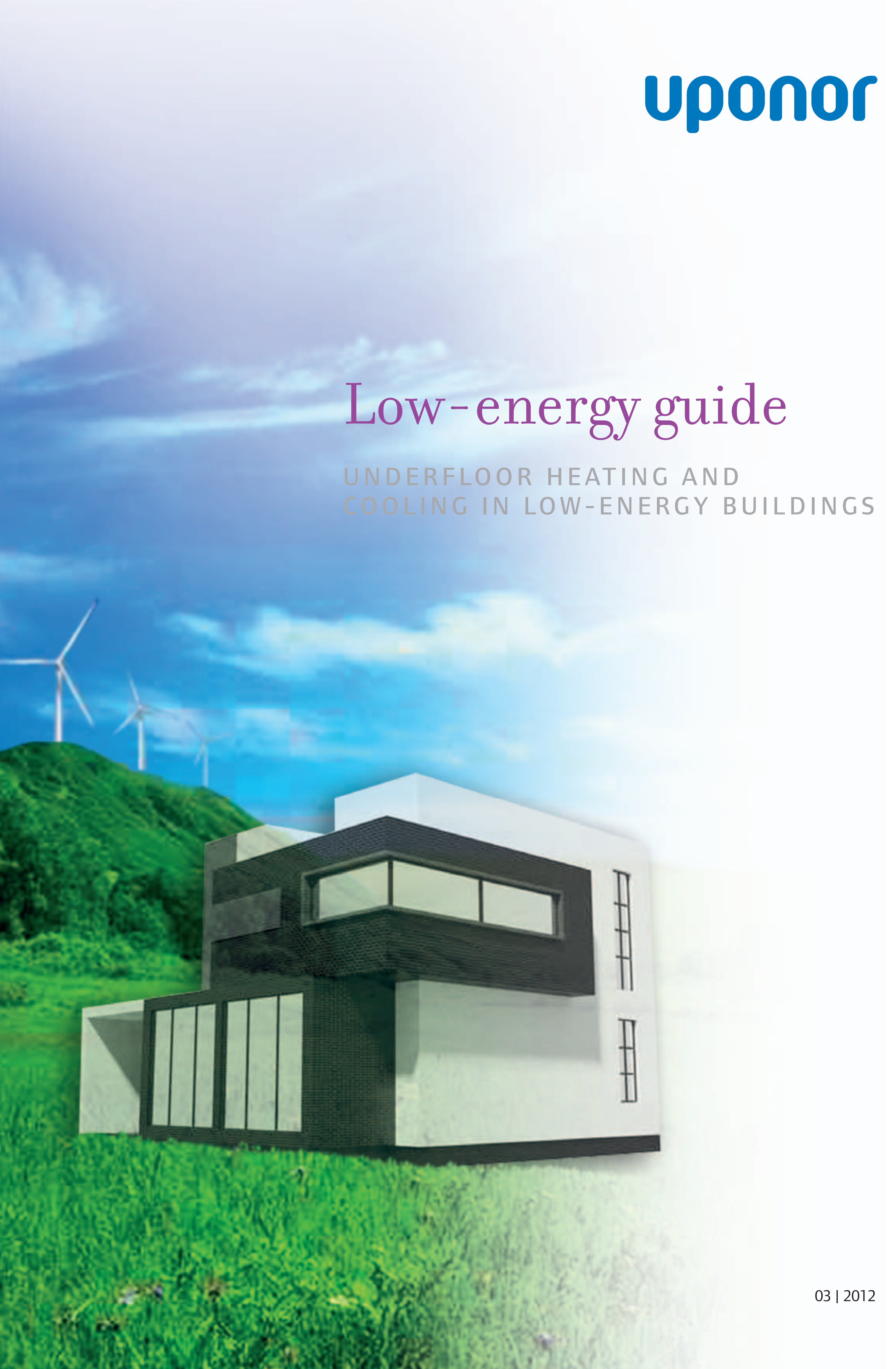

uponor

Low-energy guide

UNDERFLOOR HEATING AND COOLING IN LOW-ENERGY BUILDINGS

03 | 2012

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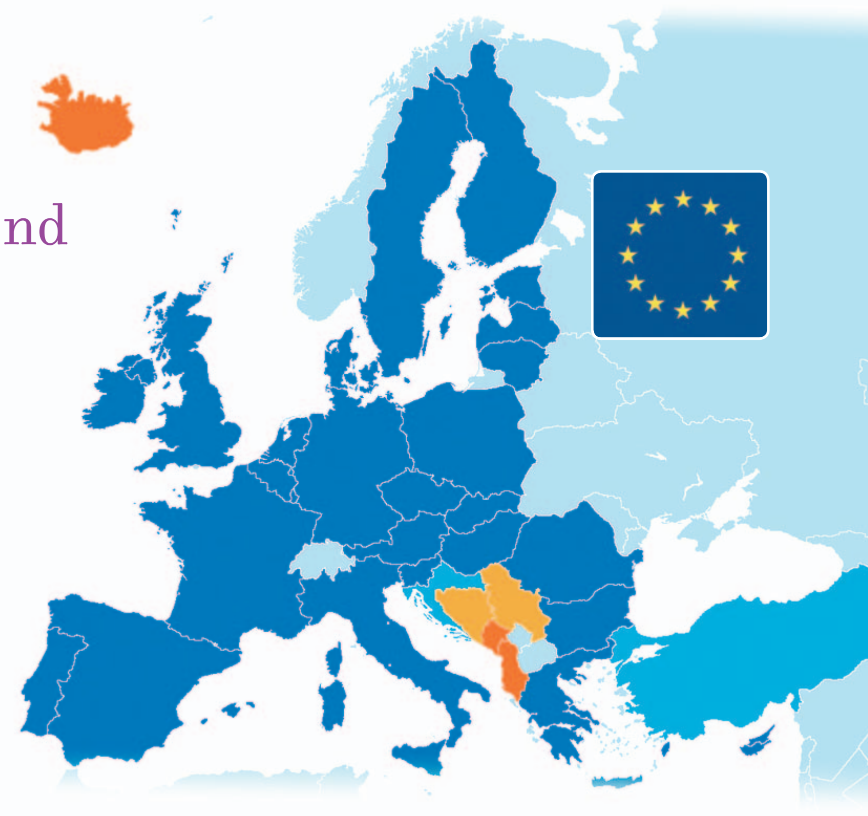
1. The low-energy trend



The building sector accounts for 40% of EU's energy use and 36% of the CO_2 emissions. More than 90% of the environmental impact from a building is from its energy use (heating, cooling, ventilation and lighting).

Improved energy efficiency is essential for both reducing costs, improving competitiveness, securing future supply and for meeting the commitments on climate change stipulated under international agreements.

The European 20-20-20 plan envisages the following goals to be achieved by the year 2020:

- 20% cut in EU's greenhouse gas emissions
- 20% energy share from renewable sources
- 20% increase in energy efficiency

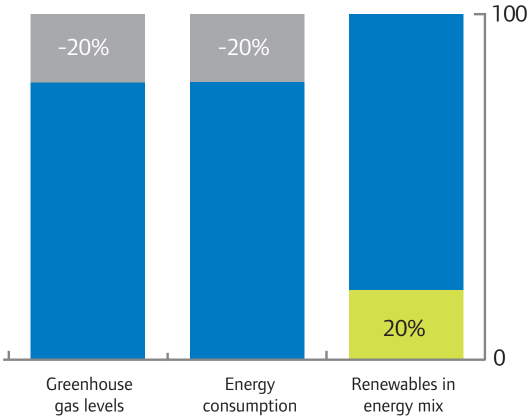


Figure 1.1: The 20-20-20 EU policy by 2020.

European regulations

The European Energy Performance of Buildings Directive (EPBD) from 2002 and its addendum from 2010 requires that every member state establish a plan to deliver very low-energy homes as an essential measure for reducing energy consumption and CO_2 emissions in the building sector. Energy performance requirements are introduced both for new buildings and for existing buildings that undergo major renovation.

In addition, the EPBD stipulates that planning of the heating and cooling supply shall be done with preference to decentralised energy supply systems based on renewable energy, cogeneration, heat pumps and district or block heating/cooling. Furthermore assessment of electrical performance shall be done with a conversion factor (penalty factor) that takes into account the appropriate fuel mix in the respective markets/countries.

The EPBD aims to promote cost-effective improvement of the overall energy performance of buildings, while taking into account local conditions and requirements. The directive sets the basic principles and requirements and leaves significant room for the European member states to establish the concrete mechanisms and numeric requirements and ways to implement them.

The EPBD recast of May 2010 introduced nearly zero energy buildings (nZEBs) requiring that all new buildings in member states shall be nZEB from 31 December 2020, and that public buildings shall lead the way and be nZEB from 31 December 2018.

What is a low-energy building?

Low-energy construction typically implies space heating requirements below 20-30 kWh/m^2 per year. But different definitions exist and different approaches will be taken and adapted in national building codes.

A zero energy building is most often defined as a building with zero net energy consumption and zero net carbon emissions. The term nZEB developed within the EPBD means a building that has a very high energy performance and requires the calculation of a primary energy indicator. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

In all European countries the implementation of strict energy requirements in national building codes is advancing at fast pace in order to meet nZEB targets. In addition to the official national building regulations, a number of volunteer labelling schemes exist. This includes concepts like passive house, energy plus house, active house and many more.

The Danish building code

The requirements for new construction and building renovation is laid down in the The Danish building regulations (BR10), and the related calculation procedure is described in SBi directive 213. This publication also includes the PC calculation program Be10. The implementation is under the responsibility of the Danish Energy Agency (Energistyrelsen) and of the Danish National Agency of Enterprise and Construction (Sbi).

Figure 1.2: Screen capture from the PC calculation program Be10.

The Danish building code (BR10) provides an overall framework that covers the building's overall need for energy input for heating, ventilation, cooling and hot water. The net energy demand is weighted by a primary energy factor. Heating (natural gas, oil or district heating) has a primary energy factor of 1, but a factor of 0.8 can be used for district heating for buildings fulfilling class 2015. Electricity has a primary energy factor of 2.5.

For space heating, the building code operates with maximum energy consumption based on a fixed element plus a variable element depending on the heated space. The standard regulation 2010 (standard BR10) stipulates a maximum energy consumption of (52.5 + 1650/A) kWh/m^2 per year and the low energy class 2015 stipulates a maximum energy consumption of (30 + 1000/A) kWh/m^2 per year, where A is the heated space in m^2 (gross floor area measured outside the external walls).

Residential standard	$\left(52.5 + \frac{1\,650}{A}\right)$	**kWh/m² per year**
Low energy class 2015	$\left(30 + \frac{1\,000}{A}\right)$	**kWh/m² per year**

Table 1.1: Energy frames for new construction. A is the area of the heated space.

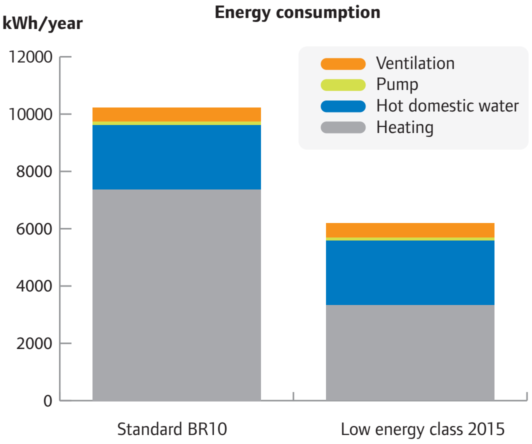


Figure 1.3: Typical distribution of the energy consumption in new dwellings according to the Be10 energy frames.

Requirements to the building envelope

In addition to energy frame for space heating, the Danish building code also sets requirements for the maximum allowed transmission losses through the building envelope. This is to ensure that the building envelope as a whole is designed with reasonable insulation. The transmission loss is calculated including all thermal bridges, which also includes the joints between windows/doors and walls.

Building	BR10 standard [W/m² envelope]	BR10 low energy class 2015 [W/m² envelope]
1 floor	5	4
2 floor	6	5
3 or more floors	7	6

Table 1.2: Maximum transmission loss through the building envelope.

Requirements to the building tightness

The building code sets requirements to the building air tightness. This is to ensure minimum heat loss from unwanted air leaks in the building.

The requirement is that the air exchange through leaks in the building envelope must not exceed 1.5 l/s per m² heated surface area by a pressure testing at 50 Pa. The air leak is determined with a blower door test and calculated as the average of measurements of over-and under pressure.

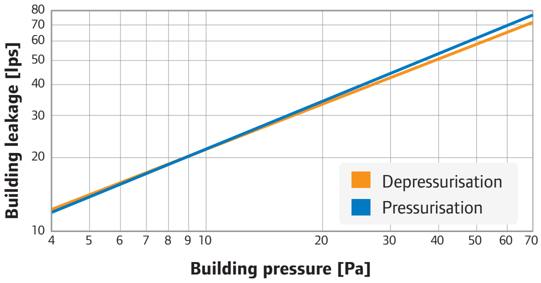


Figure 1.4: Pressure test conducted according EN 13829 with blower door equipment.

Requirements to installations

In addition to the building envelope requirements, the building codes also puts down specific requirements to the technical installations such as pumps, boilers, heat pumps as well as the heat loss from piping and auxiliaries.

Requirements for boilers (< 400 kW)

The efficiency requirements for oil and gas boilers mean that only condensing boilers can be installed in new dwellings and when renovating existing installations.

Oil boilers:	Minimum efficiency of 93% at full load and 98% at part load.
Gas boilers:	Minimum efficiency of 96% at full load and 105% at part load.

Requirements for mechanical ventilation

The building code defines a minimum efficiency for heat recovery and sets down max energy consumption requirements for balanced ventilation as well as exhaust ventilation.

Heat recovery efficiency minimum 80%

Max power consumption for air transport, SEL:

- Balanced ventilation 1000 J/m³
- Exhaust ventilation 800 J/m³

Requirements for pumps

Circulation pumps must have energy label A or equivalent. The electricity consumption of pumps is determined at nominal conditions and all pumps installed must be included in the calculation.

Requirements to the heat loss from installations and auxiliaries

The heat losses from pipes, tanks, heat exchangers, aggregates and similar are determined according to DS 452.

The heat loss from pipes is calculated according to EN 15316 part 2.3 and part 3.2. The heat loss from pipes within the building envelope is not included as a loss, as this is assumed contributing to the building net energy demand. The same rule is applied for the heat loss from ventilation ducts and aggregates within the building envelope.

Material	Thermal conductivity λ [W/(m·K)]
PB pipe	0.22
PP pipe	0.22
PE-X pipe	0.35
Low-density polyethylene (LDPE)	0.31
High-density polyethylene (HDPE)	0.42
Steel pipe	52
Copper pipe	390
Stainless steel (AISI 202)	17
Red brass (85% Cu,15% Zn)	159

Table 1.3: Thermal conductivity for different pipe material, applicable for calculating pipe heat loss.

2. Energy generation and distribution (Denmark)

A proper and correct design of a low-energy building is of course dependant on its geographical location and the available infrastructure and energy sources. In order to have the best possible performance in terms of energy efficiency, the local legal framework and the possibilities for collective as well as individual energy supply solutions should be assessed to valuate the financial and environmental impact.

The Danish energy system

The Danish energy system for electricity and heating is based on a multi-fuel strategy including coal, natural gas, oil and renewable energy sources such as wind, waste and biomass. Co-generation (CHP) of heat and power plays a vital role in the energy system and more than half of the households are being supplied with heat from a district heating system. A natural gas system covers about 20% of the domestic heat consumption and the remainder is supplied by individual heat sources.

Collective systems for domestic heating are largely dominant and low energy design needs to be adapted accordingly. In most areas with district heating there is an obligation to connect to the network but in some cases alternative solutions with individual renewable energy supply can be pursued. Alternative solutions to public supply include solar, heat pumps and individual biomass boilers based on wood pellets or straw.

Power generation mix

The mix of fuels used for electricity production is relevant for assessing the environmental impact of electricity used in heat pumps and auxiliary components such as circulation pumps.

The average fuel mix in Danish power generation is 44% coal, 20% natural gas, 2% oil and 34% waste and renewable energy (2010 figures). The renewable components includes wind, biomass, biogas, waste, straw, wood and very small contribution from solar and hydro power. Due to the relatively high share of fossil fuel, the average CO_2 contents for the fuel mix is about 59 kg/GJ which corresponds to an emission of about 146 kg/GJ (526 kg/MWh) at the end user level.

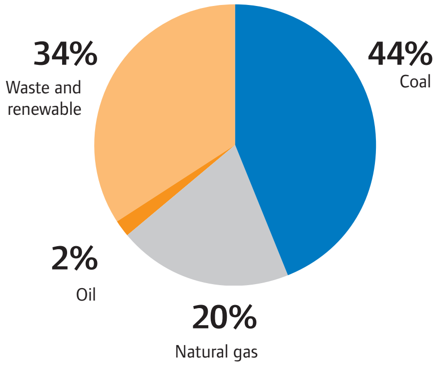


Figure 2.1: Electricity generation mix Denmark 2010.

	Share of power production 2010		CO_2 content [kg/GJ]	CO_2 emission [kg/GJ]
	TJ	%		
Oil	2 680	1.9	78	1.50
Natural gas	28 471	20.4	57	11.62
Coal	61 114	43.8	95	41.59
Waste and renewable	47 347	33.9	0	0
Total	139 613	100.0		54.71

Collective heat supply

Heat supply for domestic space heating in Denmark is predominantly district heating and natural gas. The district heating networks cover large parts of the primary urban areas, covering 46% of the total heat supply and including 60% of the households. The natural gas network supplements the district heating and covers about 20% of the total heat demand. The remaining part of the country belongs to the so-called area IV with individual heat sources such as oil fired boilers, biomass and new emerging renewable energy sources including solar and heat pumps.

The district heating fuel mix is predominantly waste heat from electricity production (CHP plants), biomass, surplus heat from waste incineration and industrial waste heat. The fuel mix and full allocation from the CHP production results in a total fuel mix of district heating fuel mix of 24% coal, 30% natural gas, 3% oil and 43% of renewable and waste energy.

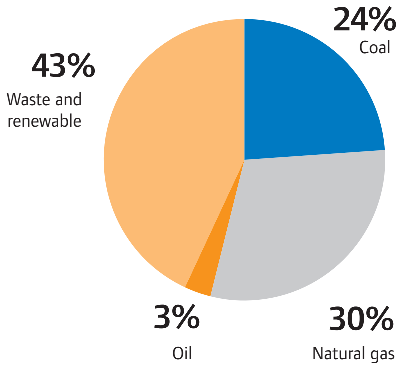


Figure 2.2: District heat generation mix Denmark 2010.

End-user heat supply

The annual Danish heat demand amounts to a total of approximately 59 TWh. The group IV household's outside the supply grids for district heating and natural gas accounts for about 20 TWh (33%). The present legislation prohibits the use of direct electricity for space heating in new residential dwelling and gives incentives to the installation of heat pumps, biomass and solar.

Due to the fuel mix in the electricity supply, the use of direct electricity for space heating results in a CO_2 emission of 30 kg/MWh. Heat pumps are stipulated as a good alternative to both oil boilers and direct electricity, but it's important that the heat pumps have an adequate COP and seasonal performance factor in order to ensure reduction in energy consumption and CO_2 emissions.

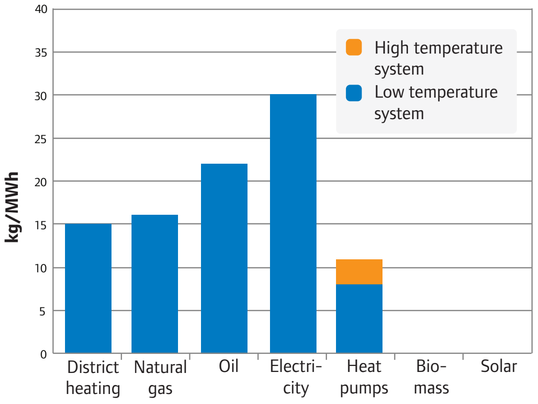


Figure 2.3: CO_2 emission from different heat sources.

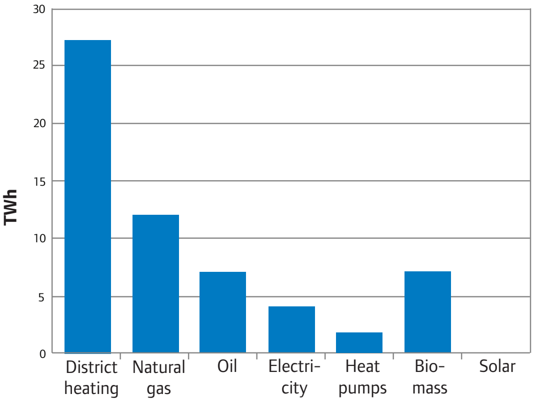


Figure 2.4: Annual heat supply from different sources.

3. Domestic energy sources

The choice of energy source is naturally a key decision for energy efficiency, primary energy consumption and the overall environmental impact of any building. The energy source often represents a relatively big investment and must be evaluated taking into consideration the total building design, including insulation standard, emitter system and available energy infrastructure and cost.

Heating of single family homes have traditionally been done with fossil fuels, such as oil or gas, using individual boilers. Alternatively the public energy infrastructure has provided the required energy as district heating or as electricity applied for direct electrical heating.

In low-energy homes the aim is to lower the energy demand and use renewable sources instead of fossil fuels. Typically heat pumps are applied instead of conventional energy sources. Some national legislation completely prohibits new build installation of individual oil and gas boilers already from 2012.

The European legal framework provided by the EPBD gives preference to heat pumps, district heating or cooling (particularly where it is based on renewable sources), cogeneration and decentralised supply systems based on renewable sources.

The present chapter focus primarily on various heat pumps installations which are typical for new built low-energy houses. In addition, optimal operation of heat supply from district heating system and traditional boilers is illustrated.

Heat pumps

Heat pump technology is widely used in low-energy houses and is an important way to reduce the primary energy consumption. A heat pump is a machine that moves heat from a location (“the source”) at a low temperature level to another location (“the sink”) at a higher temperature level. In this way the heat can be used for e.g. space heating.

To run the process, the heat pump requires supply of additional energy. For a compression heat pump the additional energy is the electricity required to run the compressor. Despite the need for additional electrical energy, a major part of the heat pump energy output can be considered renewable, due to the fact that energy is extracted from the source which can be for example air, ground and water or exhaust air from a ventilation system.

Some heat pumps are designed only to provide heating, but many models can provide both heating and cooling simply by using a reversing valve for the refrigeration cycle. This is called active cooling. Alternatively a heat pump installation, that uses ground coupled pipes as source, can be used for cooling simply by using the cold ground water directly for cooling purposes. This is called passive cooling.

Efficiency of heat pumps

The efficiency of a heat pump is defined by the so-called Coefficient of Performance (COP):

$$\mathrm{COP} = \frac{\Delta Q_{\mathrm{hot}}}{W_{\mathrm{el}}}$$

Where ΔQ_{hot} is the heat delivered for space heating (the utilisable energy) and W_{el} is the energy used to run the compressor. The COP value for heat pump is a theoretical value which is measured on a test stand using standard laboratory conditions (EN 255 or EN 14511).

The operating conditions of an installed heat pump will strongly deviate from ideal lab conditions and therefore the COP, as stated by the heat pump manufacturer, cannot be used directly to determine annual energy consumption.

To determine the annual energy consumption, the seasonal performance factor (SPF) must be used:

$$\mathrm{SPF} = \frac{Q_{\mathrm{annual}}}{W_{\mathrm{el,\ annual}}}$$

Where Q_{annual} is annual heat delivered and $W_{\mathrm{el,\ annual}}$ is the annual electricity consumption of the compressor.

The SPF shows the ratio between useful heat output and used electricity over a full year. The SPF depends on a number of factors including the operating temperatures of the system, the outside temperatures over the year and the occupancy pattern of the house (no. people etc.). Typical SPF values ranges from 2.0 to 4.8 depending on the type of heat pump installation and operation.

Influence of the supply water temperature

The overall efficiency of heat pump systems strongly depends on the supply temperature in the heating system. The lower the supply temperature, the higher the performance factor.

As an example, using a brine water heat pump with a specific heat load of 30 W/m^2, an underfloor heating system with a supply temperature at 30 °C will have operate with an SPF at 4.2. In comparison, a radiator system or air heating with fan coils will typically require a supply temperature of 55 °C, corresponding to a SPF of 3.2 (see figure 3.1). The underfloor heating system will thus yield a 25% better heat pump performance and a 25% reduction in electricity consumption.

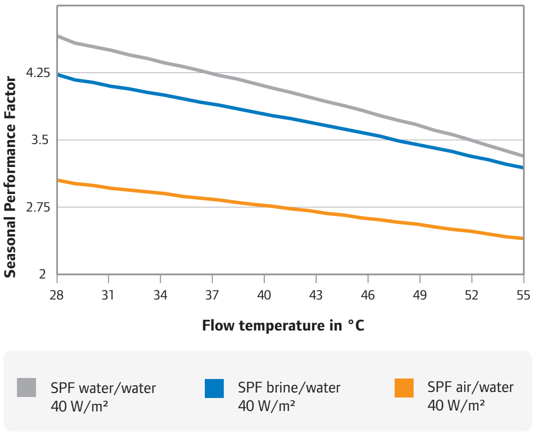


Figure 3.1: SPF as a function of supply water temperature (6 kW heat pump, calculation based on VDI4650).

Heat pumps using air as energy source (air/water heat pumps)

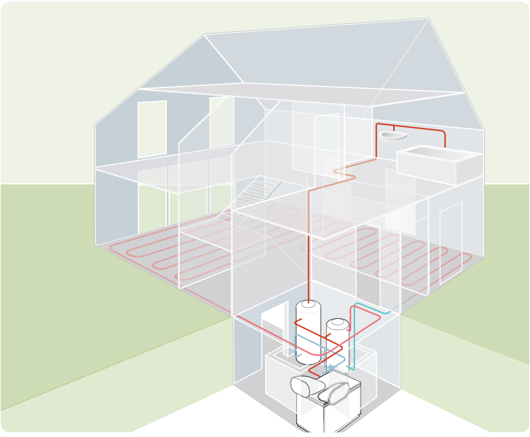


Figure 3.2: Air/water heat pump, inside installation.

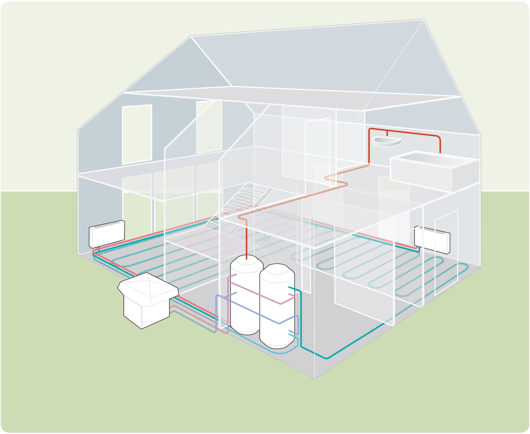
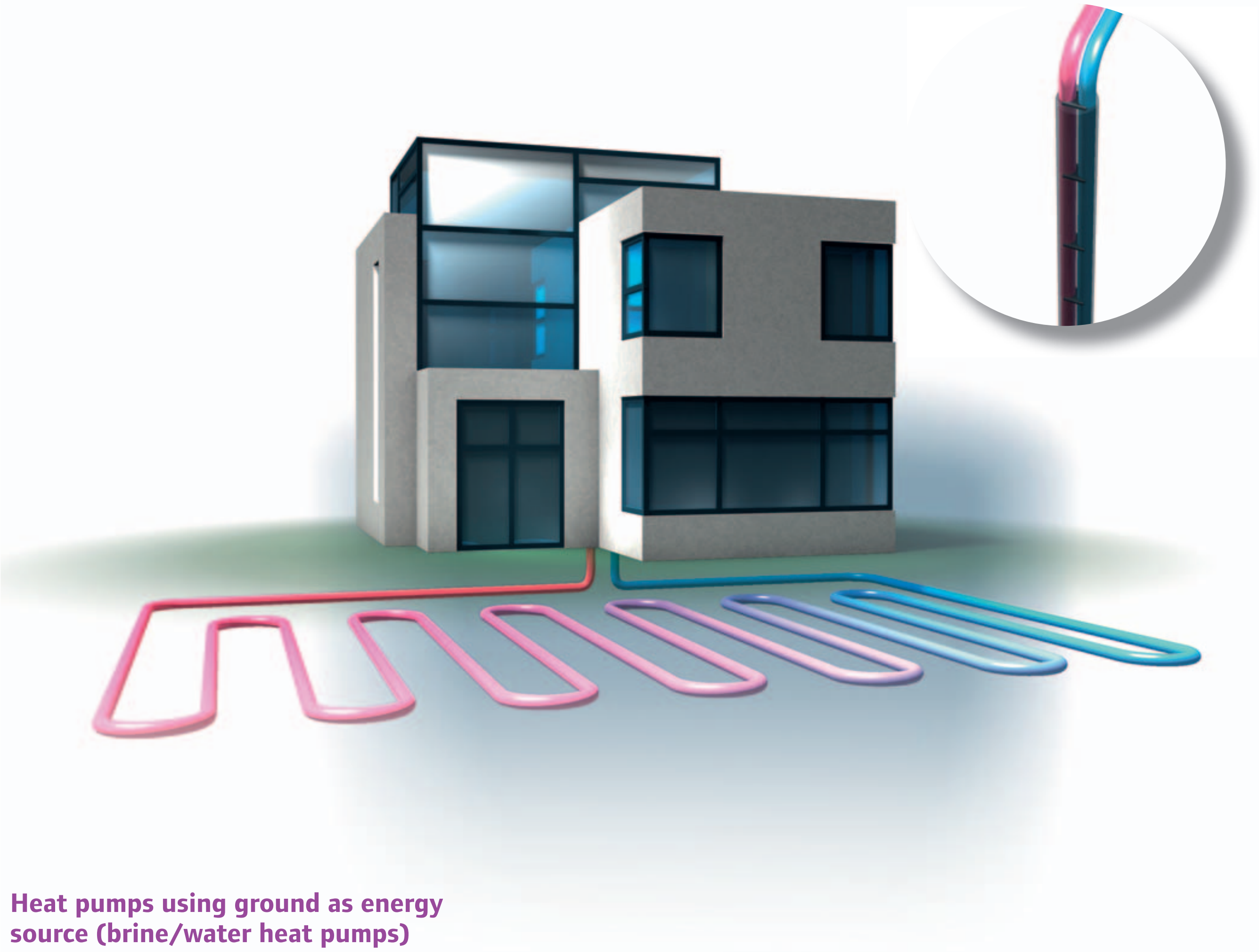


Figure 3.3: Air/water heat pump, outside installation with cooling option.

Air/water heat pumps are easy and cost efficient to install. However the performance factor will be comparatively low compared to ground coupled heat pumps; typically the annual performance factor is in the range from 2.3 to 3.1, depending on the actual installation and usage.

Air/water heat pumps can be used for active cooling.



Heat pumps using ground as energy source (brine/water heat pumps)

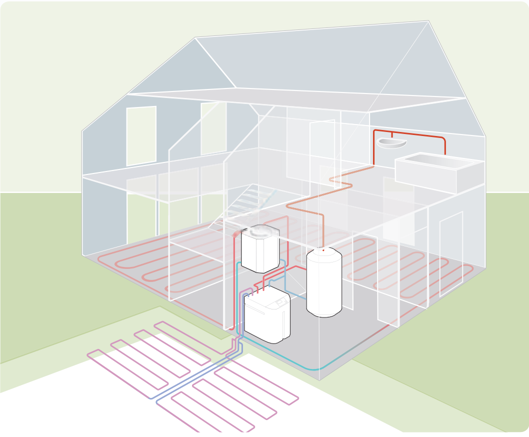


Figure 3.4: Brine/water heat pump with horizontal collector.

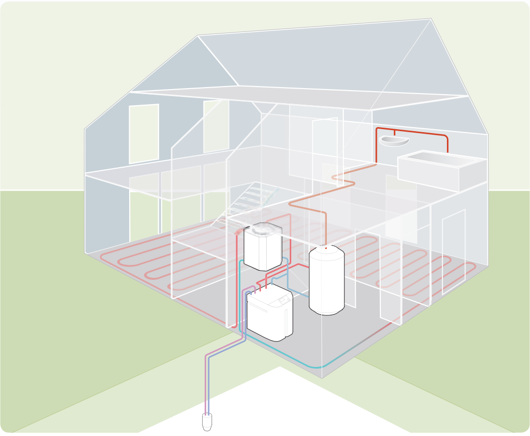


Figure 3.5: Brine/water heat pump with borehole collector.

Brine/water heat pumps have a higher efficiency than air/water heat pumps, due to the comparatively constant temperature in the ground. Horizontal as well as vertical collectors, so-called bore holes, can be used. Typically the annual performance factor is in the range from 3 to 4.5, depending on the actual installation and usage.

Ground coupled brine/water heat pumps are ideal for both active and passive cooling.

The trade-off between better energy performance and passive cooling on one side and the additional investment costs for the ground coupled energy collectors (drilling and pipe work) on the other side needs to be evaluated in the design phase.

District heating

District heating is either produced alone in heat only boilers or in cogeneration units where heat and electricity are co-produced. District heating networks can vary from small networks supplying few households from one central boiler (block heating) to large scale heating networks in big cities with multiple supply units.

When building a new house in an area where district heating is available this should be considered. The district heating option may be the optimal solution in terms of energy efficiency, cost and environmental impact, but it depends on the conditions of the local district heating company. In some areas there may be an obligation to connect to the district heating network.

A house installation for district heating is normally based on a heat exchanger that supplies hot water for the heating and tap water systems. When dimensioning the heating system it's necessary to obtain data on temperature levels, pressure and possible requirements for cooling from the local district heating company.

The local district heating company sets the price structure for the used energy. There are several different ways of setting the price and tariff structure, but often it's a combination of a fixed subscription fee, a fixed fee for installed capacity and variable fee depending on consumption.

If the consumption fee is based on m^3 consumption, the price will be lower if a good cooling (ΔT) can be provided by the emitter system. This means that emitter systems with big surfaces, such as underfloor heating, will result in a lower energy bill.

The district heating company has as general interest in a large ΔT at the consumers as this yield less thermal losses and better energy efficiency in the total system. So even if the consumption fee is based on energy use (kWh) this is often combined with a penalty for poor ΔT (e.g. less than 35 °C) and a reward for a good ΔT. Again, an underfloor heating installation will help improve the overall energy efficiency and lower the energy bill.

Individual boilers

Traditional individual boilers using fossil fuels will rarely be the adequate choice for a low-energy building. In some cases, typically in rural areas where biomass is available, individual boilers using renewable fuels like straw, wood pellets or similar may be the optimal low energy choice.

In any case, the efficiency of individual boilers depends of course on the quality of the boiler itself and the total heating system installation.

Traditional boilers works without flue gas condensation and normally has annual performance with a maximum 97% efficiency. The condensing boiler technology is more efficient as it also extracts the flue gas latent heat via condensation. Therefore condensing boilers can operate with efficiency over 100%; depending on the energy source efficiency up to 109% is possible.

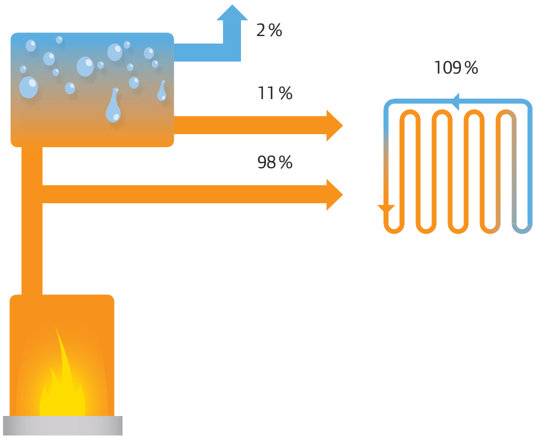


Figure 3.6: Condensing boiler. The heat system return flow is preheated in the condenser. An efficiency up to 109% can be reached.

Return water temperature

A low return water temperature is a prerequisite for utilising the condensing effect and efficiency improvement. The return water flow has to be maximum 47 °C, and the lower the temperature, the better efficiency. At around 42 °C the efficiency of a condensing boiler will reach 100%, and at 25 °C the efficiency reaches 109%.

A low temperature system, such as underfloor heating, will thus help increasing the total energy efficiency in systems with condensing boilers (see figure 3.7).

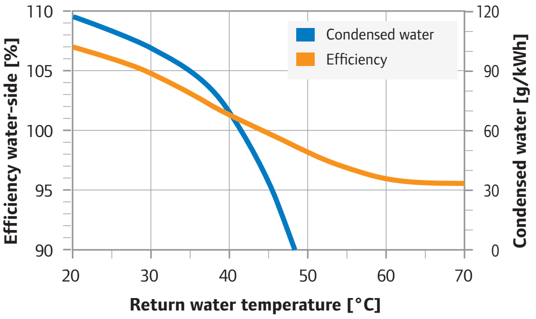


Figure 3.7: Efficiency of a condensing gas boiler as a function of the return water temperature in the heating system.

4. Heat emitter systems

The heat emitters systems used in residential new buildings are of various types. The most common installations are traditional water based systems such as underfloor heating and radiator systems. In construction with very low heat demand it is becoming increasingly common to use the ventilation system as heat emitter in addition to providing fresh air. The use of electrical panels (direct electricity) is in most cases not an option for a low-energy house.

The heat emitter system needs to have sufficient capacity to satisfy the heating peak load, even if it only occur a couple of days during the year. The design needs to include peak load calculation for the coldest day of the year, and in particular for low-energy houses one has to be careful not to rely on average values for peak load dimensioning.

The choice and design of emitter system can have a vital influence on both energy efficiency and indoor comfort. Traditional emitters have a long lifetime, many times longer than the heat source and it is therefore important that the emitter system is flexible and adaptable to future needs and energy sources.

Underfloor heating

- Operates at low temperature levels 35 – 25 °C
- Gives freedom of interior design
- Superior indoor comfort level
- Even temperature distribution
- Allows using free floor cooling in the summer
- High energy source efficiency

Radiator/panels

- Operates traditionally at high temperature levels 70 – 40 °C
- Low temperature radiator system operates at temperature levels 55 – 25 °C
- Emitters are typically installed under windows on external walls
- Allows thermostat control

Air heating

- The system is integrated with mechanical ventilation.
- Recommended capacity is normal only up to 10 W per m^2
- Allows typically only zone control
- Uneven temperature distribution
- Ventilation efficiency typical between 40 and 70%
- Low investment costs, but high annual operating cost
- Not allowed or with penalty factor in new energy frames
- Allows thermostat control
- Low control loss

Electrical panels

- Low investment costs, but high annual operating cost
- Not allowed or with penalty factor in new energy frames
- Allows thermostat control
- Low control loss

Energy performance of emitter systems

The norm EN15316 provides a calculation concept and defines building-system boundaries for heating systems. The norm follows the structure of the heating system with a calculation direction from the demand to the source and the procedure comprises three basic points:

- Net energy (building energy demand)
- Delivered energy (system energy demand)
- Primary energy

The delivered energy takes into account the losses coming from the from the heat emission, distribution and generation system. In the following the efficiency of different emission systems is examined more closely by comparing their respective losses.

Heat losses for the heat emission system

Emission losses are due to three factors, namely:

- Non-uniform temperature distribution
- Losses to the outside from embedded devices in the structure
- Losses due to non-perfect control of the indoor temperature

Calculating the efficiency of emitters systems using EN 15316, the results show that the emission losses from most emitters are in the same order of size, except air heating systems, where the emission losses are significantly higher.

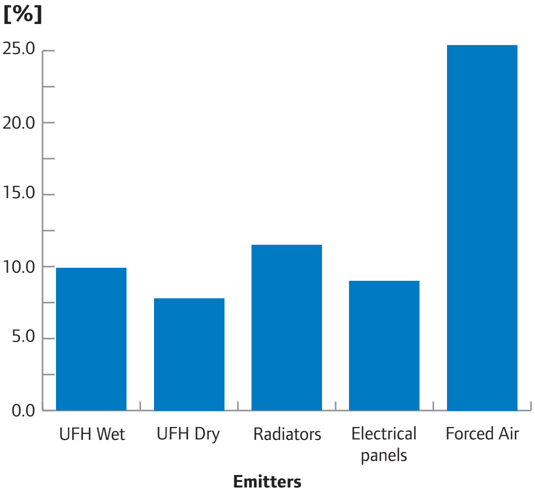


Figure 4.1: Emission losses calculated according to EN 15316. All systems have individual room control (P controller, 2K), except for the air heating system, which is controlled by master zone.

Downward heat loss with an underfloor heating emitter

An underfloor heating emitter will introduce an additional, but very limited, downward heat loss. In new built low-energy houses, the required insulation levels means, that the additional heat loss is limited to less than 2-3%.

The below table show an example of the heat loss to the ground in a dwelling with an annual heat demand of 30 kWh/m^2. The calculated heat loss is determined based on a Heat 2 heat transfer calculation (PC-program for two-dimensional transient and steady-state heat transfer).

<table>
<tr><th colspan="4">Heat demand 30 kWh/m²/year (design value)</th></tr>
<tr><th>U-value</th><th>Downward heat loss without UFH [kWh/m²/year]</th><th>Downward heat loss with UFH [kWh/m²/year]</th><th>Additional heat loss [kWh/m²/year]</th></tr>
<tr><td>0.218</td><td>3.01</td><td>4.05</td><td>1.04</td></tr>
<tr><td>0.168</td><td>2.75</td><td>3.59</td><td>0.84</td></tr>
<tr><td>0.137</td><td>2.55</td><td>3.23</td><td>0.68</td></tr>
<tr><td>0.116</td><td>2.38</td><td>2.97</td><td>0.59</td></tr>
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<tr><td>0.079</td><td>2.04</td><td>2.43</td><td>0.40</td></tr>
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Table 4.1: Calculated heat loss to the ground comparing installations with and without underfloor heating (Heat 2). Underfloor heating introduces a maximum of 2-3% additional heat loss.

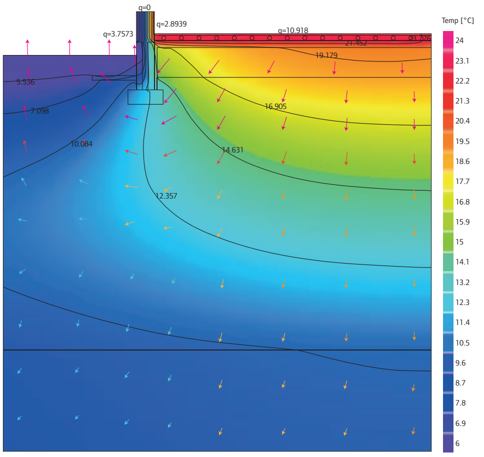


Figure 4.2: Example of a downward heat loss calculation (Heat 2).

5. Regulation and control

The purpose of a control systems is to keep one or more climate parameters within specified limits without a manual interference. Heating and cooling systems require a control system in order to regulate room temperatures during shifting internal loads and outdoor temperatures. Good control systems adapt to the desired comfort temperatures while minimising unnecessary energy use.

In residential buildings two different types of controls principles are common; zone control and individual room control.

In a **zone control system** the temperate is controlled in a common zone consisting of several rooms and heating and cooling is supplied evenly to the full zone. Not all national building codes allow zone control systems as they have major shortfalls with comfort as well as energy consumption.

In low-energy buildings there will in particular be high variations in the individual room heat loads (see figure 5.2). This means that lack of individual room control causes the room with the highest heat demand to determine the heat supply to a full zone, resulting in over temperatures and unnecessary high energy consumption.

An **individual room control system** is much preferable in order to meet room specific load variations and individual comfort requirements. Due to high variations in the individual room heat loads in low-energy buildings, an individual room control system is also required to minimise the energy consumption.

The basic principle in an individual room control system is that a sensor measures the room temperature and regulates the heating or cooling supplied to the space controlled in order to meet a user defined temperature set point. The most well know examples are radiators with thermostatic valves and underfloor heating systems with room thermostats. Individual room by room regulation is the preferred type of control in residential buildings and is also required by the majority of the building codes in Europe.

In addition to the energy consideration, individual room control also provides a superior thermal environment. Room temperature is important for people's wellbeing and comfort and often people will desire one temperature in the bedrooms, another in the bathrooms and a third in the living rooms.

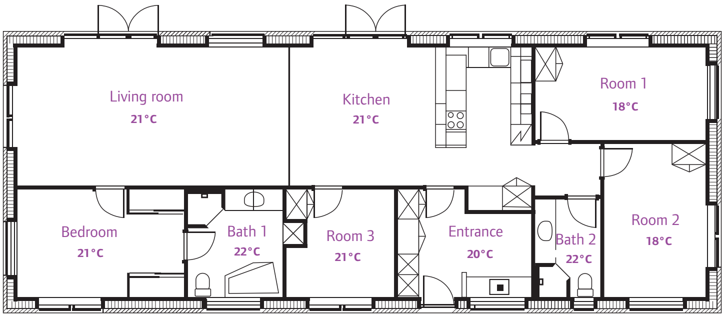


Figure 5.1: Typical desired temperature (set points) in a single family house.

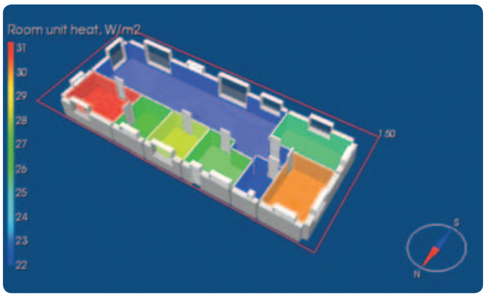


Figure 5.2: Typical variation between individual room heat demands in a low-energy house.

The self-regulating effect in underfloor heating

Radiant floor heating and cooling benefits from a significant effect called ”self control” or “self regulating effect”. The self regulating effect occurs because the heat exchange from the emitting floor is proportional to the temperature difference between the floor and the room. This means that when room temperature drifts away from the set point, the heat exchange will automatically increase.

The self regulating effect depends partly on the temperature difference between room and floor surface and partly on the difference between room and the average temperature in the layer, where the pipes are embedded. It means that a fast change of the operative temperature will equally change the heat exchange.

Due to the high impact the fast varying heat gains (sunshine through windows) may have on the room temperature, it is necessary that the heating system can compensate for that, i.e. reduce or increase the heat output.

Low-energy houses will largely benefit from the self regulating effect, because the temperature difference between floor and room will be very small. A typical low-energy house has on average for the heating season a heat load of 10 to 20 W/m² and for this size of heat load, the self regulating effect will be in the range of 30 - 90%.

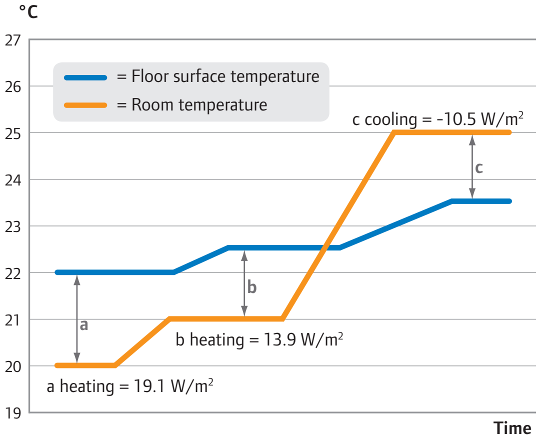


Figure 5.3: Self-regulating effect. UFH/C outputs for different temperatures between room and floor surface.

Functional description of Uponor Control System

Individual room control

For a radiant floor heating and cooling system, the control is normally split up in a central control and individual room controls. The central control unit is placed at the heat source. It controls the supply water temperature according to the outside temperature based on an adjustable heat curve. The individual room control units (room thermostats) are placed in each room and controls the water flow in the individual underfloor heating circuit by ON/OFF control with a variable duty cycle. Its done according to the set-point by opening and closing an actuator placed at the central manifold.

Individual room control with DEM technology

Uponor’s Dynamic Energy Management control principle is an advanced individual room system based on innovative technology and an advanced self learning algorithm. Instead of a simple ON/OFF control, the actuators on the manifold supplies the energy to each room in short pulses determined based on feedback from the individual room thermostats.

Uponor Control System DEM is self learning and will remember the thermal behavior of each room. This ensures an adequate and very accurate supply of energy, which means better temperature control and energy savings.

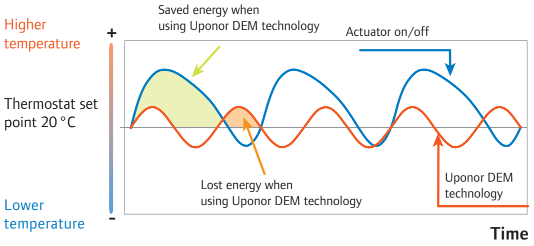


Figure 5.4: Typical behaviour in a heavy floor construction, where Uponor DEM technology ensures that a minimum of energy is lost to the construction. Compared with traditional on/off regulation, saving figures between 3-8% can be obtained.

Zone control

When using zone control for a radiant floor heating and cooling system, the central controller is normally placed at the heat source. It controls the supply water temperature according to the outside temperature based on an adjustable heat curve. The manifold system has no actuators and normally the system works at a constant flow with temperature regulation based on a reference thermostat is placed in one of the main rooms.

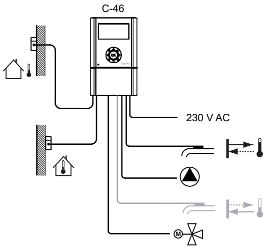


Figure 5.5: Simple zone control, the central controller provides a regulated supply temperature based on the outdoor/indoor temperature.

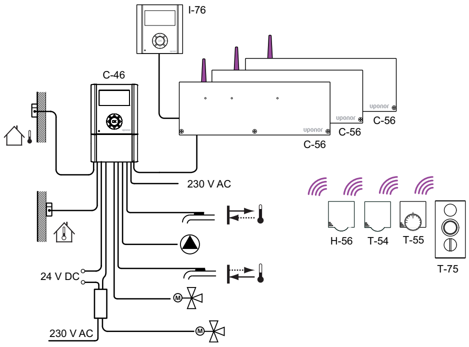


Figure 5.6: Individual room control, the central controller provides a regulated supply water temperature based on the outdoor/indoor temperature and the room thermostat controls the room temperature by using actuators.

Setback functions

Control systems normally have a setback function, which is able to adjust the room temperature according to a predefined schedule. The purpose is to operate the heating system at a lower room temperature in periods where the house is unoccupied with the aim of saving energy. Very often a night set back is used.

Setback functions must be applied with care. Temperature setback can provide savings in some cases, most notably when the house is unoccupied during longer periods like for example during holidays. But short-term setback, applied for example during night, gives in most cases very limited or no energy savings and it can be difficult to obtain the right temperature and comfort when again needed.

The thermal mass in the floor construction significantly influences the possibility for using set back functions. Light constructions have a relatively small time constant and can thus in some case be operated with short term set back. Heavy constructions have a relatively large time constant, which means that for example a night set back schedule is not providing any savings. On the contrary, applying a short term night set back in a heavy construction will cause problems in reaching the desired indoor comfort.

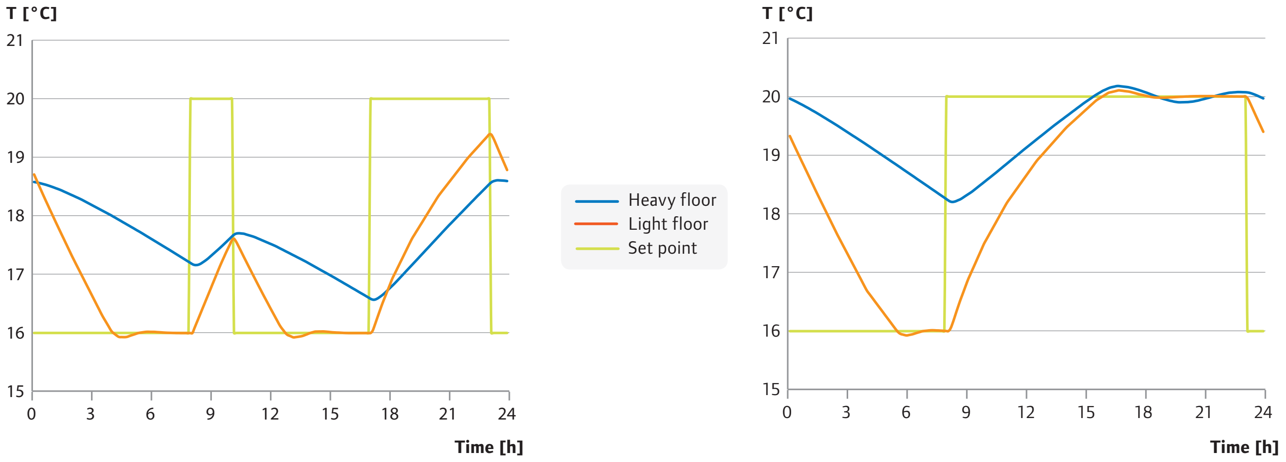


Figure 5.7: Examples of setback functions in heavy and light floor construction. Using a simple night set-back will result in discomfort in the morning hours. A complex setback with temperature lowering during the day as well is not recommendable.

In low-energy houses, special attention has to be made when the underfloor heating is operated together with the mechanical ventilation system. Using a temperature set back on the hydronic underfloor heating system will influence the efficiency of the heat recovering unit, due to the lower room temperature. To prevent this, the two systems shall be controlled equally. When this is not possible it is not recommended to use set back on the underfloor heating system alone.

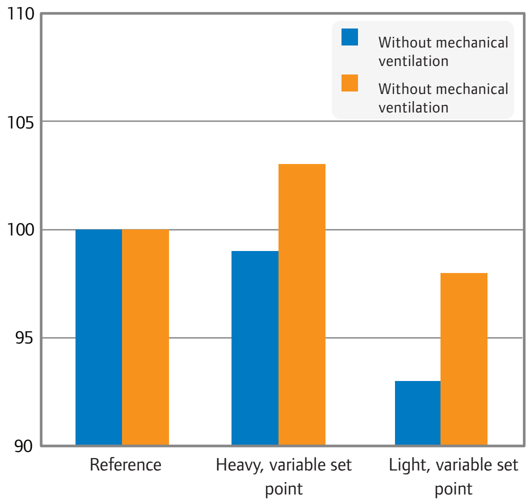


Figure 5.8: Annual energy consumption with night set-back for heavy and light floor constructions (Index 100 = reference with no set-back)

6. Design of underfloor heating and cooling

Heating and cooling systems with water conducted in pipes integrated in the floors, ceilings or walls of a building are referred to as radiant systems, as more than 50% of the energy exchange is by radiation. The most well know radiant system is traditional underfloor heating which can also be used for underfloor cooling.

A proper design of an underfloor heating cooling system in low-energy houses requires knowledge of the indoor climate criteria, the climatic conditions and the detailed parameters of the building construction.

Underfloor heating

Underfloor heating is an energy efficient emitter system that provides optimal indoor comfort. The energy efficiency is ensured by the low operating temperature and the thermal comfort is a result of uniform thermal environment with no radiation asymmetry and no cold draughts. As illustrated in figure 6.1, underfloor heating is the emitter system that comes closest to an ideal room temperature profile.

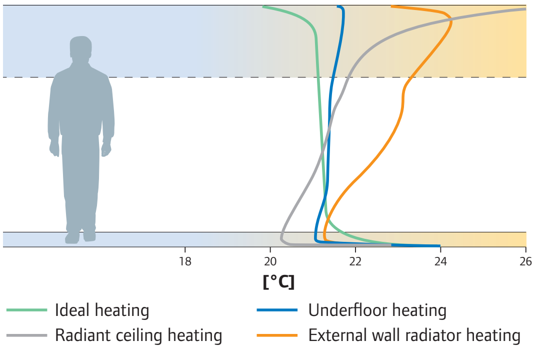


Figure 6.1: Vertical temperature profiles with different emitter systems.

Underfloor cooling

In low-energy houses it is recommendable to combine underfloor heating with underfloor cooling by installing a combined system. There is much evidence that low-energy homes will need active cooling in the summer. The very strong argument for underfloor cooling is that the cooling energy can be supplied from freely available sources. This is called “free cooling” as the only operating cost is electricity for the circulation pumps. Underfloor cooling systems typically operates at a mean water temperature of 16 to 18 °C. That will result in a floor surface temperature of minimum 20 °C, which gives a cooling capacity of approximately 40 Wm^{2}.

Thermal indoor climate

In order to provide thermal comfort, it is necessary to prevent local thermal discomfort caused by temperature deviations, draught, vertical air temperature difference, radiant temperature asymmetry, and floor surface temperatures. These factors can influence the required capacity of the HVAC system.

Optimal temperature conditions

EN ISO 7730 is an international standard that can be used as a guideline to meet an acceptable indoor and thermal environment. Indoor conditions are assessed based on predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV). PPD predicts the percentage of a large group of people that are likely to feel “too warm” or “too cold” based on a Predicted Mean Vote (PMV). (The EN ISO 7730 is not replacing national standards and requirement which always must be followed).

PMV and PPD

The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (see table below), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment.

PMV	Predicted mean vote
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cold
-2	Cool
-3	Cold

Table 6.1: Seven-point thermal sensation scale.

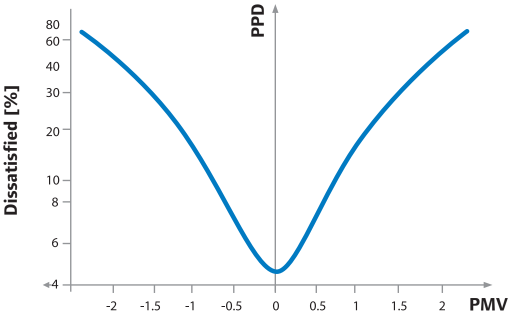


Figure 6.2: Relation between PMV and PPD.

The PPD predicts the number of thermally dissatisfied persons among a large group of people. The rest of the group will feel thermally neutral, slightly warm or slightly cool.

Table 6.2 below shows the desired operative temperature range during Summer and Winter taking into consideration normal clothing and activity level in order to achieve different comfort classes.

Class	Comfort requirements		Temperature range	
	PPD [%]	PMV [/]	Winter 1.0 clo 1.2 met [°C]	Summer 0.5 clo 1.2 met [°C]
A	< 6	- 0.2 < PMV < + 0.2	21-23	23.5-25.5
B	< 10	- 0.5 < PMV < + 0.5	20-24	23.0-26.0
C	< 15	- 0.7 < PMV < + 0.7	19-25	22.0-27.0

Table 6.2: Thermal requirements for indoor comfort class A, B and C.

ISO 7730 recommends a target temperature of 22 °C in the winter and a target temperature of 24.5 °C in the summer. The higher the deviation around these target temperatures, the higher the percentage of dissatisfied. The target temperatures are different in summer and winter due to the difference in peoples clothing.

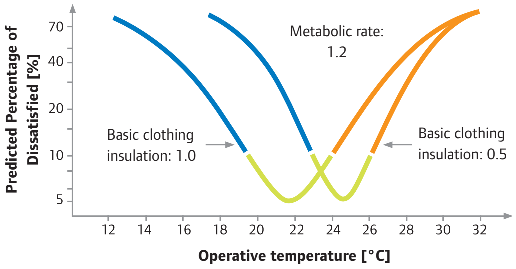


Figure 6.3: Relation between operative temperature and PPD with summer and winter clothing.

Draft rate

Radiant systems are low convective systems and will not create any problems with draft. However, down draft from a cold wall can put a limitation to the system. A cold wall can create draft known from windows. When designing wall cooling, the velocity of the air need to be within the recommendation (Class A is 0.18 m/s).

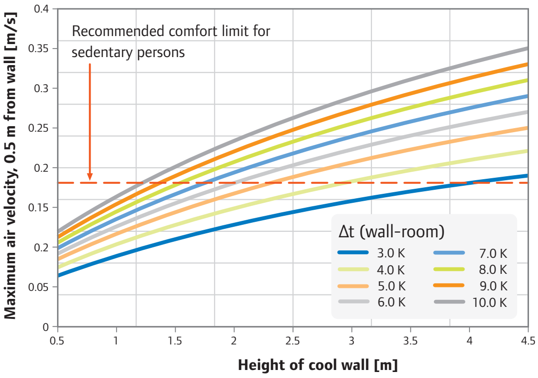


Figure 6.4: Maximum air velocity along the floor 0.5 m from a cold wall (EN15377-1).

Radiant asymmetry

The design of a radiant ceiling or wall system, shall stay within the limits of radiant asymmetry. The radiant asymmetry differs depending upon the location of the emitter system and whether it's used for heating or cooling, see figure 6.5.

With the insulation levels typically used in low-energy houses, radiant asymmetry does normally not cause any problems due to the moderate heating and cooling load. However, especially when using ceiling heating a calculation must be made for a given reference room.

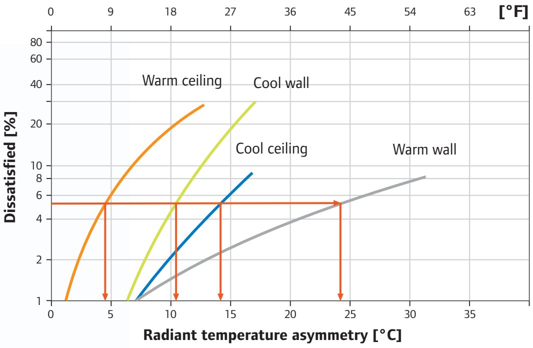


Figure 6.5: Local discomfort caused by radiant temperature asymmetry.

Surface temperatures

Underfloor heating is traditionally preferred due to the comfort of a warm floor. In low-energy houses the floor will be used for cooling as well, and is therefore relevant to assess the perceived comfort of a cold floor.

According to ISO 7730, the lowest PPD (6%) is found at a floor temperature of 24 °C. A typical floor cooling system will have to operate with a minimum floor temperature of 20 °C where the expected PPD would still be less than 10%. Such floor temperatures still provide a significant cooling effect due to the large surface area.

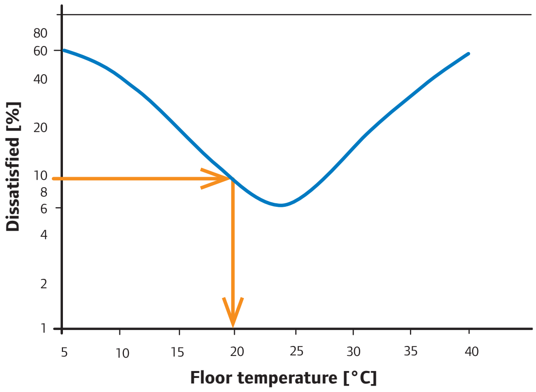


Figure 6:6: Local discomfort caused by warm and cold floors.

Peak load calculations

The first step to be taken for designing the heating and cooling system is to perform a peak load calculation. This needs to be done in accordance with the national building code.

The peak load calculation for heating is a result of the specific heat loss, infiltration loss, ventilation loss and the dimensioning outdoor temperature, the so-called design temperature. The peak load calculation can be done as simple heat loss calculation for the design day using preset standard values. But in low-energy buildings such simple approach will in most cases not be sufficient for guaranteeing sufficient heating capacity.

Alternatively to a simple static calculation, more sophisticated methods like for example building simulation programs can be applied. That allows a more detailed insight the buildings thermal behaviour and is very relevant for the design of low-energy houses. Tight and well insulated houses are sensitive to rapid changes in both internal and external conditions and will have different capacity requirement in different rooms.

In addition to the peak load calculation for heating, it is recommended that the cooling loads are calculated as well. The best way of doing this is also by simulation, in particular because the biggest cooling loads are not necessarily occurring on the warmest day in the summer.

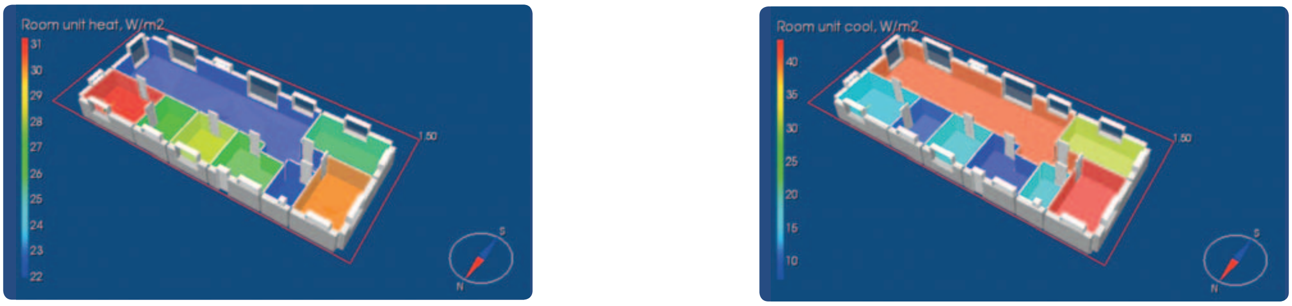


Figure 6.7: Example of peak load calculations done with building simulation software (IDA ICE).

Design temperature and heating output

The underfloor heating design and construction needs to be done by choosing a floor construction type and a design temperature of the water in the piping system that can provide sufficient heating and cooling output to cover the peak loads.

The design temperature plays and important role for the overall energy efficiency in the heating system. A low supply water temperature ensures a maximum efficiency of the heat source. It is therefore of vital importance to chose a floor construction that allows the lowest possible design temperature.

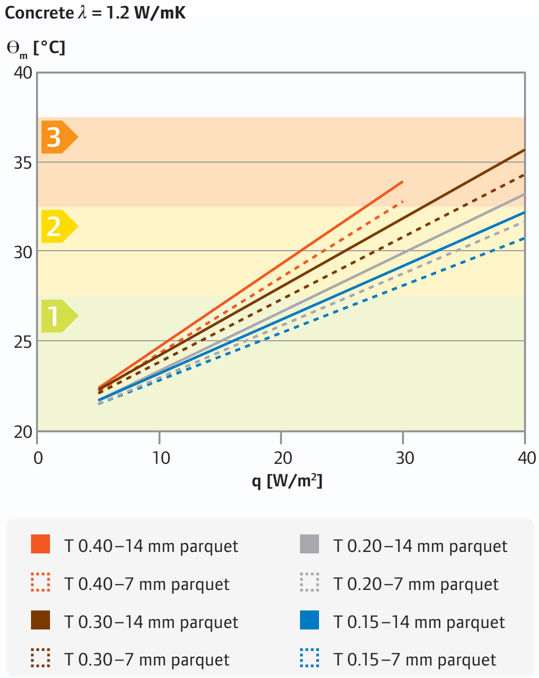


Figure 6.8: Required design temperature as a function of the required heating output for different floor construction types. A low design temperature (T class 1) results in optimal energy efficiency.

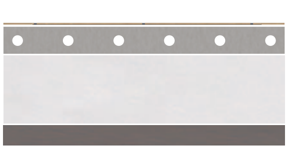
Floor construction types

Floor constructions vary from building to building. Underfloor heating systems are generally classified as either underfloor heating in concrete construction or underfloor heating in wooden construction.

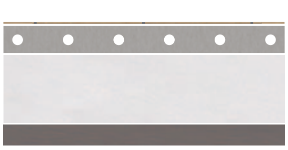
In concrete construction the underfloor heating pipes are placed directly in the concrete with various methods of fixation. The floor surface material can be of different kind, with either a wooden surface or tiles as the most normal in modern houses.

In wooden construction the pipes needs to be installed with a heat emission plate for securing an even distribution of the heat in the floor construction. The construction can be with chip boards or in between the joists. The surface material is typically wood or tiles.

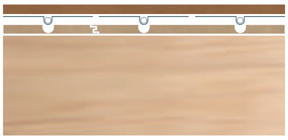
Concrete construction, λ = 1.8 W/mK

Floor construction principle	Surface material																		
	c/c mm	Tiles 10 mm						Laminate 7 mm Include 2 mm underfloor						Parquet 14 mm Include 2 mm underfloor					
		T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM
	150	1	x	x	40	42	12 to 20 mm	2	x	x	40	34	12 to 20 mm	2	x	x	40	32	12 to 20 mm
	200	1	x	x	40	42	12 to 20 mm	2	x	x	40	32	12 to 20 mm	2	x	x	40	30	12 to 20 mm
	300	1	x	x	34	40	12 to 20 mm	2	x	x	38	29	12 to 20 mm	2	x	x	34	27	12 to 20 mm
	400	2	x	x	20*	35	12 to 20 mm	3	x	x	30*	26	12 to 20 mm	3	x	x	30*	24	12 to 20 mm

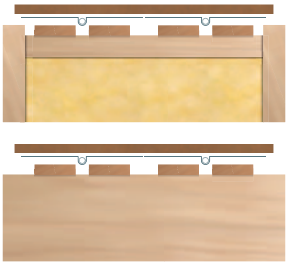
Concrete construction, λ = 1.2 W/mK

Floor construction principle	Surface material																		
	c/c mm	Tiles 10 mm						Laminate 7 mm Include 2 mm underfloor						Parquet 14 mm Include 2 mm underfloor					
		T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM
	150	1	x	x	40	42	12 to 20 mm	1	x	x	30	31.9	12 to 20 mm	2	x	x	40	30	12 to 20 mm
	200	1	x	x	39	42	12 to 20 mm	2	x	x	40	29.8	12 to 20 mm	2	x	x	38	28	12 to 20 mm
	300	2	x	x	40	35	12 to 20 mm	2	x	x	34	26.6	12 to 20 mm	2	x	x	31	25	12 to 20 mm
	400	2	x	x	20*	30	12 to 20 mm	3	x	x	30*	23.4	12 to 20 mm	3	x	x	30*	22	12 to 20 mm

Wooden construction chipboard and heat emission plate

Floor construction principle	Surface material																		
	c/c mm	Tiles 10 mm Include 13 mm gypsum board						Laminate 7 mm Include 2 mm underfloor						Parquet 14 mm Include 2 mm underfloor					
		T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM	T class	Heat	Cool	MC H	MC C	DIM
	125	no	no	no	no	no	12 mm	2	x	no	40			2	x	no	36		12 mm
	200	2	x	no	36	no	17 mm	2	x	no	37			2	x	no	34		17 mm

Wooden construction on top and between joist with additional chipboard 22 mm above the heat emission plate

Floor construction principle	Surface material																		
	c/c mm	Tiles 10 mm						Laminate 7 mm Include 2 mm underfloor						Parquet 14 mm Include 2 mm underfloor					
		T class	Heat	Cool	MC H	MC C	-	T class	Heat	Cool	MC H	MC C	-	T class	Heat	Cool	MC H	MC C	-
	300	2	x		30		20 mm	3	x		35			3	x		32		

*) Limit by surface temperature variation.
The cooling capacity is based on a mean water temperature of 15.5 °C.

Table 6.3: Maximum heating capacity (MC H) and maximum cooling capacity (MC C) for different floor construction types (W/m^2). The cooling capacity is based on a mean water temperature of 15.5 °C.

Heavy or light floor construction

The choice between a concrete floor construction and a wooden floor construction is a choice between a construction with a high thermal mass (heavy construction) and low thermal mass (light construction).

A light floor construction benefits from a fast reaction time. This is as advantage in the intermediate seasons where fast changes in the heating a cooling output of the systems is often required. A fast reacting system is also an advantage for using set back functions, like for example lowering the room temperature during night time.

A heavy construction has a bigger thermal mass and will therefore behave differently over time. It has the ability to accumulate thermal energy and will provide very stable temperatures on the floor and in the rooms. With rapid changes in the thermal loads, resulting for example from direct sun radiation, the heavy construction will benefit from a large degree of self-regulating effect, meaning that heat output automatically will decrease when the room temperatures increase.

The reaction time of a floor construction depends on the thermal capacity in the construction as well as the thermal conductivity. A light (wooden) construction will have a short reaction time, while a heavy (concrete) construction will have long reaction time. The reaction time construction is defined as the time it takes for the system to reach a 63% of a changed set temperature.

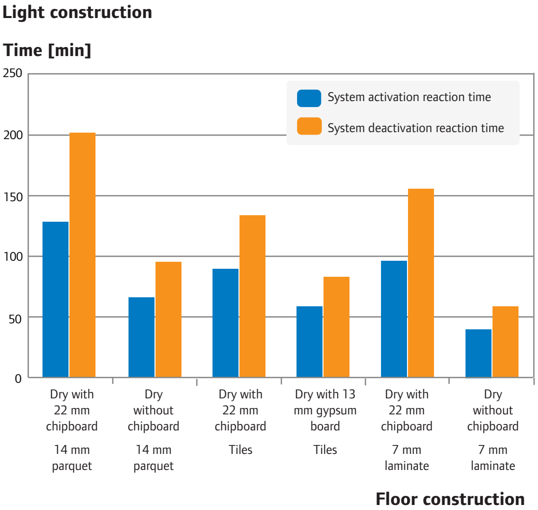


Figure 6.9: Reaction time for different floor construction types (HEAT 2 7.1 simulation).

Optimising the underfloor heating system

An optimal underfloor heating system in low-energy construction operates at the lowest possible supply water temperature. Several parameters can be fine-tuned for providing the best efficiency of the installation. This includes the choice of material, the pipe installation distance, pipe depth and pipe diameter. These can relatively easily be changed and optimized in concrete construction, while wooden construction techniques normally operate with preset geometric parameters. In either case it is recommended to install the pipes as near the floor surface as possible.

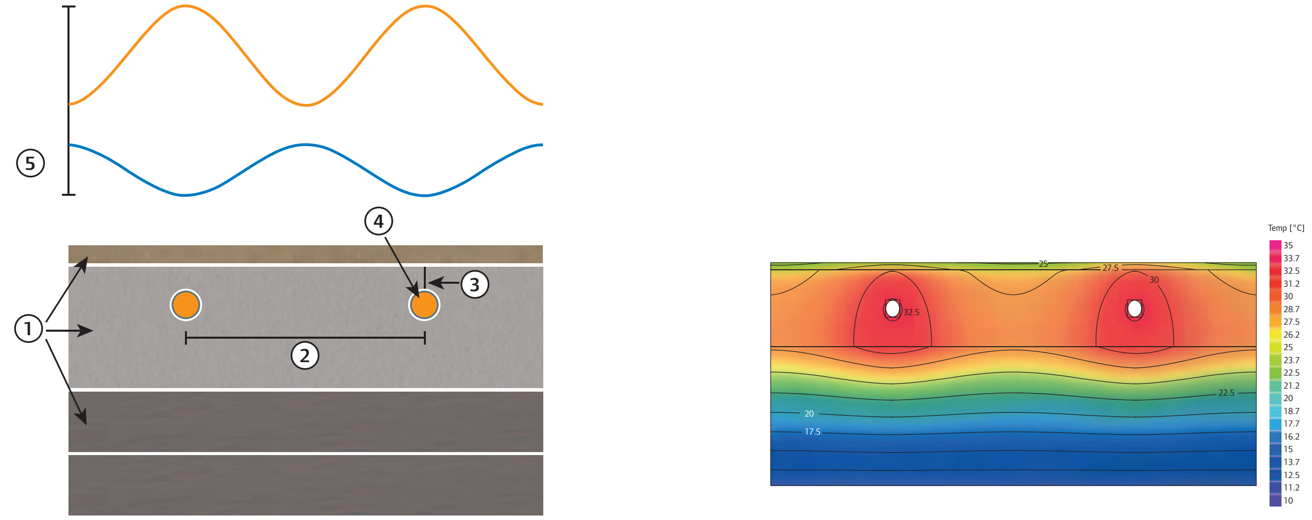
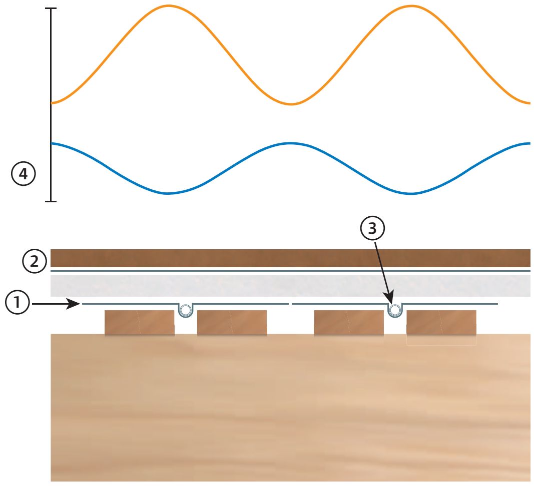
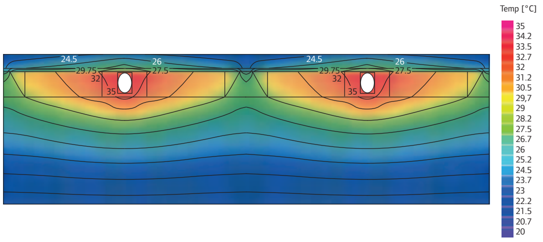
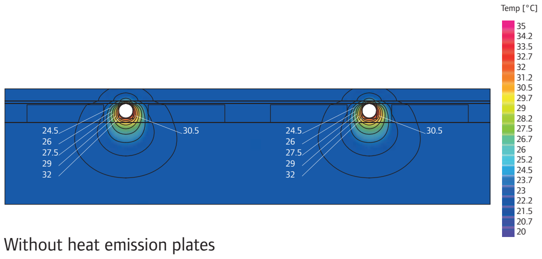


Figure 6.10: Example of a concrete construction with underfloor heating. Factors that influence the system efficiency are 1 = construction material thermal properties, 2 = pipe installation distance, 3 = pipe depth, 4 = pipe diameter and 5 = surface temperature variation (HEAT 2 7.1 simulation).





With heat emission plates



Without heat emission plates

Figure 6.11: Example of dry wooden construction with underfloor heating. Factors that influence the system efficiency are 1 = thickness of the heat emission plate, 2 = construction material thermal properties and 3 = surface temperature variation. Pipe diameter and installation distance are usually prefixed (HEAT 2 7.1 simulation)

Heat exchange from dry constructions (wood)

Figure 6.12 shows the heat exchange for different dry underfloor heating system configurations. The diagrams can be used for Uponor dry solutions available in Nordic, which are 12 mm systems with heat emissions plates (HEP) c/c 125 mm, 17 mm systems with HEP c/c 200 mm, and 20 mm systems with HEP c/c 300 mm.

Some construction types may require an additional material layer above the HEP in order to increase the strength and to maintain an even surface temperature. This is in particular the case for constructions with large centre distances between the pipes (c/c > 200 mm). This will however have a negative influence on the energy efficiency.

For optimal performance of the underfloor heating system, it is recommended to select constructions with no need for an additional layer between the surface material and the heat emission plates. This will results in the lowest possible water temperature and optimal efficiency. The use of additional 22 mm chipboard will for example result in a required mean water temperature increase of typically 4-5 K. Depending on the energy source that can influence the energy efficiency and overall energy consumption negatively with 10% or more.

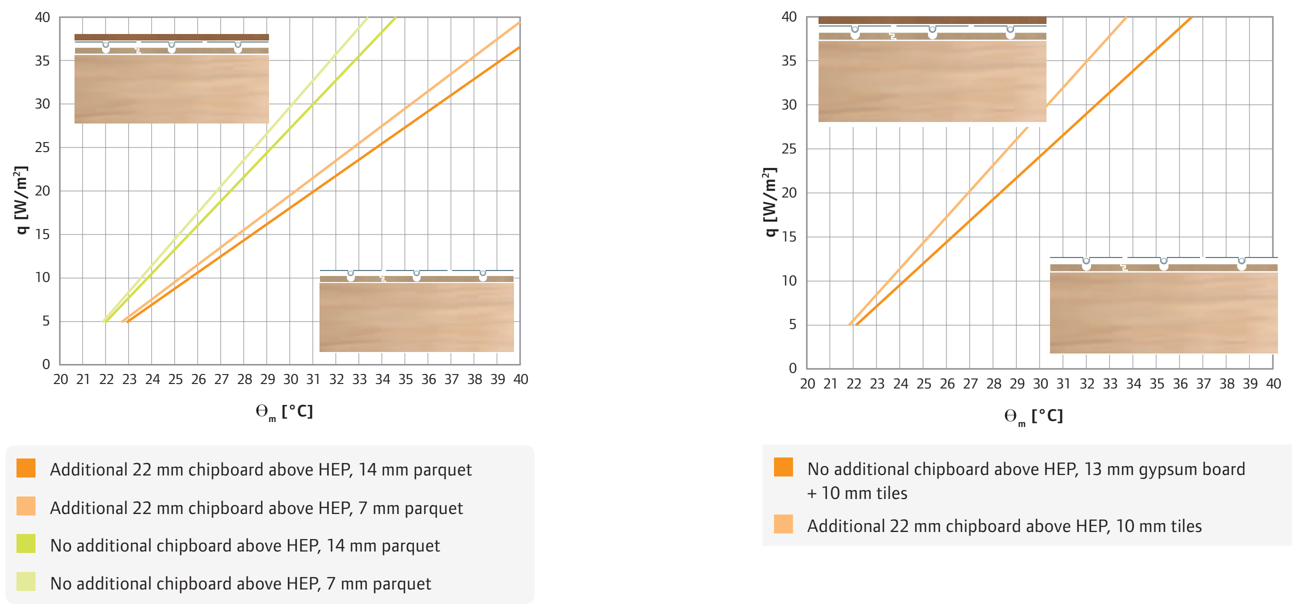


Figure 6.12: Heat exchange to the room as function of the mean water temperature in the underfloor heating pipes (dry construction).
HEAT 2 7.0 simulation with heat transfer coefficient of 10.8 W/(mK) for the floor surface and room temperature 20 °C.

Heat exchange from wet constructions (concrete)

Figure 6.13 shows the heat exchange for different wet underfloor heating system configurations. The diagrams can be used with pipes that has external diameter from 12 mm up to 20 mm.

In a wet construction there is more freedom to choose the geometric parameters compared to a dry construction. For optimal performance of the underfloor heating system, it is recommended to choose the pipe system layout, materials and geometry so that it results in the lowest possible water temperature in the pipes.

The parameters influencing the required mean water temperature is the distance from the pipes to the floor surface, the pipe distance (c/c) as well as the thermal conductivity (λ-values) of the concrete and floor covering materials (wood or tiles).

It is recommended to use pipe installation distance c/c 400 mm only for heat demand up to 20 W/m² with tile floor and 30 W/m² with wooden surface. This is to maintain an even surface temperature distribution (< 2 K).

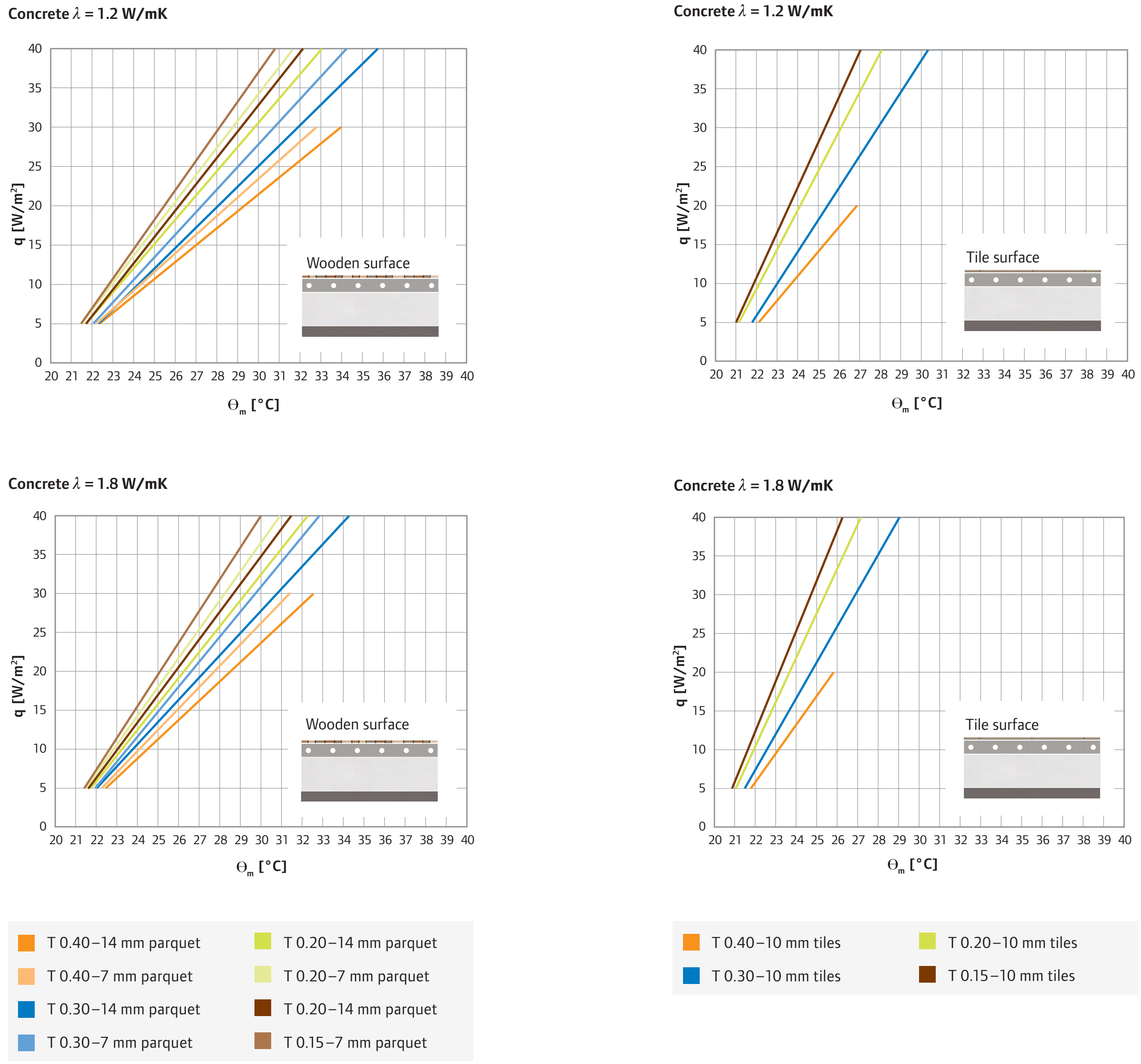


Figure 6.13: Heat exchange to the room as function of the mean water temperature in the underfloor heating pipes (wet construction). HEAT 2 7.0 simulation with heat transfer coefficient of 10.8 W/(mK) for the floor surface and room temperature 20 °C.

Heat exchange with underfloor cooling

Figure 6.14 shows the cooling capacity of a concrete floor as a function of the pipe spacing. In cooling mode a heat transfer coefficient between the floor and the room of 7 W/m²K is applied. The capacity is presented for two different temperature sets: one with mean water temperature 15.5 °C (corresponding to supply 14°C and return 17 °C) and one with mean water temperature 18.5 °C (corresponding to supply 17 °C and return 20 °C).

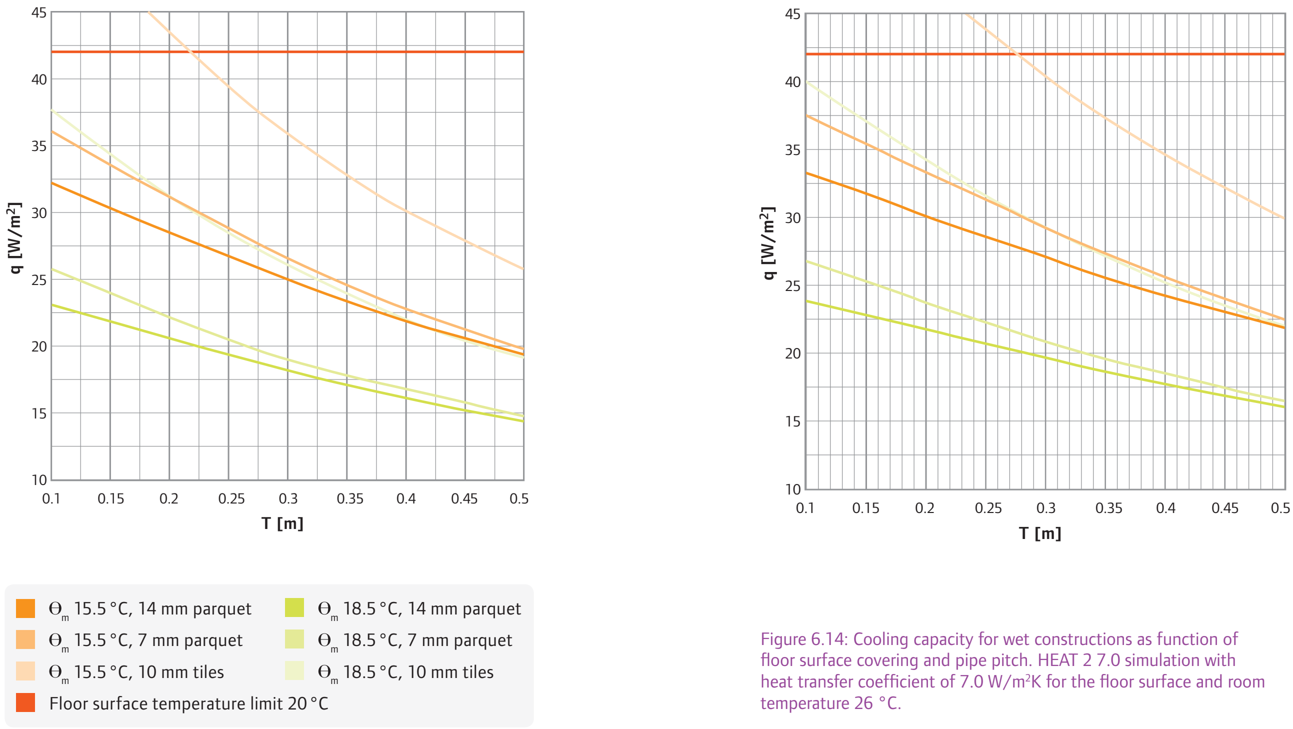
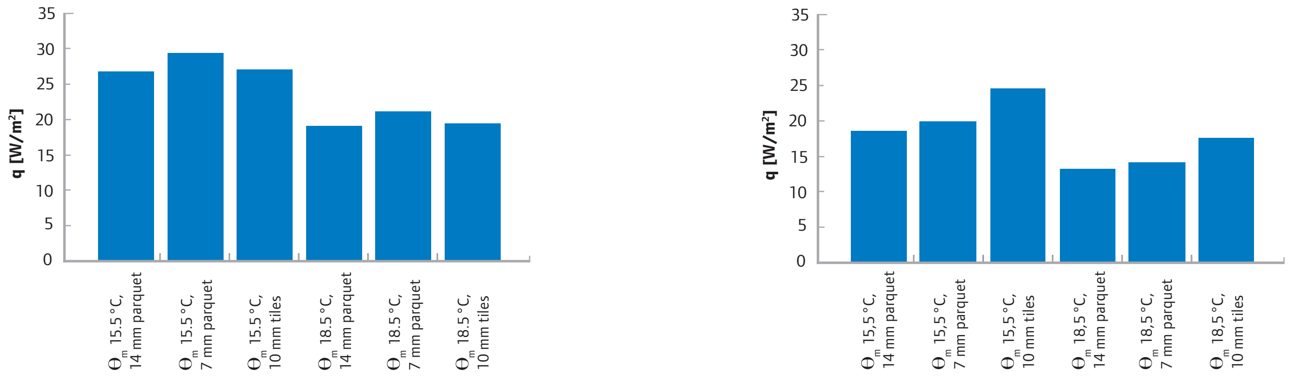


Figure 6.14: Cooling capacity for wet constructions as function of floor surface covering and pipe pitch. HEAT 2 7.0 simulation with heat transfer coefficient of 7.0 W/m²K for the floor surface and room temperature 26 °C.

Figure 6.15 shows the cooling capacity of dry wooden constructions with chipboards and heat emission plate for different types of floor surface covering. The capacity is presented for two different temperature set: one with mean water temperature 15.5 °C (corresponding to supply 14 °C and return 17 °C) and one with mean water temperature 18.5 °C (corresponding to supply 17 °C and return 20 °C).


Dry construction without additional chipboard

Dry construction with additional 22 mm chipboard

Figure 6.15: Cooling capacity for dry constructions as function of floor surface covering. HEAT 2 7.0 simulation with heat transfer coefficient of 7.0 W/m²K for the floor surface and room temperature 26 °C.

Dew point control

An underfloor cooling system shall always be equipped with a dew point control in connection with the control system. The dew point control shall ensure that the cooling temperature applied is always above the dew point in the room surfaces. This is to prevent condensation and possible moisture problems. The dew point control normally operates with a safety factor depending of the accuracy of the control system and reliability of humidity sensors.

Relation factors

System diagrams for capacity and mean water temperature are normally given for fixed pipe diameter and installation depths. Deviations in the depth and diameter can be estimated by using relation factors. In low-energy construction, the influence of changing the pipe diameter and the pipe depth in concrete construction is limited and the relation factors are limited to a few percent.

Relation factor for the pipe diameter (concrete construction)

In buildings with low heat demand, the pipe diameter doesn’t have a big influence on the mean water temperature. When the peak heat demand is less than 50 W/m^2 the influence is less than 5% between a 10 mm pipe and a 20 mm pipe. With a peak heat demand less than 20 W/m^2 the influence is reduced to less than 3%.

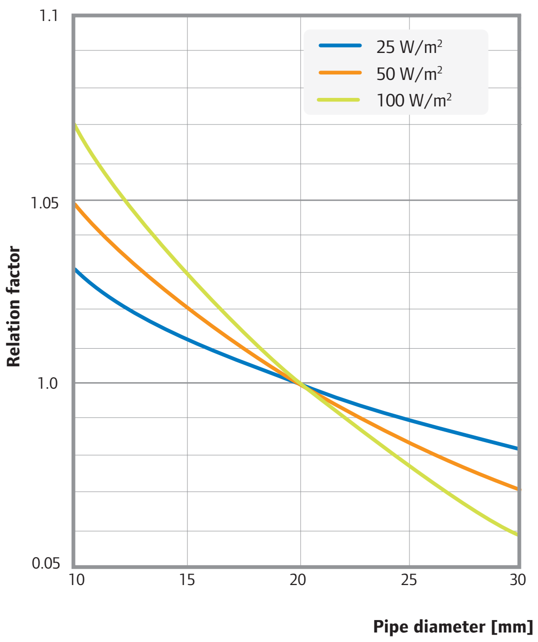


Figure 6.16: Relation factor for the pipe diameters influence on the required mean water temperature.

Relation factor for the pipe installation depth (concrete construction)

In a concrete construction it is generally recommended to install the underfloor heating pipes in a depth of 20-70 mm. In a low-energy house the influence on the required mean water temperature will be less than 5% in this interval, as seen on figure 6.17.

The depth of the installation has an influence on the floor temperature distribution. A deep installation will ensure a very even temperature distribution on the floor, while a surface near installation in principle introduces temperature variations on the surface. In low-energy construction this in praxis not a problem, since even a surface near installation results in a temperature variation < 3 K on the floor.

When a floor covering material with low thermal conductivity is used (like for example parquet or wood) the pipes can be positioned very close to the surface for decreasing the response time.

When using a floor covering with low thermal conductivity (like for example tiles) the thickness of the floor covering included within the concrete thickness for practical calculation purposes.

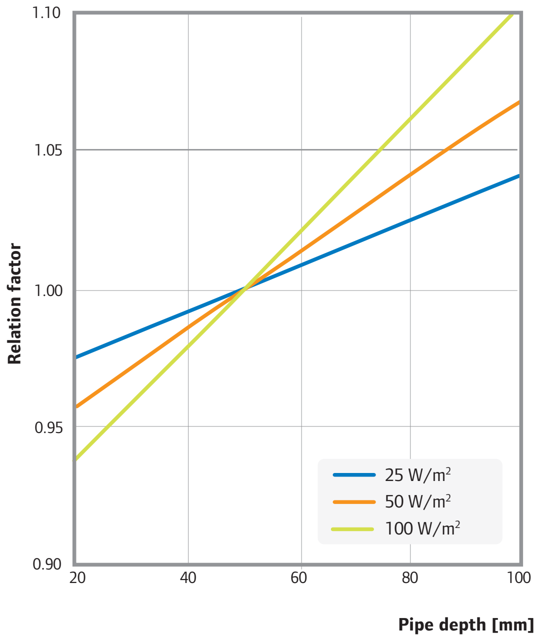


Figure 6.17: Relation factor for the pipe depths influence on the required mean water temperature.

Flow and pressure drop in the pipes

The required heat exchange determines the needed floor temperature and the mean water temperature in the pipes is then given by adding the temperature gradient through the floor construction.

The required flow rate in the pipes is determined by the heat exchange and the ΔT (difference between supply water temperature and return water temperature in the pipes). A standard design criterion is ΔT= 5 K, but in low-energy construction it is recommended to use a design criterion of ΔT= 3 K. This will lower the mean water temperature, which is an advantage for the energy efficiency. With a low ΔT the system is also better suited for cooling and the loops will have a sufficiently high flow rate.

Flow calculations

The relationship between the total heat exchange to the house Φ [W] and the mass flow q_m in the underfloor heating pipes is given by the energy equation:

$$\Phi = q_m c_p \Delta T = q_v \rho c_p \Delta T$$

The mass flow q_m can then be calculated as:

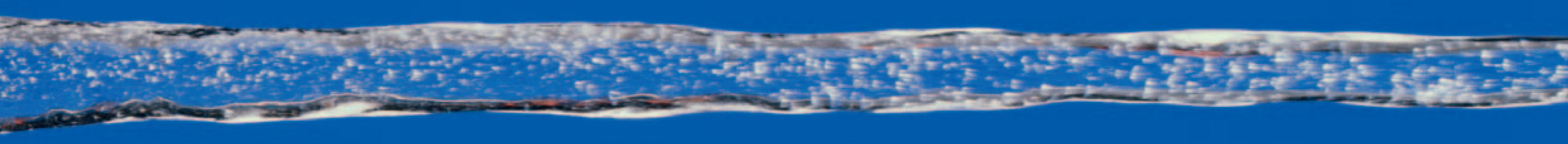
$$q_m = \frac{\Phi}{c_p * \Delta T}$$

The volume flow q_v can then be calculated as:

$$q_v = \frac{\Phi}{\rho * c_p * \Delta T}$$

Where,

q_m	is the mass flow [kg/s]
q_v	is the volume flow [m^3/s]
c_p	is the specific heat capacity of the water [J/kg K]
ρ	is the density of the water [kg/m^3]
ΔT	is the temperature difference between supply and return water [K]



Pressure drop calculations

In order to dimension the necessary pump capacity, the total pressure drop needs to be calculated (in addition to the flow calculation).

The total pressure drop can be obtained by adding the pressure drop across:

1. The pipe loops
2. Manifolds
3. Supply and return pipes
4. Boiler, valves etc

Alternatively to a detailed pressure drop calculation, the different loops can be designed using table 6.4, which shows the maximum area that a loop can cover with a pressure drop lower than 20 kPa. This can serve as a reasonably good rule of thumb for the pumps currently available on the market for single family homes.

Maximum area per loop when pressure loss < 20 kPa

		Pipe diameter (external x wall thickness) and installation distance											
Heat demand, W/m²	ΔT supply - return K	12 x 2 c/c 125 mm	12 x 1.7 c/c 125 mm	14 x 1.6 c/c 200 mm	14 x 2 c/c 200 mm	16 x 2 c/c 200 mm	17 x 2 c/c 200 mm	17 x 2 c/c 300 mm	17 x 2.3 c/c 200 mm	20 x 2 c/c 300 mm	20 x 2.3 c/c 300 mm	17 x 2 c/c 400 mm	20 x 2 c/c 400 mm
20	3	11	12	21	18	24	28	32	26	45	42	35	50
30	3	8	9	16	14	19	21	24	20	35	32	27	38
40	3	6	7	13	11	15	17	20	16	28	26	22	32
50	3	5	6	11	9	13	15	17	14	24	22	19	27
20	5	15	16	30	25	35	39	45	37	64	59	50	71
30	5	11	12	22	19	26	30	34	28	49	45	38	54
40	5	9	10	18	16	22	25	28	23	40	37	31	44
50	5	8	9	16	14	19	21	24	20	35	32	27	38
20	7	18	21	37	32	43	49	57	47	81	74	62	89
30	7	14	16	28	24	33	38	43	36	61	56	48	68
40	7	11	13	23	20	27	31	36	29	51	46	39	56
50	7	10	11	20	17	23	27	30	25	43	40	34	48

Table 6.4: Maximum area (m^2) that a pipe loop can cover with $\Delta p < 20$ kPa.

For practical calculations the amount of piping (length) per square meter is often a useful figure. Table 6.5 provides an easy usable multiplication factor that gives the total pipe length by multiplying the area with the c/c dependant factor.

Pipes [m/m²]					
c/c 125 mm	c/c 150 mm	c/c 200 mm	c/c 250 mm	c/c 300 mm	c/c 400 mm
8.0	6.7	5.0	4.0	3.3	2.5

Table 6.5: Total length of pipe per m^2 as function of pipe centre distance.

Turbulent/laminar flow

The very low heat demand in a low-energy building will influence the required flow in the underfloor heating pipes. Using traditional design criteria with a temperature difference of 5 K between supply and return will result in very low flows in some of the pipe loops in the house.

A low water flow in the pipes is likely to reduce the velocity to such level that the flow is laminar and not turbulent. This will reduce the heat exchange coefficient from the water to the pipe surface and thus give a larger ΔT from the mean water temperature to the floor surface.

It is recommend to design all loops with velocities above the laminar-turbulence transition value (Re = 2320). Table 6.6 provides the minimum required flow and velocity for different pipe dimensions.

Designation Uponor	Dimension [mm]	Minimum velocity [m/s]	Minimum flow [l/s]
Uponor evalPEX Q&E	25 × 2.3	0.092	0.029
Uponor pePEX	20 × 2.3	0.124	0.022
Uponor pePEX	20 × 2.0	0.117	0.023
Uponor evalPEX Q&E	20 × 1.9	0.116	0.023
Uponor pePEX	17 × 2.0	0.145	0.019
Uponor evalPEX Q&E	16 × 2.0	0.157	0.017
Uponor evalPEX Q&E	14 × 2.0	0.188	0.014
Uponor evalPEX Q&E	12 × 2.0	0.236	0.011
Uponor evalPEX Q&E	12 × 1.7	0.221	0.012

Table 6.6: Total length of pipe per m^2 as function of pipe centre distance.

Hydraulic balancing of the system

In an underfloor heating installation, the different loops in the different rooms will typically have different length and different flow. The means that the unbalanced loops will have different pressure drop. In order to achieve an even heat distribution between the individual rooms, it is necessary to balance the loops so that they have the same pressure loss.

Hydraulic balancing is typically done with valves placed at each circuit in the manifold. It is thus important that the pressure loss difference between the shortest and longest loop is less than the maximum pressure loss that can be created with the balancing valve. Table 6.7 shows the maximum pressure difference allowed between the shortest and the longest loop when using Uponor manifolds (Pro manifold and WGF manifold).

			Pro manifold	WGF manifold
Active area [m^2]	Heat loss [W m^2]	Flow [l/s] Δt 5	Maximum Δ pressure between loops [kPa]	Maximum Δ pressure between loops [kPa]
4	20	0.004	0.7	1.8
4	25	0.005	1.1	2.9
4	30	0.006	1.6	4.1
4	35	0.007	2.2	5.6
4	40	0.008	2.9	7.3
5	20	0.005	1.1	2.9
5	25	0.006	1.8	4.5
5	30	0.007	2.5	6.5
5	35	0.008	3.4	8.8
5	40	0.010	4.5	11.5
6	20	0.006	1.6	4.1
6	25	0.007	2.5	6.5
6	30	0.009	3.6	9.3
6	35	0.010	5.0	12.6
6	40	0.011	6.5	16.5
7	20	0.007	2.2	5.6
7	25	0.008	3.4	8.8
7	30	0.010	5.0	12.6
7	35	0.012	6.8	17.2
7	40	0.013	8.8	22.5
8	20	0.008	2.9	7.3
8	25	0.010	4.5	11.5
8	30	0.011	6.5	16.5
8	35	0.013	8.8	22.5
8	40	0.015	11.5	29.4
9	20	0.009	3.6	9.3
9	25	0.011	5.7	14.5
9	30	0.013	8.2	20.9
9	35	0.015	11.2	28.5
9	40	0.017	14.6	37.2
10	20	0.010	4.5	11.5
10	25	0.012	7.0	17.9
10	30	0.014	10.1	25.8
10	35	0.017	13.8	35.1
10	40	0.019	18.0	45.9

Table 6.7: Maximum pressure difference allowed between the shortest and the longest loop.

Electronic balancing of the system (DEM)

Best in class control technology operates with sophisticated algorithms for the heat supply which at the same time eliminates the need for mechanical balancing. State of the art is the Uponor DEM controls (Dynamic Energy Management). DEM operates by pulsed heat supply in each loop based on a self-learning algorithm and balances the loops automatically.

In low-energy construction it is recommend always using Uponor DEM controls. This will eliminated any problems with low flow and variation in the heat demand and thus secure the best comfort for the end-user.

Pipe installation technique

When the pipe layout is designed, the first attention should be made to the position of the manifold and the routing from the manifold to the rooms. The manifold should be placed as central in the house as possible and the routing of the pipes from the manifold to each room should follow the external walls or other potentially cold areas.

The choice of loop configuration depends on the construction techniques and local practices. For low-energy construction it is recommended to use a sinus installation for the loop configuration.

A **sinus installation** is easy to install and gives an even temperature distribution on the floor surface. The main advantage of a sinus installation is that it easily adapts to all kinds of floor constructions. It can also be easily modified for different energy requirements by altering the pipe pitch. A sinus installation is the most suitable configuration for underfloor heating and cooling in single family houses.

In a **parallel installation** the supply and return pipes in the loop layout runs parallel to each other. It provides an even mean temperature but higher temperature variation within small areas. It is suitable for heating larger areas with a relatively high heat demand (typical industrial premises) and hence not the obvious choice for low-energy homes.

A **spiral installation** is basically a variation of a parallel installation but is shaped as a spiral. This configuration is suitable for construction with a relatively high heat demand. It is less suitable for installation in wooden floor structures. A spiral installation is therefore normally not recommendable for low-energy houses. But the configuration overcomes the rigidity problem encountered in some pipes since there are no sharp bends. It also allows the pipe to be laid at a small pitch.

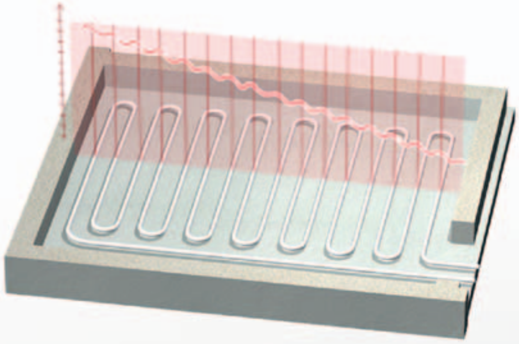


Figure 6.18: Sinus installation.

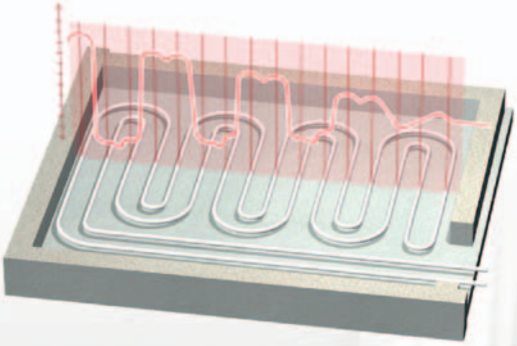


Figure 6.19: Parallel installation.

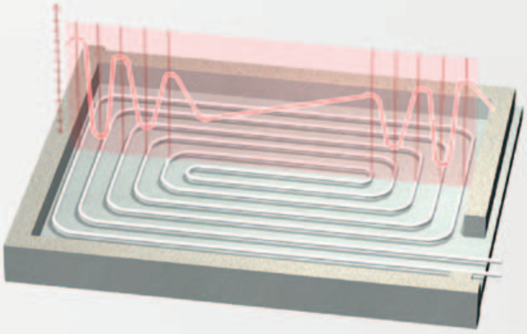


Figure 6.20: Spiral installation.

7. Case study: a low-energy house in Denmark

An optimal design for energy and indoor climate in low-energy houses is not a simple task. Traditional design methods are normally based on rules of thumb and average values for thermal loads and various contributions from sun radiation, people, equipment etc. But in well insulated low-energy houses the building physics and thermal behavior is complex and thus difficult to predict with simple methods.

The optimal basis for a good low energy design is to perform a full year thermal simulation of the house. By doing this, all aspects of indoor climate, energy consumption and the need for heating, cooling and mechanical ventilation can be analysed.

A building simulation provides a full thermal calculation for the entire building carried out for a full year with time steps of typically 1 hour. All thermal aspects such as outdoor conditions, indoor thermal loads, air exchange rates, U-values and outdoor conditions are taken into account. A number of proven buildings simulation tools are commercially available.

Building simulations

The present building simulations were carried out with the building simulation software IDA ICE 4.0. IDA is applying weather data based on a test reference year including actual outdoor temperatures, sun and wind data. The simulations were made for typical low-energy houses with annual heating consumption in the range of 20 to 50 kWh/m^2 per year with heat loads in the range of 20 to 40 W/m^2. A typical Danish low-energy house corresponding to the Danish building standards BR10 was exposed to a test reference year in order to validate the influence of climatic parameters including external temperature, humidity and solar radiation.

Building geometry and U-values

A floor plan of the house is shown in figure 7.1 with the corresponding building data in table 7.1.

The simulations were made for building geometries corresponding to the current building codes in Denmark. The building was modelled based on a real house currently build by Danish house manufactures. All employed data such as U-values, loads, ventilation and infiltration rates were specified according to the Danish building regulation BR10.

Weather data from a Danish reference year is used, and most findings would be applicable in similar climatic conditions in Northern Europe. Internal loads with a total maximum of 5 W/m^2 (persons 1.5 W/m^2 and equipment and lights 3.5 W/m^2) were specified according to a detailed occupancy schedule. The "standard house" input data corresponds to the minimum requirements in the current building code, whereas the "low energy" input data corresponds to the insulation and tightness requirement stipulated in the low energy class 2015.

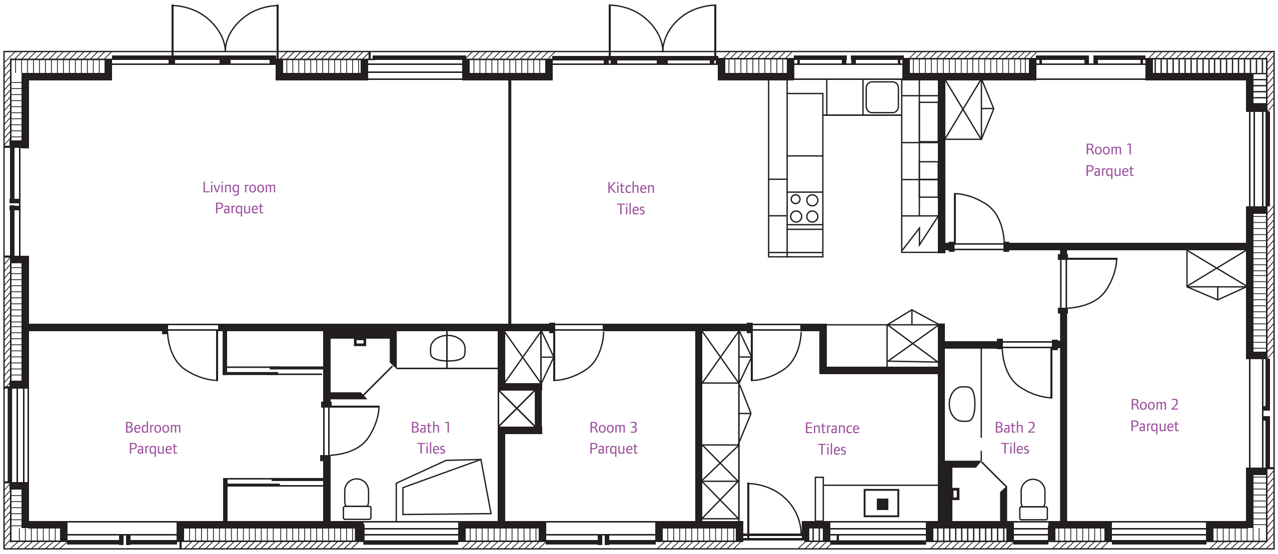


Figure 7.1: Floor plan of the case study house (south façade upwards).

	Standard	Low-energy
U-value, External walls	0.23	0.18
U-value, Roof	0.13	0.10
U-value, Ground floor	0.10	0.09
U-value, Windows	1.56	1.09
U-value, Doors	1.56	1.09
Ventilation max supply efficiency	85%	85%
Infiltration	0.13 l/s per m^2	0.06 l/s per m^2

Table 7.1: Input data for building envelope, ventilation and infiltration.

Internal loads with a total maximum of 5 W/m^2 (persons 1.5 W/m^2 and equipment and lights 3.5 W/m^2) were for each case specified according to a detailed schedule occupancy schedule (see table 7.2).

	Occupancy			1 April to 30 September				Room temperature > 24 °C and outdoor temperature > 16 °C	
	All year			South	West	East	North	Open window	
Room	Met	Time occupancy	Other time	Blinds on	Blinds on	Blinds on	Blinds on	Morning	Evening
Room 1	1	22.00-06.00	0	08.00-17.00	12.00-21.00			07.00-08.00	21.00-22.00
Room 2	1	22.00-06.00	0		12.00-21.00		none	07.00-08.00	21.00-22.00
Bedroom	2	22.00-06.00	0			06.00-14.00	none		21.00-22.00
Bathroom 1	1	06.00-07.00	0				none	06.00-07.00	
Room 3	0	-	0				none	07.00-08.00	21.00-22.00
Bathroom 2	1	17.00-18.00	0				none		17.00-18.00
Entrance	0	-	0				none		
Living room/kitchen	0.5*4	18.00-22.00	0	08.00-17.00		06.00-14.00	none		17.00-20.00

Table 7.2: Detailed schedule for occupancy, shading, window opening and ventilation by-pass (active when room temperature > 24 °C and outdoor temperature > 16 °C).

Heat loads

Table 7.3 shows the peak loads for the heat demand. The low-energy building standard typically reduce the annual energy consumption by 30% or more while the peak loads only typically reduce it by 15%.

There is a relatively high peak load variation between rooms with peak loads of up to 22 W/m^2 (south facing rooms) and 32 W/m^2 (north facing rooms). The relatively high variation is caused by the orientation and the fact that some rooms are located in the centre of the house and not surrounded by any external walls.

Room	Area	Heat powers [W/m^2]	
		Standard	Low-energy
Room 1	14	30.8	25.4
Room 2	13	35.3	29.8
Bedroom	15	36.3	31.2
Bathroom 1	9	29.7	26.4
Room 3	10	32.5	28.0
Bathroom 2	5	25.0	22.2
Entrance	10	30.1	26.7
Living room/kitchen	64	26.4	21.6
Average [W/m^2]		29.6	24.9

Table 7.3: Peak loads for the heat demand (air change rate 0.5 ach supplied at T_{min} = 18 °C).

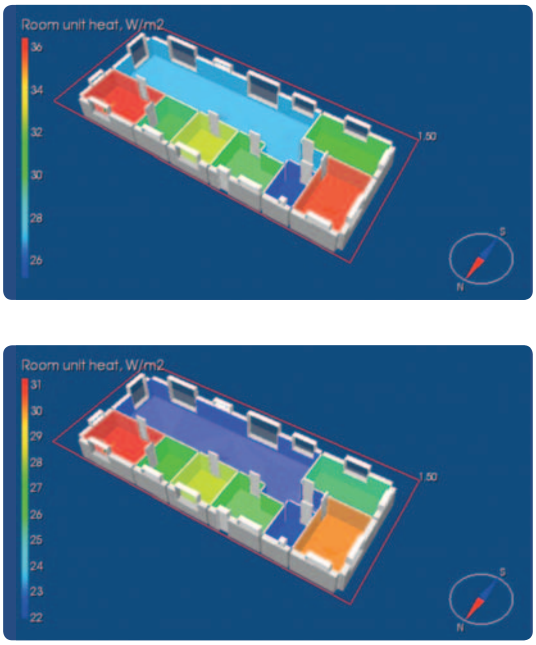


Figure 7.2 Heating peak loads and variations for different rooms (standard house BR10 top and low energy class 2015 bottom).

Figure 7.3 shows the duration curve for the heat demand. The heating season for the standard house adds up to about 4 500 hours while the low energy insulation measures reduce the heating season to about 4 000 hours. Peak loads above 18 W/m^2 (total 2 500 W) for the standard house and 14 W/m^2 (total 2 000 W) for the low-energy house only occurs for a very limited time period of about 70 hours per year. It is nevertheless crucial to take the extreme peak into consideration when designing the capacity of the heating system, in order to meet the indoor comfort requirements.

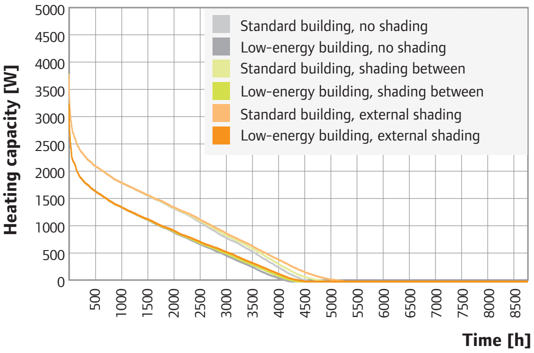


Figure 7.3: Duration curves for the heat demand.

Cooling loads

Table 7.4 shows the peak loads for the cooling demand. Applying the insulation standards of the current building codes and the emerging low energy standard (class 2015) is seen to introduce significant cooling loads up 63 W/m^2 in particular in rooms exposed to the south and south-west. Also for the cooling loads a very high variation occurs mainly due to the room orientation. When calculating the cooling peak loads, internal loads and sun were included. The latter has the most significant importance. Hence the cooling peak loads doesn't necessarily occur on the "warmest day" but are rather dependent on the building geometry and its orientation.

Room	Area [m^2]	Cooling loads [W/m^2]					
		Standard building			Low-energy building		
		No shading	Shading between glassing	External shading	No shading	Shading between glassing	External shading
Room 1	14	46.2	30.6	19.7	49.3	32.1	20.6
Room 2	13	57.1	40.7	27.0	61.4	43.6	28.4
Bedroom	15	15.6	13.8	13.6	16.1	14.3	13.9
Bathroom 1	9	9.5	8.6	8.5	9.7	9.9	9.3
Room 3	10	14.7	14.2	14.1	16.4	16.5	15.7
Bathroom 2	5	17.9	16.4	16.0	17.9	17.1	15.9
Entrance	10	6.6	6.3	6.3	7.3	7.5	6.9
Living room/kitchen	64	56.0	38.2	24.4	60.4	40.6	25.4
Total [W]		**5 595**	**3 974**	**2 753**	**6 009**	**4 244**	**2 881**
Average [W/m^2]		**40.0**	**28.4**	**19.7**	**42.9**	**30.3**	**20.6**

Table 7.4: Cooling peak loads.

The calculated cooling loads excluded the part being covered by the ventilation system. The inlet air of the ventilation system was supplied with a temperature of 18 °C at an applied air change rate of 0.5 ach for the total volume of the building. During the summer period there was a by-pass for the HRV unit when the outdoor temperature exceeded 18 °C. As long as the outdoor temperature is lower than the indoor temperature it is possible to allow the colder outdoor air to enter the room and reduce overheating.

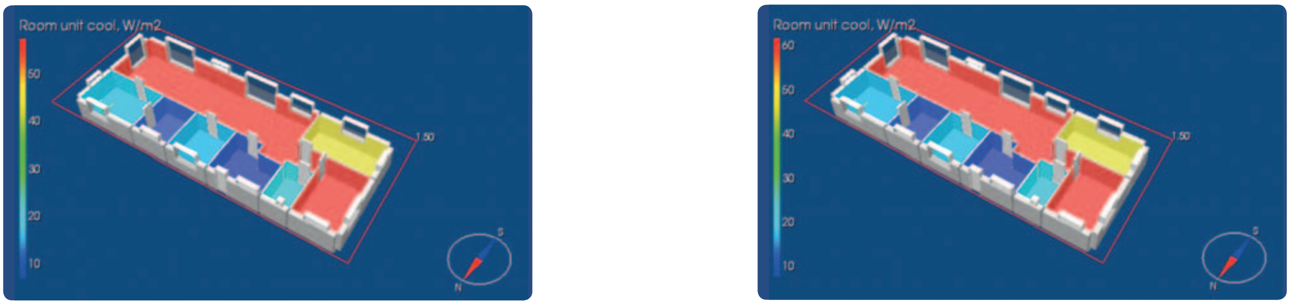


Figure 7.4: Cooling peak loads and variations for different rooms, standard BR10 left, low energy class 2015 right (case with no shading).

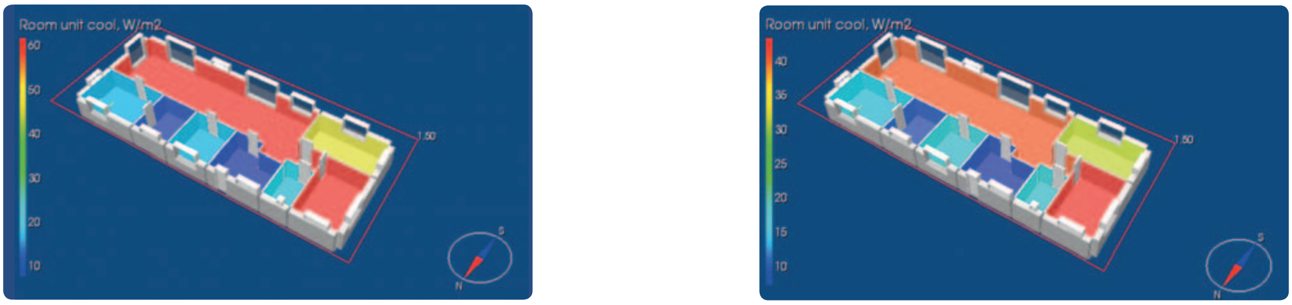


Figure 7.5: Cooling peak loads and variations for different rooms, standard BR10 left, low energy class 2015 right (case with shading between glasses).

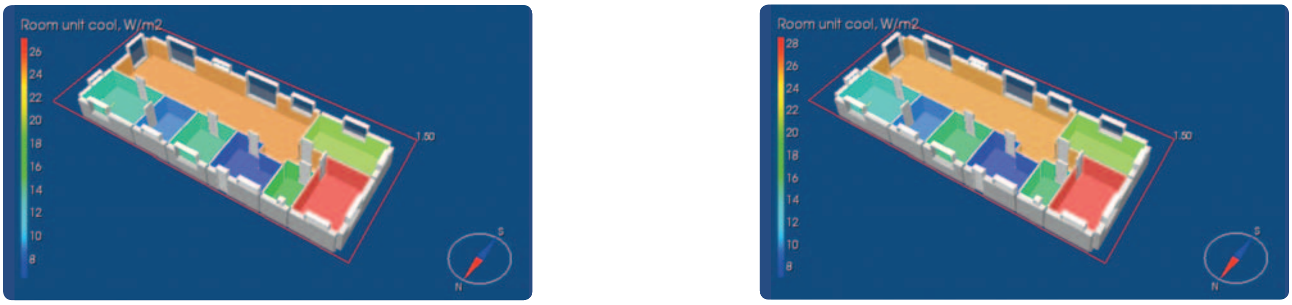


Figure 7.6: Cooling peak loads and variations for different rooms, standard BR10 left, low energy class 2015 right (case with external shading).

Cooling loads up to 42 W/m^2 occurs for a house constructed according the standard building norm, whereas a house build after the low energy standard will be exposed to cooling loads up to 46 W/m^2. The cooling peak loads are mainly caused by sun radiation, while internal loads have a minor effect.

Figure 7.7 shows the duration curves for the cooling loads. Shading can to some extend reduce the cooling loads but not eliminate them. The applied shading are external shading with an 86% shading factor. The shading are applied in the period from 1 April to 30 September and only during day time between 8 am to 5 pm when the house is assumed not to be unoccupied. Weekend occupancy patterns are assumed to be similar to working days.

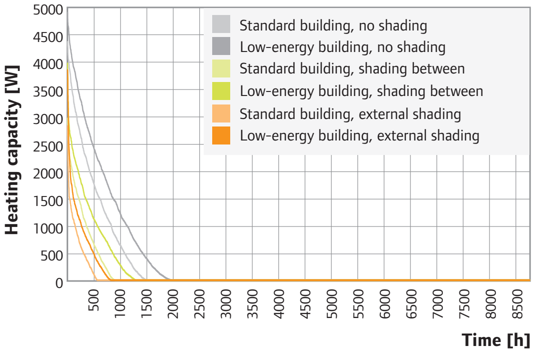


Figure 7.7: Duration curves for the cooling loads

Indoor temperature management with underfloor cooling

The large cooling loads occurring in a low-energy house needs to managed in order to ensure an adequate thermal indoor climate.

According to the indoor climate comfort criteria's, thermal comfort requires an indoor temperature between 20 and 24 °C in the winter and 23-26 °C in the summer. If there is no cooling at all in the building, the temperature will be outside the comfort range in about 20% of the time for a standard house and for about 30% of the time in a low-energy house as illustrated in the duration curve figure 7.7.

The first step for reducing cooling loads should always be passive measures such as natural ventilation, HRV by-pass for cold outside air and proper use of shading of the windows from direct sun radiation. But the simulations clearly illustrate that passive measures are not sufficient for reducing the cooling loads.

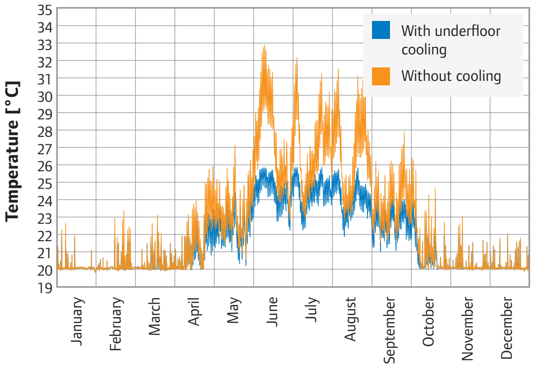
Figure 7.8 shows that window opening and HRV by-pass wasn't enough to maintain room temperatures below 26 °C in the simulated low-energy houses. Passive measures can reduce cooling peak loads to 25 W/m^2. The remaining part of the cooling loads needs to be removed by an active cooling system.

Using electricity for active cooling by the ventilation system will not be possible within low energy frames. Instead it its suggested to using active cooling using a combined underfloor heating and cooling system. The cooling need can be met by using floor cooling with a flow temperature relatively close to room temperature, typically at 14-17 °C. With this favorable temperature level the cooling needs can be covered with minimal energy consumption, for example via free cooling from the ground or with a ground-coupled heat pump.

The simulated underfloor cooling was specified so that max cooling output was 30 W/m^2, the supply water temperature 14 °C and return 17 °C. The thermostat set point was 24 °C. In all cases underfloor cooling was enough to keep the room temperatures below 26 °C.

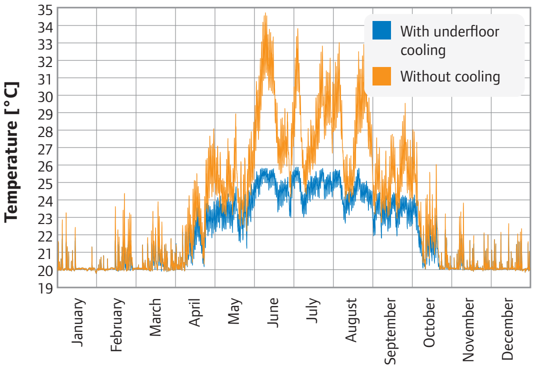
Ventilation return air dry bulb temperature
Standard building, no shading

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used



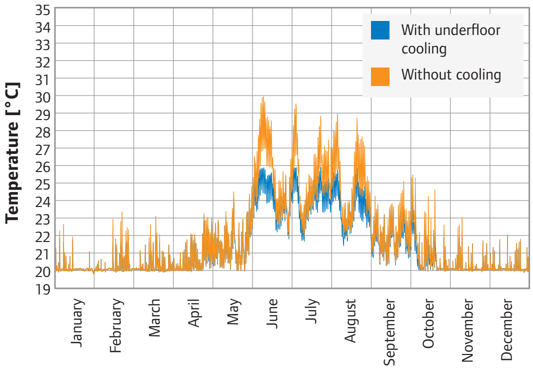
Ventilation return air dry bulb temperature
Low-energy building, no shading

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used



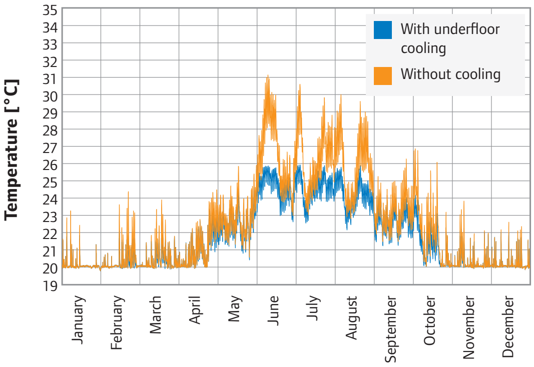
Ventilation return air dry bulb temperature
Standard building, shading between

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used



Ventilation return air dry bulb temperature
Low-energy building, shading between

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used



Ventilation return air dry bulb temperature
Standard building, external shading

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used

Ventilation return air dry bulb temperature
Low-energy building, external shading

Window opening and HRV by-pass are used during cooling season when underfloor cooling is not used

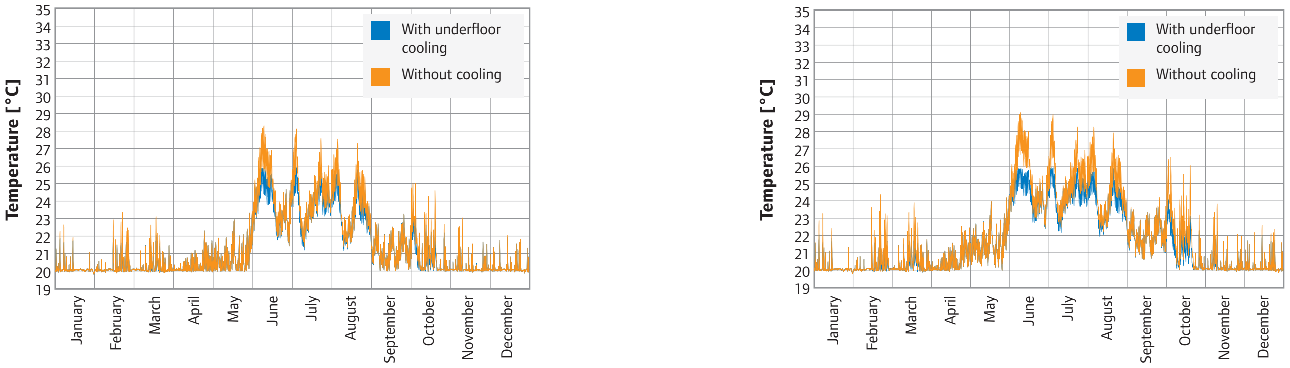
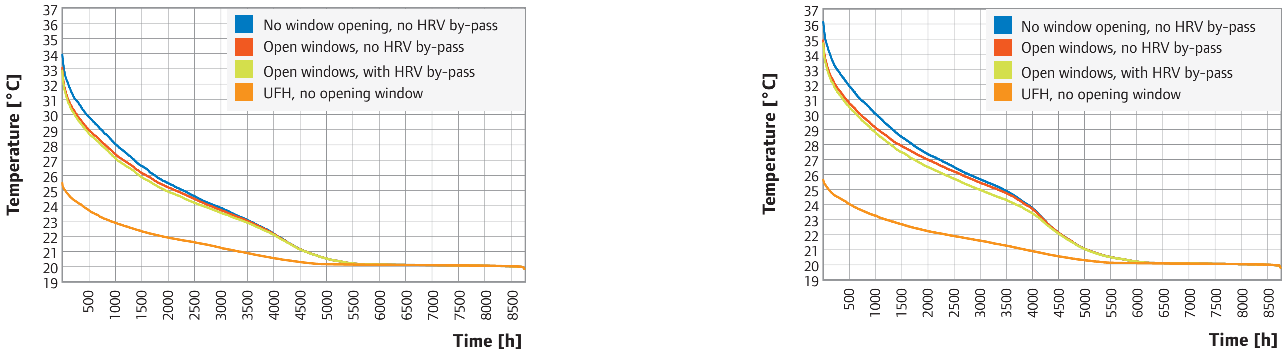


Figure 7.8: Average room temperature with and without underfloor cooling.

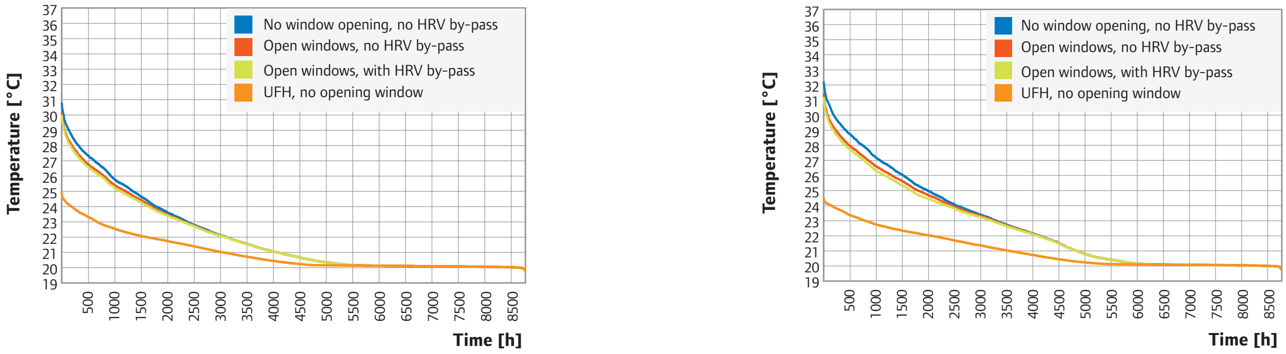
HRV return air dry bulb temperature
Standard building, no shading

HRV return air dry bulb temperature
Low-energy building, no shading



HRV return air dry bulb temperature
Standard building, shading between

HRV return air dry bulb temperature
Low-energy building, shading between



HRV return air dry bulb temperature
Standard building, external shading

HRV return air dry bulb temperature
Low-energy building, external shading

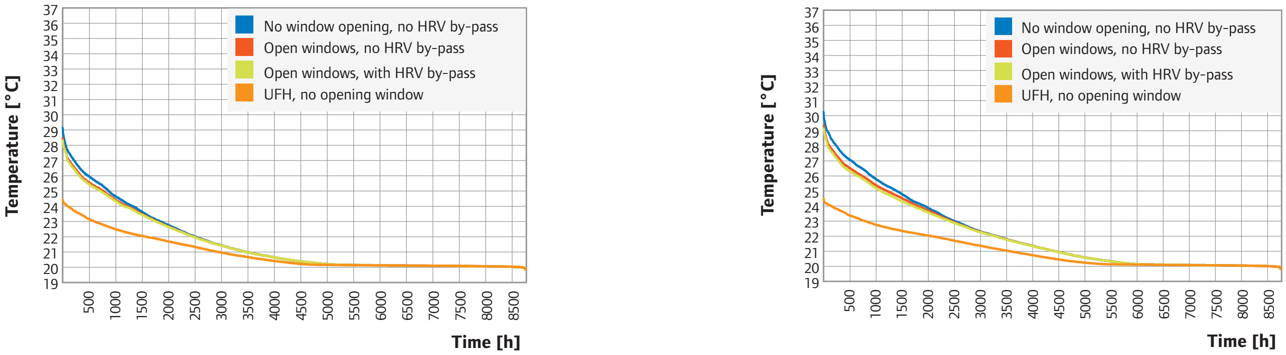


Figure 7.9: Duration curves for the room temperature with and without underfloor cooling.

Required system capacity

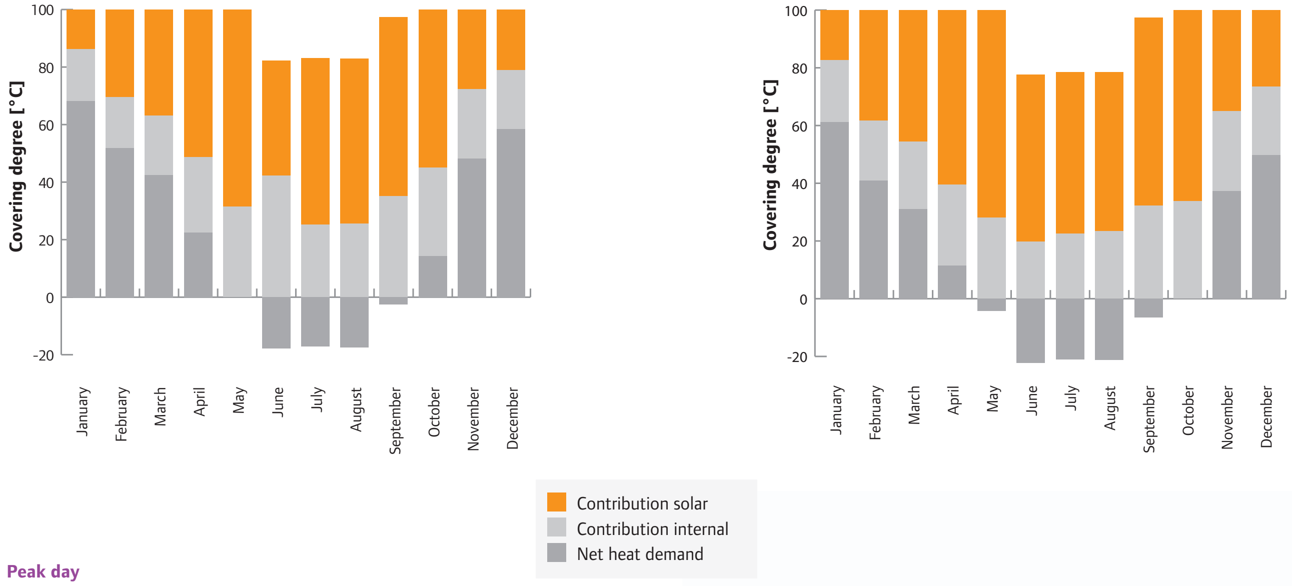
The design of the required capacity of the heating and cooling system needs to be done based on the calculated peak loads. The building simulations has shown that there are large variations in between individual room peak loads, which already indicates that it will not be enough to design system capacity based on average considerations.

A typical design misconception is that the free heat contributions from the sun, people and equipment are equally distributed over time. As seen in figure 7.10 this is far from being the case. Nevertheless, capacity dimensioning is in many cases done with average values, assuming an average contribution from the sun and an internal load based on a specific number of people using the house.

It is obviously difficult to predict the individual user pattern in a given house and difficult to predict the exact thermal conditions on the coldest day (design day). But the recommendation is to design the system capacity preferably with a detailed calculation by simulation or alternative with a worst case scenario taking into account the large variations in loads over time and inside the house.

Standard building full year

Low-energy building full year



Peak day

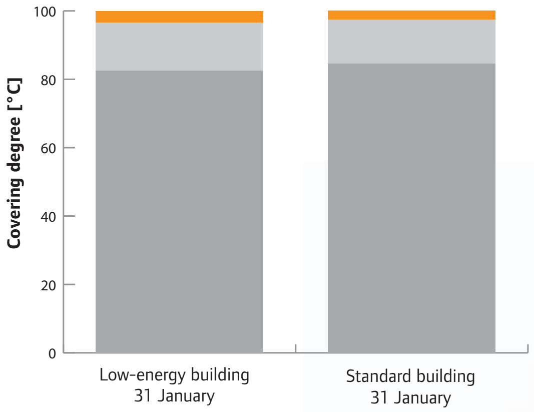
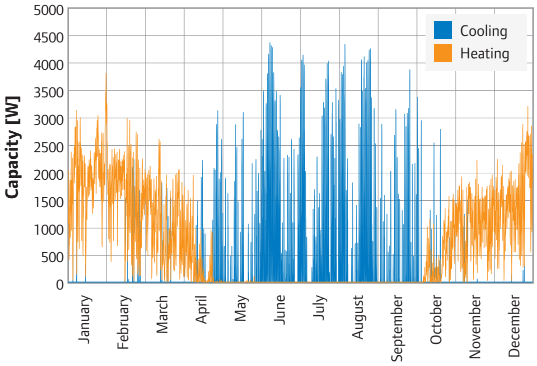


Figure 7.10: During the coldest month (January) solar transmission and internal loads nearly cover 40% of the heat demand on an average basis in the low-energy house. On the coldest day, however, the free contribution is less than 20%.

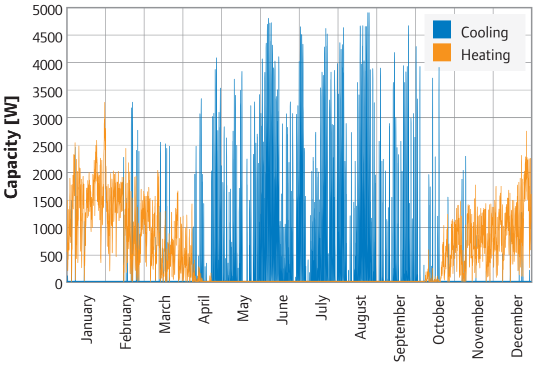
Required heating and cooling power
Standard building, no shading

Window opening and HRV by-pass are used during cooling season



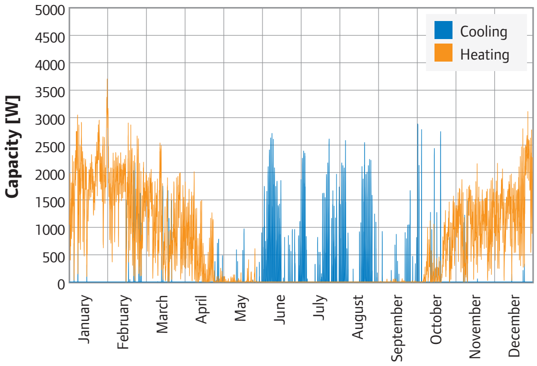
Required heating and cooling power
Low-energy building, no shading

Window opening and HRV by-pass are used during cooling season



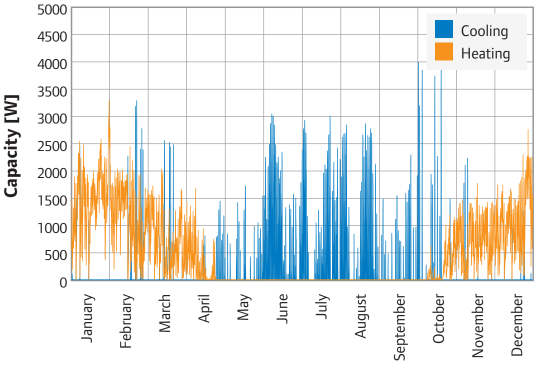
Required heating and cooling power
Standard building, shading between

Window opening and HRV by-pass are used during cooling season



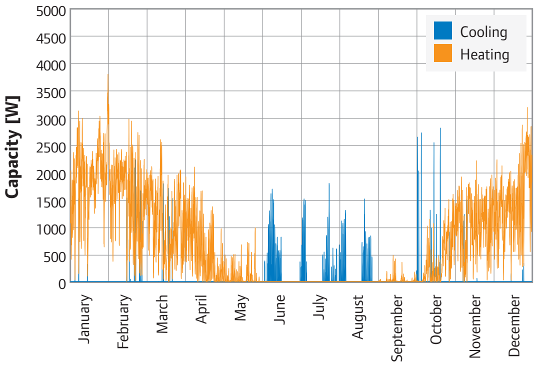
Required heating and cooling power
Low-energy building, shading between

Window opening and HRV by-pass are used during cooling season



Required heating and cooling power
Standard building, external shading

Window opening and HRV by-pass are used during cooling season



Required heating and cooling power
Low-energy building, external shading

Window opening and HRV by-pass are used during cooling season

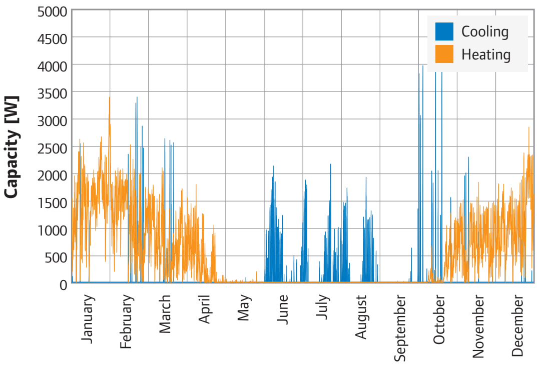


Figure 7.11: Required heating and cooling capacity (notice the large cooling loads in the intermediate seasons).

Net energy demand

Table 7.5 shows the annual energy consumption in terms of net energy demand for space heating, domestic hot water, ventilation and electricity for pumps. The net energy demand for space cooling is not included here, as it is assumed that possible space cooling is provided by underfloor cooling using free cooling from the ground.

		Energy demand [kWh/m²]					
		Space heating					
Case	Area [m²]	No shading	Shading between glassing	External shading	Domestic hot water	Ventilation	Pumps
Standard BR10	139	39.0	40.0	41.2	13.1	3.3	0.5
Low energy class 1015	139	26.8	27.4	28.0	13.1	2.8	0.4

Table 7.5: Annual energy demand

Annual energy consumption and emissions

Figure 7.12 shows the annual energy consumption for different emitter systems and with different heat sources. The figures include heating, ventilation and domestic hot water. As seen, low temperature emitter systems ensure the best energy performance as well as the lowest CO_2 emissions (figure 7.13).

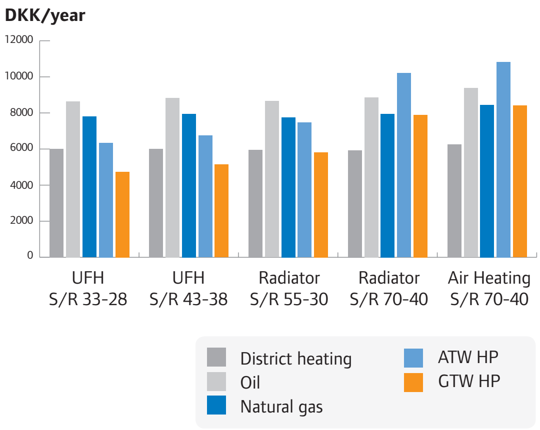


Figure 7.12: Annual running cost of different emitter systems and with different heat sources.

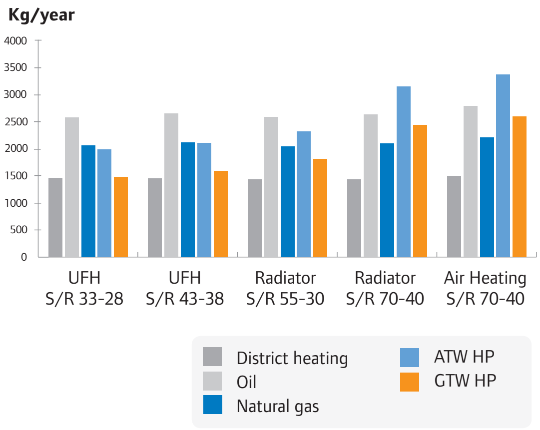


Figure 7.13: Annual CO_2 emission of different emitter systems with different heat sources.

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