünstige Passivhäuser Nr. 52, *Inbetriebnahme und Betriebsoptimierung.* In German
- Protokollband des Arbeitskreises kostengünstige Passivhäuser Nr. 45, *Richtig messen in Energiesparhäusern.* In German
- Feist W. (2007). Ch. D4, *Passivhäuser in der Praxis*, in Bauphysik Kalender 2007: Gesamtenergieeffizienz von Gebäuden, pp. 675-741. John Wiley & Sons, Ltd (2007), In German
- Jürgen Schnieders: „Wirkung von Position und Art der Lüftungsöffnungen auf den Schadstoffabtransport“, Arbeitskreis kostengünstige Passivhäuser Phase III, Protokollband Nr. 23, Einfluss der Lüftungsstrategie auf die Schadstoffkonzentration und – ausbreitung im Raum, S. 85-123, 1. Auflage, Hrsg. Wolfgang Feist, Darmstadt, Juli 2003, in German
- Leitfaden für energieeffiziente Bildungsgebäude, in German

7. Formalia

7.1. Imprint

Wolfgang Hasper
Instrumentation and Controls for Buildings in Passive House Standard
Version February 18, 2026
Typeset with Computer Modern 11p

Passivhaus Institut GmbH
Rheinstraße 44/46
D-64283 Darmstadt
Registergericht: Amtsgericht Darmstadt
Registernummer: HRB 99027
Geschäftsführer:
Jessica Grove-Smith, Jürgen Schnieders, Jan Steiger, Jan Vahala
Tel.: +49 (0) 6151 82699-0
mail@passiv.de
www.passiv.de

7.2. Disclaimer

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A. Calculation of the Thermal Condition

Example code (Python) to calculate the Thermal Condition of a building from measured room temperatures. The resulting core temperature requires additional smoothing over a 24-h period.

```
# Passivhaus Institut GmbH, Wolfgang Hasper, 2026

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# A dynamic resistor-capacitor (RC-) model of a massive concrete member
# to approximate the concrete core temperature from measured
# room temperatures as are usually available in building automation systems
# in order to save the spending on dedicated concrete core temperature sensors.
# The synthetic concrete core temperature presents a useful form of low pass filter, the
# result indicates the thermal condition of the
# building and can hence be used to control systems accordingly.
#
# Assumptions:
# Over long periods of time equalised radiative temperature within the
# entire room can be assumed for well-insulated buildings ("thermal short-circuit"):
# The radiative heat exchange between room-defining surfaces (~5.8 W/K) dominates any
# other heat transferring processes.
# Hence the assumption room temperature = surface temperature of the concrete member is a justified
# approximation.
# This eliminates all complications of the variable convective heat transfer coefficient.
# The model is further symmetric.
#
# The model considers 5 layers of reinforced concrete
# and 1 unit area (1m²)
# The innermost node is the symmetry point (index 5)
#
# density       rho             kg/m³
# spec capacity c               Ws/(kgK)
# conductivity  LAMBDA          W/(mK)
# heat flux     Q               W
# conductance   L               W/(m²K)
# capacity      C               Ws/(Km²)
# total nodes   N               -
# node          n               -
# time step     DT              sec
# layer thickness               m
# Room temp.   tr               °C
```

```
# start conditions:
# temperature within neutral band to ensure a reasonable start
# in summer or winter

# room temperature tr is fed into the function in regular intervals
def RCmodel(tr):

    # constants
    RHO = 2400
    C = 1080
    LAMBDA = 2.1
    D1 = 0.025
    D2 = 0.025
    D3 = 0.025
    D4 = 0.025
    D5 = 0.025

    # surface heat transfer coefficient, approx. 5.8 W/(m²K) radiative,
    # convective disregarded as highly depending on direction of heat flow
    L0 = 5.8

    L1 = LAMBDA / D1 # W/(m K) * 1/m  = W/(K m²)
    L2 = LAMBDA / D2
    L3 = LAMBDA / D3
    L4 = LAMBDA / D4

    # symmetry / adiabatic boundary
    # L5 = 0

    # area specific capacity of each layer
    C1 = D1 * RHO * C # m * kg/m³ * Wsec/(kgK) = Wsec/(m²K)
    C2 = D2 * RHO * C
    C3 = D3 * RHO * C
    C4 = D4 * RHO * C
    C5 = D5 * RHO * C

    DT = 60 # Internally the model operates on a 60 sec timestep, for reasons of numerical stability

    # Model geometry:
    #                      q1         q2        q3        q4        q5        q6 = 0 = symmetry

    # Room temperature tr -L0 -  C1 - L1 - C2 - L2 - C3 - L3 - C4 - L4 - C5 - L5
    #                            t1        t2        t3        t4        t5
    #
    # The temperature t5 of C5 is the desired result

    global t1
    global t2
    global t3
    global t4
    global t5

    # loop the model for the number of 60-sec time steps that fit the room temperature data interval
    # e.g. for a 10 minute room temperature data interval this will be 10 loop cycles (0...9)
    for x in range (9):
        #n = 1
        q1 = L0 * (tr-t1) + L1 * (t2-t1) # W/(K m²) * K = W/m²
        q2 = L1 * (t1-t2) + L2 * (t3-t2)
        q3 = L2 * (t2-t3) + L3 * (t4-t3)
        q4 = L3 * (t3-t4) + L4 * (t5-t4)
        q5 = L4 * (t4-t5)

        t1 = t1 + (q1/C1 * DT) #  W/m² * m² K/(W sec) * s = K
        t2 = t2 + (q2/C2 * DT)
        t3 = t3 + (q3/C3 * DT)
        t4 = t4 + (q4/C4 * DT)
```

```
        t5 = t5 + (q5/C5 * DT)

    return t5

# for control applications best use a 24 hour running mean of t5 / the thermal condition, in order to
# smooth out the slight diurnal cyle}
```

B. Heat Recovery Control, Preferred Variant

Example code (Python) for the control logic of the heat recovery in MVHR for PASSIVE HOUSE buildings. The seasonal adjustment is made according to the Thermal Condition of the building.

```
# Passivhaus Institut GmbH, Wolfgang Hasper, 2025

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# You should have received a copy of the GNU General Public License along with this program.
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# A mock-up of heat recovery (HR) controls suitable for application in MVHR for Passivhaus buildings.
# This code snippet can be used as a template for the actual control logic but as-is is only inteded
# to highlight the algorithms and interactions / cases.

# intended to be run cyclic every one minute

# constants
NEUTRAL_WARM = 22.5
MIN_SUP = 16.5
MAX_ROOM = 25.0

# input variables
# main governor is the Thermal Condition of the building [°C] measured in the core
# of the structure or calculated from measured room temperatures
thC = 22.0
# auxiliary governors are supply air temperature (sup), outdoor air temperature (oda)
# and extract air temperature (eta), [°C]
sup = 19.5
oda = 12.0
eta = 23
# EDIT the above values to study the controller output for certain sets of boundary conditions
# In a real-world application these quantities are, of course, continuosly measured.

# output variables
# initialised to pragmatic values on startup:
heatRecoveryPercent : int = 100
heatRecoveryComfort : int = 0

# loop the controller a few times to illustrate behaviour.
# This FOR loop is not applicable in the normal, cyclic controller.
for x in range (110):

    # full HR while building is not warm:
    if thC < NEUTRAL_WARM and eta <= MAX_ROOM:
        heatRecoveryPercent = 100
```

```
# cover the unlikely event that eta temperature (as proxy of instant room temperature) rises
# beyond comfortable range in the winter, as might happen with exceptionally much free heat.
# simple linear control should do (more sophisticated optional):
elif thC < NEUTRAL_WARM and eta > MAX_ROOM:
    heatRecoveryPercent -= 1

# no HR once the building is warm:
elif thC >= NEUTRAL_WARM and oda <= eta:
    heatRecoveryPercent = 0

# employ HR when it is hot outside to reduce ventilation heat load:
elif thC >= NEUTRAL_WARM and oda > eta:
    heatRecoveryPercent = 100

# finally, always ensure a minimum sup temperature, for comfort reasons,
# again a simple linear control should suffice (more sophisticated optional):
if sup < MIN_SUP:
    heatRecoveryComfort +=1

# HR cannot rise beyond 100% or below 0%
if heatRecoveryPercent > 100:
    heatRecoveryPercent = 100
elif heatRecoveryPercent < 0:
    heatRecoveryPercent = 0
if heatRecoveryComfort > 100:
    heatRecoveryComfort = 100
elif heatRecoveryComfort < 0:
    heatRecoveryComfort = 0

# comfortable SUP temperature takes priority:
if heatRecoveryComfort > heatRecoveryPercent:
    heatRecoveryPercent = heatRecoveryComfort

# now the value of heatRecoveryPercent is our desired output:
print (heatRecoveryPercent)
```

C. Heat Recovery Control, Alternative Variant

Example code (Python) for the control logic of the heat recovery in MVHR for Passive House buildings. The seasonal adjustment is made via a running average of the outdoor temperature and the extract air temperature.

```
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# If not, see <https://www.gnu.org/licenses/>.

# A mock-up of heat recovery (HR) controls suitable for application in MVHR for Passivhaus buildings.
# This code snippet can be used as a template for the actual control logic but as-is is only inteded
# to highlight the algorithms and interactions / cases.

# intended to be run cyclic every one minute

# constants
ETA_MAX = 23
SUP_MIN = 16.5

# input variables
# one governor is the 24-h running mean of the outdoor temperature
meanOutTemp = 13
# auxiliary governors are supply air temperature (sup), outdoor air temperature (oda)
# and extract air temperature (eta), [°C]
sup = 18
oda = 9.0
eta = 21.4
# EDIT the above values to study the controller output for certain sets of boundary conditions
# In a real-world application these quantities are, of course, continuosly measured.

# output variables
# initialised to pragmatic values on startup:
heatRecoveryPercent : int = 100
heatRecoveryComfort : int = 0

# loop the controller a few times to illustrate behaviour.
# This FOR loop is not applicable in the normal, cyclic controller.
for x in range (110):

    # full HR while building is not warm and cold weather prevails:
    if eta < ETA_MAX and meanOutTemp <= 16.5:
        heatRecoveryPercent = 100

    # cover the unlikely event that eta temperature (as proxy of instant room temperature) rises
```

```
# beyond comfortable range in the winter, as might happen with exceptionally much free heat.
# simple linear control should do (more sophisticated optional):
elif eta > ETA_MAX:
    heatRecoveryPercent -= 1

# employ HR when it is hot outside to reduce ventilation heat load:
if meanOutTemp > 16.5 and oda > eta:
    heatRecoveryPercent = 100

# finally, always ensure a minimum sup temperature, for comfort reasons,
# again a simple linear control should suffice (more sophisticated optional):
if sup < SUP_MIN:
    heatRecoveryComfort +=1

# HR cannot rise beyond 100% or below 0%
if heatRecoveryPercent > 100:
    heatRecoveryPercent = 100
elif heatRecoveryPercent < 0:
    heatRecoveryPercent = 0
if heatRecoveryComfort > 100:
    heatRecoveryComfort = 100
elif heatRecoveryComfort < 0:
    heatRecoveryComfort = 0

# comfortable SUP temperature takes priority:
if heatRecoveryComfort > heatRecoveryPercent:
    heatRecoveryPercent = heatRecoveryComfort

# now the value of heatRecoveryPercent is our desired output:
print (heatRecoveryPercent)
```

D. Control of Flow Temperature

Example code (Python) for the logic of the controls for flow temperature setpoint for heating and cooling in Passive House buildings.

```
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# A mock-up of the logic for flow temperature setpoints suitable for Passivhaus buildings.
# This code snippet can be used as a template for the actual control logic but as-is is only inteded
# to highlight the algorithms and interactions / cases.

'''
modes of operation as per Thermal Condition:

0, Stand-by (Vacation)     17.2 (17.4) Heating enable

1, Heating                 20.4 (20.6) Heating enable

2, Neutral Cool            20.6 Shading open, MVHR operating

3, Neutral Warm            22.5 (22.3) Shading closed at  150 W/m2
                                        MVHR bypass at ODA < ETA

4, Passive Cooling         23.5 (23.3) Night ventilation enable,
                                        Shading closed at  150 W/m2
                                        MVHR bypass at ODA < ETA

5, Active Cooling          24.5 (24.4) Cooling enable
                                        Shading closed at  150 W/m2
                                        MVHR bypass at ODA < ETA
'''
tank = 22.5 # setpoint neutral init value
# EDIT the following to play around
thC = 20.0 # current Thermal Condition
mode = 1 # manual setting here for demonstration

# stand-by mode
if mode == 0:
    tank_min = 30.0
    tank_max = 45.0
    thC_min = 16.5
    thC_max = 17.4

    tank = (( tank_min - tank_max) / (thC_max - thC_min)) * (thC - thC_min) + tank_max

    if tank > tank_max: # cap temp, for safety
        tank = tank_max
    elif tank < thC_min:
        tank = thC_min
```

```
# heating mode
if mode == 1:
    tank_min = 30.0
    tank_max = 55.0
    thC_min = 17.2
    n = 1.33 # heater exponent
    P = 0 # parallel shift
    S = 2 # slope
    roomT = 20.0 # room temp setpoint

    # linear control
    # tank = (( tank_min - tank_max) / (thC_max - thC_min)) * (thC - thC_min) + tank_max

    # classic exponential control
    tank = roomT + P + (S * ((tank_max - roomT) * ((roomT - thC) / (roomT - thC_min)) **(1/n) ))

    if tank > tank_max: # cap temp
        tank = tank_max
    elif tank < tank_min:
        tank = tank_min

# neutral modes
if mode > 1 and mode < 5:
    tank = thC # neutral value; better switch off systems!

# cooling mode
if (mode == 5):
    tank_min = 12.0
    tank_max = 18.0
    thC_min = 24.5
    thC_max = 25.5

    tank = (( tank_max - tank_min ) / ( thC_min - thC_max )) * (thC - thC_min) + tank_max

    if tank < tank_min: # cap temp
        tank = tank_min
    elif tank > thC_max:
        tank = thC_max

print("The flow temperature setpoint is :",round(tank,2)," °C")
```

E. Control of an Asymmetric Heat Pump Cascade

Example code (Python) for the logic of the controls for an asymmetric cascade of two heat pumps for PASSIVE HOUSE buildings.

```
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# A mock-up of the logic for asymmetric heat pump controls suitable for Passivhaus buildings.
# This code snippet can be used as a template for the actual control logic but as-is is only inteded
# to highlight the algorithms and interactions / cases.

# intended to be run cyclic every one minute

# constants
# heat pump rated thermal output, inverter controlled 100...25%
HP1MAX = 20 # kW
HP2MAX = 10 # kW
LOADCAPFACTOR = 0.85 # prefer loading slightly below max

hp1Percent = 0.0
hp2Percent = 0.0

powerDemand = 18
# kW or equivalent flow temperature in a real system, EDIT to play around

if powerDemand <= HP2MAX * LOADCAPFACTOR:
    hp1Percent = 0
    hp2Percent = powerDemand / HP2MAX * 100

if powerDemand > HP2MAX * LOADCAPFACTOR and powerDemand <= HP1MAX * LOADCAPFACTOR:
    hp1Percent = powerDemand / HP1MAX * 100
    hp2Percent = 0

if powerDemand > HP1MAX * LOADCAPFACTOR and powerDemand <= HP1MAX * LOADCAPFACTOR + HP2MAX * LOADCAPFACTOR:
    hp1Percent = HP1MAX * LOADCAPFACTOR / HP1MAX * 100
    hp2Percent = (powerDemand - HP1MAX * LOADCAPFACTOR) / HP2MAX * 100
    if hp2Percent < 25:
        hp2Percent = 25
        hp1Percent = (powerDemand - HP2MAX * hp2Percent / 100) / HP1MAX * 100

if powerDemand > HP1MAX * LOADCAPFACTOR + HP2MAX * LOADCAPFACTOR:
    hp1Percent = 100
    hp2Percent = (powerDemand - HP1MAX) / HP2MAX * 100


print("hp1Percent: ")
```

```
print(hp1Percent)

print("hp2Percent: ")
print(hp2Percent)
```