Beyond nearly zero-energy buildings: Experimental investigation of the thermal indoor environment and energy performance of a single-family house designed for plus-energy targets

Kazanci, Ongun Berk; Olesen, Bjarne W.

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Beyond nZEB: Experimental investigation of the thermal indoor environment and energy performance of a single-family house designed for plus-energy targets

A detached, one-story, single family house in Denmark was operated with different heating and cooling strategies for one year. The strategies compared during the heating season were floor heating without ventilation, floor heating supplemented by warm air heating (ventilation system), and floor heating with heat recovery from exhaust air. During the cooling season, the house was cooled by floor cooling and was ventilated mechanically.

Air and globe (operative, when applicable) temperatures at different heights at a central location were recorded. The thermal indoor environment, local thermal discomfort and overheating were evaluated based on EN 15251:2007, EN ISO 7730:2005 and DS 469:2013, respectively. Energy performance was evaluated based on the energy production and HVAC system energy use.

The thermal indoor environment during the heating season was satisfactory but it was not possible to reach the intended operative temperature when the outside temperatures were very low. During the cooling season, the cooling demand was high and overheating was a problem.

Although the house was designed as a plus-energy house, it did not perform as one under the Danish climate conditions. It would be possible to decrease the heating and cooling demand during the design phase through careful consideration of parameters such as the orientation, glazing area, solar shading, and thermal mass. With a lower demand, plus-energy levels can be achieved even with the minimum contribution from the energy producing components.

Introduction

Due to the depletion of fossil fuels and due to the remarkable global effects of greenhouse gas emissions, energy efficiency measures are being implemented in a variety of sectors that use significant amounts of energy. The buildings sector is one of these and a broad range of research activities are being carried out to find ways to decrease the energy consumption of buildings. The main driver behind these efforts is the massive energy requirements of buildings; buildings are responsible for 40% of the energy consumption in the member states of the European Union (European Commission 2010).

Building energy codes are becoming tighter and nearly zero-energy building (nZEB) levels are dictated for new buildings by 2020 in the European Union (European Commission 2010). A further goal is to design plus-energy houses, i.e. houses that produce more energy from renewable energy resources than they import from external resources in a given year, according to the definition given by the European Commission (2009). These trends are reflected in different initiatives such as the Passive House movement (Passivhaus Institut 2015; the International Passive House Association 2015) and recently in the Active House Alliance (2015). The idea of plus-energy houses is also being promoted with competitions such as Solar Decathlon (2012), where multidisciplinary teams from universities compete to design, build and operate plus-energy houses. Plus-energy houses could have a significant role in the energy system in a number of ways: they can compensate for the old buildings that are too expensive to upgrade to nZEB levels, and they can act as small power plants in the energy system.

When striving for energy efficiency in buildings, it should not be overlooked that people spend most of their time indoors (Olesen and Seelen 1993). Buildings are built for people to live in and to have a comfortable, healthy and productive indoor environment, not to save energy. Thus, energy savings should not be achieved at the cost of occupant thermal discomfort. Instead, both of these goals should be achieved simultaneously.

The international focus on the residential sector is increasing (ASHRAE 2014) and there have been a number of surveys that monitored energy performance and indoor environment in passive houses (Schnieders and Hermelink 2006; Larsen et al. 2012; Brunsgaard et al. 2012). One commonly encountered problem in low-energy and passive houses is overheating (too high temperatures). Overheating has been reported from different countries such as Denmark by Larsen and Jensen (2011), from Sweden by Janson (2010) and Rohdin et al. (2014), and from Finland by Holopainen et al. (2015). Maivel et al. (2015) also reported overheating in new apartment buildings in Estonia. Some of the main reasons of overheating are large glazing areas, poor or lack of solar shading, lack of ventilation (Larsen 2011), lack of thermal mass, and lack of adequate modeling tools in the design phase (Phillips and Levin 2015).

In addition to overheating, varying room temperatures (Rohdin et al. 2014; Holopainen et al. 2015), too low air temperatures in winter, stuffiness and poor air quality, and too low floor surface temperatures in winter (Rohdin et al. 2014) are some of the other problems that were encountered in low-energy and passive houses. A discussion of research needs regarding the indoor environmental quality in low-energy houses can be found in Phillips and Levin (2015).

There are still unsolved issues and problems to be addressed regarding low-energy, passive or plus-energy houses and designers and engineers can therefore benefit from research on the design, construction and operation of such buildings. In this context, a detached, one-story, single family house, which was initially designed to be a plus-energy house (Kazanci et al. 2014), was operated from 26/09/2013 to 1/10/2014 to compare a number of different heating and cooling strategies (Kazanci and Olesen 2014a; Kazanci and Olesen 2015a). The thermal indoor environment and energy performance of the house were monitored during this period.

The house was designed for, and participated in the competition Solar Decathlon Europe 2012 in Spain, and since then it has been used as a full-scale experimental facility. During the experiments reported here it was unoccupied and the internal heat gains were simulated by means of heated dummies.

The performance of the different heating and cooling strategies was evaluated in terms of the resulting thermal indoor environment, local thermal discomfort (vertical air temperature difference between head and ankles) and overheating, according to EN 15251 (European Committee for Standardization 2007), EN ISO 7730 (European Committee for Standardization 2005) and DS 469 (Danish Standards 2013), respectively. The energy production and the energy consumption of the heating, cooling and ventilation systems of the house were used to evaluate its energy performance.

Details of the house

Construction details

The test house was a single family, detached, one-story house with a floor area of 66.2 m^2 and a conditioned volume of 213 m^3. The house was constructed from pre-fabricated wooden elements that were made from layers of laminated veneer lumber boards, which in combination with I beams in between formed the structural elements. The house was insulated with a combination of 200 mm mineral wool (between the boards of the structural elements) and 80 mm compressed stone wool fibers (40 mm on each side, outside the boards of the structural elements). A drawing of the structural element is given in Kazanci et al. (2014). The walls, roof and floor structures were formed by installing prefabricated elements in a sequential order and the joints were sealed. The North and South glazing façades were inserted later and the joints between the glazing frame and the house structure were sealed. The house was supported on 200-300 mm concrete blocks and the space between the ground and the house's floor structure was covered which created a crawl-space below the house.

Inside the house, there was a single space with a high and inclined ceiling, which combined kitchen, living room and bedroom. The technical room was completely insulated from the main indoor space, and had a separate entrance. The wall between the technical room and the indoor space was insulated with the same level of insulation as the envelope. The glazing façades were partly shaded by the roof overhangs. No solar shading was installed in the house except for the skylight window. All windows had a solar transmission of 0.3. The largest glazing façade was oriented to the North with a 19° turn towards the West. Figure 1 shows the exterior views of the house.

FIGURE 1

The surface areas and thermal properties of the envelope are given in Table 1.

TABLE 1

Details of the heating, cooling, and ventilation system

The sensible heating and cooling of the house relied on the low temperature heating and high temperature cooling principle via the hydronic radiant system in the floor. The system was a dry radiant system, consisting of a piping grid installed in the wooden layer. The details of the floor system were: chipboard elements with aluminum heat conducting profiles (thickness 0.3 mm and length 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. A wooden floor covering was used with a thickness of 14 mm and a thermal conductivity of 0.13 W/mK. The available floor area for the embedded pipe system installation was 45 m^2, which is 68% of the total floor area. The design flow rates in the heating and cooling modes were 619 kg/h and 336 kg/h, respectively. The flow rates were calculated according to EN 15377-2 (European Committee for Standardization 2008). Figure 2 shows the details of the floor heating and cooling system used in the house.

FIGURE 2

The heat source and sink of the house for space heating and cooling was outdoor air, using a reversible air-to-brine heat pump. The minimum and maximum cooling capacities and the nominal power input in the cooling mode were 4.01, 7.1, and 2.95 kW, respectively. The minimum and maximum heating capacities and the nominal power input in the heating mode were 4.09, 7.75, and 2.83 kW, respectively.

A flat-plate heat exchanger was installed between the hydronic radiant system of the house and the air-to-brine heat pump. The pipes between the heat exchanger and the heat pump were filled with an anti-freeze mixture (40% ethylene glycol) to avoid frost damage during winter.

A mixing station, which linked the radiant floor heating and cooling system with the heat source and sink, and a controller adjusted the flow and supply temperature to the floor loops. The radiant system was controlled based on the operative temperature set-point that was inserted on a room thermostat (a matt gray half-sphere) in 0.5 K intervals and on the relative humidity inside the house to avoid condensation during summer.

The house was ventilated mechanically by an air handling unit (AHU). The mechanical ventilation was only used to provide fresh air into the house since the main sensible heating and cooling terminal of the house was the radiant system. This also made it possible to have lower airflow rates compared to a system where space heating and cooling is mainly obtained by an air system (Olesen 2012). The design ventilation rate was 0.5 ach (the Danish Ministry of Economic and Business Affairs 2010). The intake air was taken from the crawl-space.

Passive and active heat recovery options were available in the AHU. The passive heat recovery was obtained by means of a cross-flow heat exchanger and this passive heat recovery system had an efficiency of 85% (sensible heat). By-pass was possible depending on the intake air temperature. The active heat recovery was achieved by means of a reversible air-to-water heat pump that was coupled to the domestic hot water tank. The AHU could supply fresh air at a flow rate of up to 320 m^3/h at 100 Pa. Humidification of the supply air was not possible due to the limitations of the AHU. The two air supply diffusers can be seen on the technical room wall in Figure 3.

FIGURE 3

The house was designed as a plus-energy house and the roof of the house was covered with photovoltaic/thermal (PV/T) panels. PV/T panels convert the incoming solar radiation into electricity (PV) and thermal energy (T). The electricity was generated by mono-crystalline cells and the total cell area was 50.8 m^2. The house was connected to the grid and there was no storage of electrical energy. The installed nominal power was cut down to 9.2 kWp by two inverters. The thermal part of the PV/T panels was not operational until the summer of 2014 and only limited data are available from this period; therefore they are not further described in this study. Detailed information regarding the performance of the thermal part and its effects on the electricity production of the PV cells were reported by Kazanci et al. (2014).

Further details of the components and the system can be found in Kazanci et al. (2014), Skrupskelis and Kazanci (2012), Kazanci and Olesen (2014b).

Materials and methods

The house was located in Bjerringbro, Denmark and it was used as a full-scale experimental facility where the thermal indoor environment and energy performance of the house were monitored for a full year, from 26/9/2013 to 1/10/2014.

Experimental set-up

The house was unoccupied during the measurement period but the occupancy and equipment schedules (internal heat gains) were simulated by means of heated dummies. Each dummy was a circular aluminum duct, with a diameter of 220 mm and with a height of 1 m. It had closed ends and an electrical heating element (wire) was installed on the internal surfaces of the duct, with an adjustable heat output up to 180 W (Skrupskelis and Kazanci 2012).

The occupancy and equipment schedules were adjusted with timers. Two dummies were used to simulate occupants (the dummies had the same surface temperatures as a person would have) at 1.2 met (ON from 17:00 to 08:00 on weekdays and from 17:00 to 12:00 on weekends), one dummy (equipment #1, 120 W, 1.8 W/m^2) was always ON to simulate the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W, 2.7 W/m^2) was used to simulate the house appliances that are in use only when the occupants are present and the fifth dummy was used to represent additional lights (180 W, 2.7 W/m^2, ON from 06:00 to 08:00 and from 17:00 to 23:00 until 27th of May 2014, and after this date, ON from 20:00 to 23:00 every day). The house had ceiling mounted lights ON from 21:00 to 23:00 every day (140 W, 2.1 W/m^2). Additionally, there was a data logger and a computer (80 W, 1.2 W/m^2), and a fridge (30 W, 0.4 W/m^2) which were always ON.

Measurements and measuring equipment

A number of physical parameters, energy consumption and production were measured and recorded. The temperatures (air and globe) were measured at heights of 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.2 m, 2.7 m, 3.2 m and 3.7 m at a central location in the occupied zone following EN 13779 (European Committee for Standardization 2007). The measurements above the occupied zone were taken to evaluate the effects of thermal stratification based on the different heating and cooling strategies. The stratification is particularly important for this house because of its high and inclined ceiling. The thermal stratification from the floor to the ceiling was used as an indicator of the performance of the heating strategy regarding heat loss from the conditioned space to the outdoors.

Globe temperatures were measured with a gray globe sensor, 40 mm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person (Simone et al. 2007) and, thus, at 0.6 m and 1.1 m heights will represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded by a metal cylinder to avoid heat exchange by radiation. Both the globe and air temperature sensors have ±0.3°C accuracy in the measurement range of 10-40°C (Simone et al. 2013). The output from the sensors was logged by a portable data logger.

A panoramic view of the interior of the house, the measurement location and the sensors used for the measurements may be seen in Figure 3.

The energy consumptions of the air-to-brine heat pump, mixing station, and the controller of the radiant system were measured with wattmeters. The energy consumption of the AHU and energy production of the house (from the PV/T panels) were measured through a branch circuit power meter (BCPM). The wattmeters that were used to measure the consumption of the mixing station and the controller of the radiant system had an accuracy of ±2% ±2 W. The wattmeter that was used to measure the consumption of the air-to-brine heat pump had an accuracy of 3%. The BCPM's accuracy was 3% of the reading.

A full specification of the parameters measured and the measuring equipment can be found in Kazanci and Olesen (2014b).

Experimental settings

Heating season

Different heating strategies were compared during the heating season. In the beginning of the heating season, floor heating was controlled according to different operative temperature set-points (without any ventilation). Afterwards, floor heating was supplemented by warm air heating from the ventilation system, and during the last part of the heating season, the ventilation system was only used to provide fresh air (with passive heat recovery from the exhaust air) while floor heating was providing the required space heating. The building code in Denmark requires that each habitable room and the dwelling as a whole must have a fresh air supply and individual room temperature control (the Danish Ministry of Economic and Business Affairs 2010). The design ventilation rate was 0.5 ach.

The most important boundary conditions for these strategies in the heating season are given in Table 2 (FH: floor heating, HR: heat recovery, HRPH: heat recovery and pre-heating, corresponding to warm air heating). The numbers in the abbreviations are related to the indoor temperature set-points.

TABLE 2

Cooling season

The HVAC system was operated similarly during the cooling season. The house was cooled by floor cooling and was ventilated with the mechanical ventilation system (with passive heat recovery from the exhaust air). Different operative temperature set-points and different ventilation rates were tested. Internal solar shading covering 20 m^2 (manually operated) was installed on the North façade on 30/07/2014 and it was used in the fully down position until the end of the experiments.

The house was not cooled from 20/06/2014 to 23/06/2014 (the floor cooling and the AHU were OFF), to allow repairs to be made to the HVAC system.

The most important boundary conditions for the strategies used in the cooling season are given in Table 3 (FH: floor heating, CS: cooling season, FC: floor cooling, HV: higher ventilation rate, S: solar shading). The numbers in the abbreviations are related to the indoor temperature set-points.

TABLE 3

Results and discussion

Heating season

The performance of different heating strategies was evaluated based on the indoor environment category achieved according to EN 15251 (European Committee for Standardization 2007), and the measured temperature stratification. The categories are given according to EN 15251 (European Committee for Standardization 2007) for sedentary activity (1.2 met) and clothing of 1.0 clo. The indoor environment categories achieved with different heating strategies are given in Table 4.

TABLE 4

Figure 4 shows the operative temperature at 0.6 m height and the external air temperature during the heating season.

FIGURE 4

It may be seen from Table 4 and Figure 4 that even though different heating strategies were used, the overall performance regarding the indoor environment was satisfactory, i.e. 80% of the time in Category 2 according to EN 15251 (European Committee for Standardization 2007). It may also be seen that there were periods when the indoor environment was outside Category 3: for 2% of the time it was in Category 4.

The results show that it was possible to keep the indoor operative temperature close to the set-point, although the systems struggled to achieve this when the outside temperatures were below -5°C (for 2% of the time only Category 4 was achieved). In addition to the increased heating demand, one possible explanation for this is that both the air-to-brine heat pump and the AHU were affected by the lower outside air temperatures.

The operative temperature set-point of 20°C was too low. This is because even though the ventilation system would be heating the indoor space, the floor heating system did not start the water circulation in the loops until the operative temperature had dropped below 20°C. This resulted in several periods with room temperatures below 20°C.

Vertical air temperature difference between head and ankle levels (for sedentary occupants, 1.1 m and 0.1 m above the floor, respectively) at the measurement location was evaluated according to EN ISO 7730 (European Committee for Standardization 2005), as an indicator of local thermal discomfort. The average temperature differences as a function of the heating strategy are given in Table 5 and the temperature difference during the entire heating season may be seen in Figure 5.

TABLE 5

FIGURE 5

It may be seen from Table 5 and Figure 5 that the vertical air temperature difference was the highest for the cases where the floor heating was supplemented by warm air heating from the ventilation system. For each heating strategy and for the overall heating season, the average temperature difference was less than 2 K indicating that the requirements of Category A were met according to EN ISO 7730 (European Committee for Standardization 2005) at the measurement location.

The thermal stratification is an inevitable physical phenomenon and it can be used to analyze the indoor environment created by different heating strategies. The thermal stratification is important for occupant thermal comfort (due to local thermal discomfort) and for heat loss from the building. A high temperature gradient will increase the energy consumption and local thermal discomfort (Müller et al. 2013). In Table 6, average air temperatures at selected heights are given based on the heating strategy.

TABLE 6

Figure 6 shows the air temperature differences between the selected heights for the heating season.

FIGURE 6

The results shown in Table 6 and Figure 6 indicate that the thermal stratification inside the house was greatest when the floor heating was supplemented by warm air heating from the ventilation system. On average, the temperature difference between the highest (3.7 m) and lowest (0.1 m) measurement points was 2.8 K when the floor heating was supplemented by warm air heating while in other cases it was between 0.7 K and 0.9 K. Figure 6 shows a clear increase in the temperature difference (thermal stratification) between the highest and lowest points when the floor heating was supplemented by warm air heating, and the temperature difference reached almost 4 K in some periods.

Because of the lower density of the warm supply air compared to the room air, the supply air tends to flow along the ceiling and not to mix well with the room air. Due to this phenomenon and the thermal stratification, in the cases where the floor heating was supplemented by warm air heating, the space above the occupied zone was being heated. This increases the heat loss from the indoor space and especially where there are glass façades with higher U-values compared to the external walls. Increased thermal stratification is a phenomenon to avoid (unless an underfloor air distribution or a displacement ventilation system is used); especially in a house with a high and tilted ceiling, as in this test house, so it is recommended to use a radiant floor heating system in spaces with high ceilings.

Cooling season

The performance of different cooling strategies was evaluated based on the indoor environment categories given in EN 15251 (European Committee for Standardization 2007) for sedentary activity (1.2 met) and clothing of 0.5 clo. In addition, the hours above 26°C and 27°C were calculated following DS 469 (Danish Standards 2013). According to DS 469 (Danish Standards 2013), 26°C should not be exceeded for longer than 100 hours during the occupied period and 27°C should not be exceeded for longer than 25 hours. Even though these specifications are given for offices, meeting rooms, and shops, it is considered to be applicable also for residential buildings, and according to DS 469 (Danish Standards 2013), mechanical cooling would normally not be installed in residential buildings in Denmark.

The indoor environment categories achieved, and the hours above 26°C and 27°C as a function of the cooling strategy are given in Table 7, and the operative temperature and external air temperature during the cooling season are given in Figure 7.

TABLE 7

FIGURE 7

The house performed worse in the cooling season than in the heating season in terms of providing a satisfactory thermal indoor environment; for 57% of the time the operative temperature was in Category 2 and for 19% of the time it was outside the recommended categories in EN 15251 (European Committee for Standardization 2007). This occurred mainly in the transition periods (i.e. May and September) and due to overheating, which was a problem during the cooling season, except in August and September. The hours above 26°C and 27°C exceeded the values recommended in DS 469 (Danish Standards 2013). Decreasing the operative temperature set-point and increasing the ventilation rate helped to address the increased cooling load, but with a higher energy consumption. This is mainly due to the longer operation of the floor cooling and to increased cooling effect of the supply air.

The results show that even though the floor system was in heating mode during most of May, which is a part of the transition period, floor cooling could have been activated in the second half of May, which would have reduced the hours above 26°C and 27°C, and improved the indoor environment.

The main reasons of overheating were the large glazing façades including the lack of solar shading, the orientation of the house and the lack of thermal mass to buffer sudden thermal loads. In the current location of the house, direct solar radiation from the South façade was not a problem, because of the orientation and longer overhang on the South façade. Most of the overheating hours were in the late afternoon (i.e. from 18:00 until sunset), when there was direct solar gain through the North façade.

The vertical air temperature difference between head and ankles was evaluated according to EN ISO 7730 (European Committee for Standardization 2005) as an indicator of local thermal discomfort. The average temperature differences as a function of the cooling strategy are shown in Table 8 and the temperature difference during the cooling season may be seen in Figure 8.

TABLE 8

FIGURE 8

For each cooling strategy and on average, the vertical air temperature difference was lower than 2 K indicating that the requirement for Category A was met at the measurement location, according to EN ISO 7730 (European Committee for Standardization 2005). The high values of fluctuation may be attributed to direct solar radiation on the sensor at 1.1 m height.

Thermal stratification at the measurement location was also evaluated. The average temperature at chosen heights as a function of the cooling strategy and the temperature difference between the lowest and highest measurements points are given in Table 9. The air temperature difference between the selected heights over the cooling season is shown in Figure 9.

TABLE 9

FIGURE 9

It may be seen from Table 9 and Figure 9 that there was a natural pattern of thermal stratification and average values were slightly higher compared to the values obtained in the heating season (except for floor heating supplemented by warm air heating). This effect could be explained by the floor cooling. The sudden increases in the temperature difference could be due to direct solar radiation on the sensors.

In this study, operative temperature was used as an indicator of the thermal indoor environment, and vertical air temperature difference between head and ankles was used as an indicator for local thermal discomfort, but human thermal comfort is also affected by other factors such as floor surface temperature, radiant temperature asymmetry and draught (European Committee for Standardization 2005). All of these factors would have to be considered before any definitive conclusion on occupant thermal comfort can be drawn.

Energy performance

The energy performance of the house was evaluated by considering the energy produced by the PV/T panels on the roof and the energy used by the HVAC system. The monthly electricity production from the PV/T panels is given in Table 10.

TABLE 10

The annual electricity production from the PV/T panels (4043.9 kWh) was lower than had been predicted by the simulations, 7434.3 kWh (Kazanci et al. 2014). This difference could have occurred for several reasons: it was observed during the competition period in Solar Decathlon Europe 2012 (17th-28th of September 2012) that the output of the PV/T panels was lower than the expected values (Kazanci and Olesen 2014b), the climate could have differed from the weather files used in simulations and the location was different. In addition to these factors, some of the PV/T panels were damaged during disassembly/assembly and transportation of the house, and finally, some trees around the house threw shadows on the PV/T panels.

For the HVAC system's energy consumption, the air-to-brine heat pump, mixing station, controller of the radiant system, and AHU were considered. During the heating season, the set-point of the heat pump was 35°C until 21/11/2013 and after this date, it was 40°C. The set-point of the heat pump was changed to 15°C on 27/05/2014. The energy consumption of the components for each strategy is given in Table 11.

Heating degree days (HDD) and cooling degree days (CDD) were calculated for each case using a base temperature of 17°C and 23°C, respectively. Figure 10 shows the total average energy consumption of the cases together with the calculated degree days following the methodology described by Quayle and Diaz (1980).

TABLE 11

FIGURE 10

In Table 11, the heat pump energy consumption includes the heat pump cycle consumption, an integrated pump and the heat pump control system. The mixing station's consumption includes the circulation pump of the radiant floor heating system, a motorized mixing valve and the control unit. The consumption of the controller of the radiant system includes a control unit and an actuator at the manifold for each of the four loops (to open or close the loops). The AHU's consumption includes fans (supply and exhaust), control system, by-pass damper, internal heat pump cycle (active heat recovery) and its related equipment.

The results show that the energy consumption increased markedly when the warm air heating (FH21-HRPH and FH20-HRPH) was in operation, and these strategies struggled to provide the intended thermal indoor environment despite the increased energy consumption. The energy consumption during the cases FH20 and FH21 were close to each other, but a better thermal indoor environment was achieved with FH21. The last two cases in the heating season, FH21-HR and FH20-HR, have lower energy consumption and achieved a better thermal indoor environment compared to the cases with the same set-points without ventilation (FH21 and FH20). The FH22 strategy had the lowest energy consumption (although it had the highest operative temperature set-point) and the most satisfactory thermal indoor environment, although this was partly due to the relatively high external air temperatures during this period.

During the cooling season, the increased ventilation rate and lowered operative temperature set-point increased the energy consumption. This was expected, due to higher power input to the fans in the AHU and longer operation time of the pump in the floor cooling system. The increased energy consumption contributes to a better thermal indoor environment, but other strategies should be employed to reduce the cooling demand by means of energy efficient measures (e.g. lower ventilation rates when the house is unoccupied, natural ventilation when the outside conditions are suitable, decreased glazing area, solar shading, a better orientation of the house and so forth). The effects of different building and HVAC system improvements on the energy consumption and thermal indoor environment were parametrically studied and reported in Andersen et al. (2014).

It would be possible to increase the energy performance of the house by means of simple modifications, e.g. 29% (1051 kWh, 15.9 kWh/m^2 conditioned floor area) of the heat pump's consumption was due to the brine pump that is integrated into the heat pump and it was always ON due to the internal control algorithm of the heat pump. This energy consumption can be decreased by synchronizing the mixing station pump and this pump (as there is no storage in between).

The overall energy performance of the house during the measurement period is summarized in Table 12. In the overall energy balance, positive values indicate energy surplus while negative values indicate energy deficit, i.e. the house used more energy than it produced on an annual basis.

TABLE 12

Operation and performance

The results from the measurement period show that the control of heating and cooling system through set-points and the interaction of the radiant floor heating and cooling system with the ventilation system have considerable effects on the thermal indoor environment and on the energy performance. The optimal system combination is when the floor heating and cooling system is emitting or removing the necessary heat and the ventilation system is only used to provide the necessary supply of fresh air without actively heating or cooling the intake air. This would simplify the system operation since only one system will heat or cool the indoor space, and lower airflow rates can be used since the only task of the ventilation system will be to provide fresh air.

The heating and cooling set-points should be carefully selected to avoid periods with too low or too high indoor temperatures. This requires choosing set-points so that the radiant floor heating and cooling system has enough time to provide the necessary indoor conditions. It should also be noted that a higher indoor temperature set-point in the heating season would result in a higher energy use because of the longer operation time of the heating system, and because of the increased operating temperatures in the heating system which affect the heat pump performance. A similar effect will be observed in the cooling season with a lower indoor temperature set-point.

The fresh air intake for the AHU was under the house and this proved to be a beneficial approach; it was observed that the temperature below the house was warmer than the external air temperature during winter and colder than the external air temperature during summer, so it buffered the variations in the external air temperature to a certain extent. Figure 11 shows the external and intake air temperatures.

FIGURE 11

Although this application was beneficial for this location, it may not always be appropriate (e.g. a radon barrier might be needed in locations where radon is a concern). A definitive conclusion on the benefits of this approach must consider the effects of heat loss to this space in comparison to heat loss to the ground.

Throughout the 12-month operation of the house, the heating and cooling systems were active with respective set-points also during the transition periods (i.e. May and September) but it is not practical to provide constant heating or cooling during the transition periods, therefore the heating and cooling system operation and the switchover between these modes require careful consideration. Operation of the systems needs to be improved to avoid unnecessary heating and cooling in the transition periods.

A recent study analyzed the horizontal temperature distribution in the present house and found that the radiant floor cooling created a uniform thermal indoor environment in the cooling season, despite the large glazing façades (Kazanci and Olesen 2015b).

Earlier studies with different simulation software (Skrupskelis and Kazanci 2012; Andersen et al. 2014) showed that the current orientation of the house was optimal in terms of thermal indoor environment and energy performance, but based on the present results, a reversed orientation, i.e. the façade with the longer overhangs towards the North, would have been more energy effective, as it would decrease the solar heat gain during the cooling season and increase the solar heat gain during the heating season.

Previous studies (Kazanci et al. 2014; Skrupskelis and Kazanci 2012; Andersen et al. 2014) showed that the large glazing façades (including the lack of solar shading) of the house resulted in a high heating and cooling demand and this drastically decreased the energy performance of the house. This was confirmed by the experiments; the currently installed heating and cooling systems of the house struggled to achieve a comfortable thermal indoor environment during the cold periods and overheating was a significant problem during the cooling season.

The results show that the house would have benefited from a higher thermal mass to buffer the sudden thermal loads, especially during the periods in cooling season when there was direct solar gain and during the transition periods. This confirms a previous simulation study (Andersen et al. 2014) which showed that the house would benefit from increased thermal mass, in terms of energy performance and thermal indoor environment.

During the heating season, when the outside temperatures were below -5°C, the heating system of the house struggled to reach the operative temperature set-points. An evident reason for this was the increased heating demand. The air-to-brine heat pump and the AHU were also affected by the lower external air temperatures. The initial design of the heating and cooling system incorporated a ground heat exchanger to obtain free cooling during summer and a coupled heat pump for the heating season, as the heat sink and source of the house (Kazanci and Olesen 2014b). This would have been beneficial, since the performance of a ground-coupled heat pump would not have been affected significantly by the varying external air temperatures. Also, it would have been beneficial during the cooling season by significantly decreasing the energy consumption for cooling (Skrupskelis and Kazanci 2012).

The house was initially designed as a plus-energy house and shown by previous simulation studies that it performs as one on a yearly basis (Kazanci et al. 2014), but the measurement results show that it did not produce any energy surplus under the climate conditions in Denmark (Table 12). This is mainly due to the lower electrical output from the PV/T panels (4044 kWh) than estimated in the design conditions (7434 kWh), high heating and cooling energy consumption (4613 kWh, 69.7 kWh/m^2 conditioned floor area), changes in the house's heating and cooling systems resulting in higher energy consumption than the design values, differences in the simulations and in the actual components of the house.

The results presented in this study are not influenced by the users since there were no users and the heat gains were controlled, therefore the results are purely related with the design and operation of the house and its systems.

During the experiments, it was not possible to make changes in the building envelope (except for the installation of the internal solar shading), so the modifications were on the heating, cooling and ventilation system operation. The design of the current building diverged from the ideal design of an energy efficient nZEB where the heating and cooling demands of the house would have been minimized in the design phase. The results of this study show that it is not enough and it is not energy efficient to address the heating and cooling loads through adjusting set-points and adjusting the flow rates of air and water.

Although the results reported in this study are for a particular house, the results regarding the systems and their operation have implications on a broader scale. In order to achieve high energy performance together with a comfortable thermal indoor environment, the initial step is to reduce the heating and cooling demands of the house as much as possible during the design and this should be done in a holistic way where orientation, shading, thermal mass, air-tightness, thermal bridges, etc. are considered simultaneously. This is crucial since the demand determines the final energy consumption. After it is assured that the heating and cooling demands are minimized, the resulting demand should be addressed with the most energy efficient and environmentally friendly heating and cooling strategies. The radiant low temperature heating and high temperature cooling systems enable the integration of natural heat sources and sinks (ground, night-time radiative cooling, solar, sea-water, etc.) into the heating and cooling systems and they also provide a draught-free and uniform thermal indoor environment, therefore they are a promising means of achieving high energy performance without sacrificing occupant thermal comfort.

Once it is ensured that the demand of the building (including plug loads) is minimized, the most energy efficient heating and cooling systems are chosen, and the control of these systems are optimized, then it would be possible to reach plus-energy targets even with a minimal contribution from the energy producing components in future buildings.

Conclusion and future research

A detached, one-story, single family house designed for plus-energy performance was operated for one year. During this period different heating and cooling strategies were compared and the energy performance of the house and its thermal indoor environment were monitored. The main conclusions are as follows.

- During the heating season, it was possible to provide the intended operative temperature inside the occupied zone except for the periods when the external air temperatures were below -5°C.
- Radiant floor heating combined with heat recovery from ventilation was the optimal heating strategy as it provided a uniform temperature distribution within the space and decreased the heat losses due to thermal stratification.
- The performance of the house in terms of maintaining a comfortable thermal indoor environment was worse in the cooling season than in the heating season. Overheating was a significant problem, and the main reasons for this were the large glazing façades, the orientation of the house, the lack of solar shading, and the lack of sufficient thermal mass to buffer the sudden thermal loads.
- The operation of the heating and cooling system during the transition periods was problematic and this affected the thermal indoor environment and energy performance negatively.
- The house had a high heating and cooling demand that could easily have been reduced at the design phase. Although, it might be possible to address the excessive heating and cooling loads by adjusting set-points, water and airflow rates, these would result in increased energy consumption,

as in the present study. It is crucial to minimize the demand before attempting to satisfy it in the most energy efficient way.

- Although the house was designed as a plus-energy house, it did not perform as one under the climatic conditions of Denmark. This was mainly due to the electrical output from the PV/T panels being lower than had been assumed in the simulations, but also to the unnecessarily high energy consumption of the house and the fact that the heating and cooling system differed from that of the initial design. It would be possible to increase the energy performance of the house by making simple modifications to the operating strategies and to the architectural design of the house. It would then be possible to achieve plus-energy levels with the same active (energy producing) components.

The present study resulted in possible future investigations including:

- Space heating and night radiative cooling possibilities with PV/T panels;
- Consideration of several plus-energy houses' role in the energy system;
- Optimization of the operation of heating and cooling system during transition periods. Can enough thermal mass let the house run without active heating or cooling during transition periods and how to evaluate the thermal comfort during these periods?
- Possibility of using phase change materials (PCM), either passively or actively, to increase the effective thermal mass of the building and its effects on the thermal indoor environment and energy performance;
- Benefits of using a predictive control algorithm to control the heating and cooling systems of the house, especially during the transition periods.

Although every building is different, there are certain general rules to be followed during the design and operation phases. The main findings of this study, together with these possible future investigations, could benefit the design and operation of future nZEB and plus-energy houses and could help to improve the thermal indoor conditions without increasing the energy use.

Acknowledgments

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Figures:

Figure 1. *Exterior views of the house, seen from North-West (left) and South-West (right)*

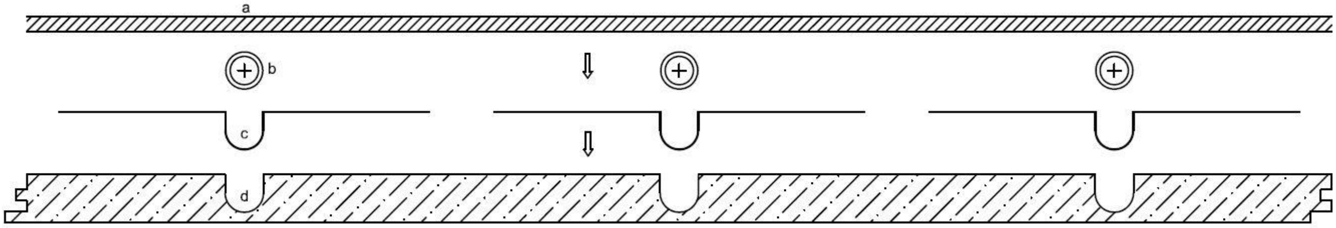

Figure 2. *a) Floor covering b) Pipe, 17x2.0 mm c) Heat distribution plate, 0.3 mm, d) Under-floor plate, 22 mm*

Figure 3. *Panoramic view of the interior (left), the measurement location (middle) and the globe and air temperature sensors (right)*

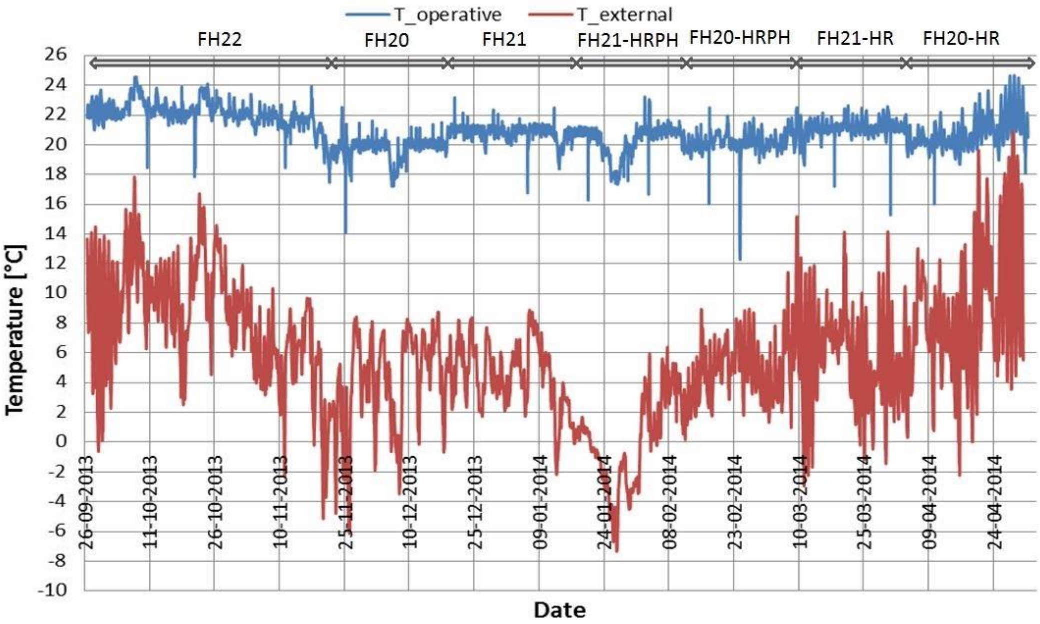

__Figure 4.__ Operative temperature and external air temperature during the heating season

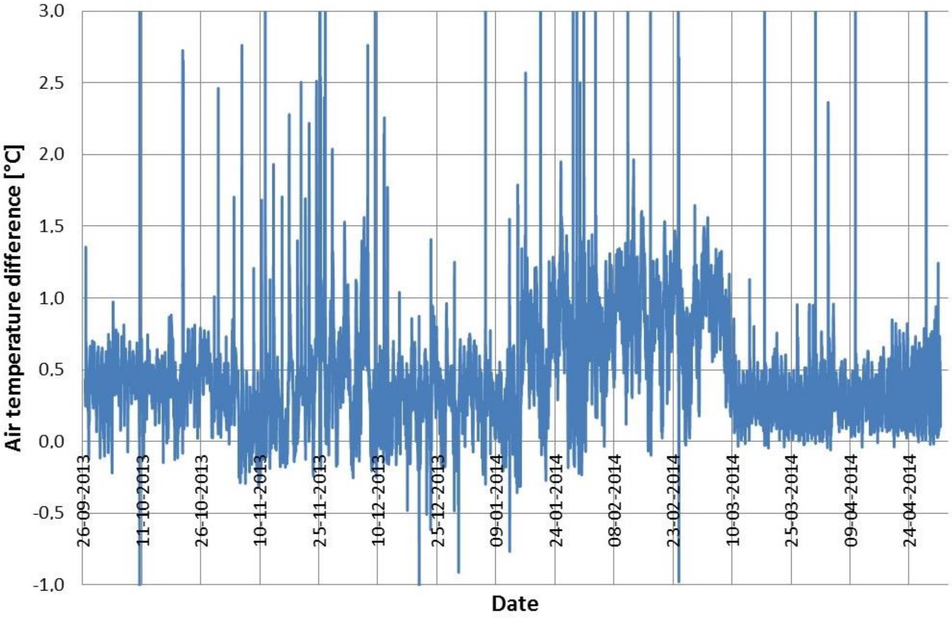

__Figure 5.__ Vertical air temperature difference between head and ankles during heating season

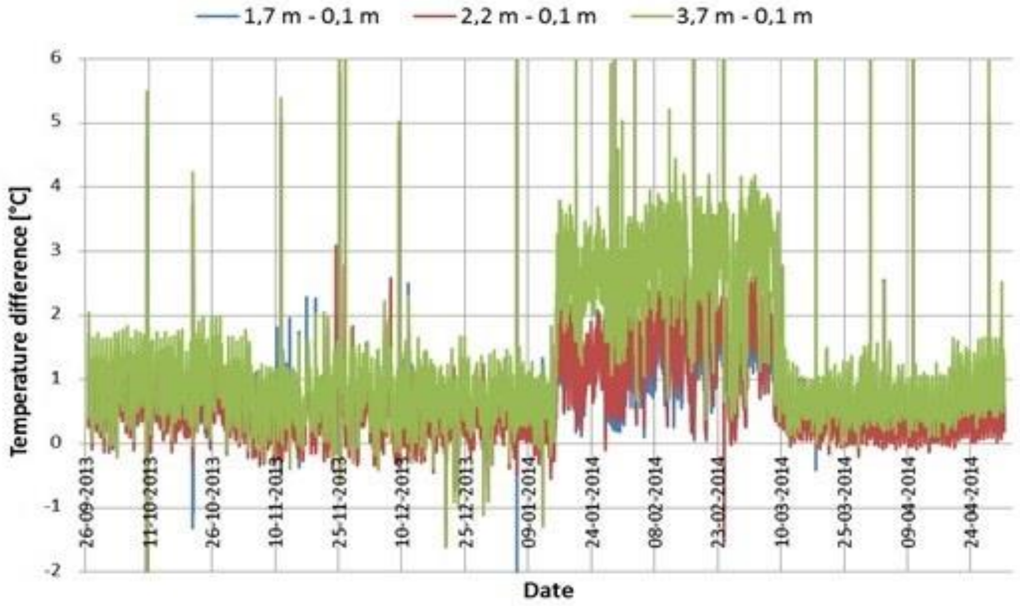

Figure 6. *Air temperature difference between the selected heights, heating season*

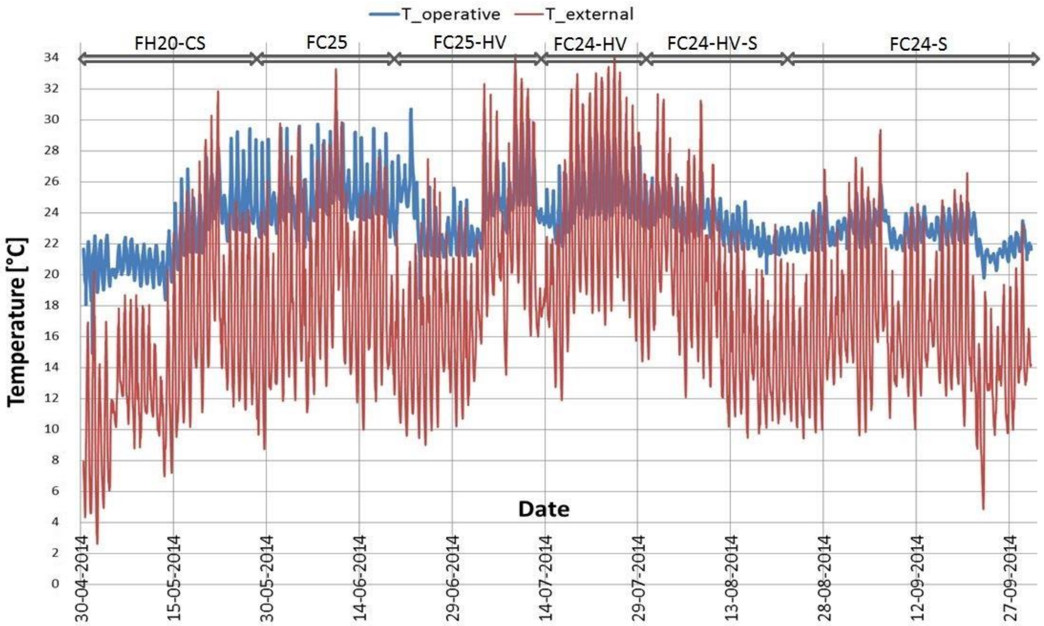

Figure 7. *Operative temperature and external air temperature during the cooling season*

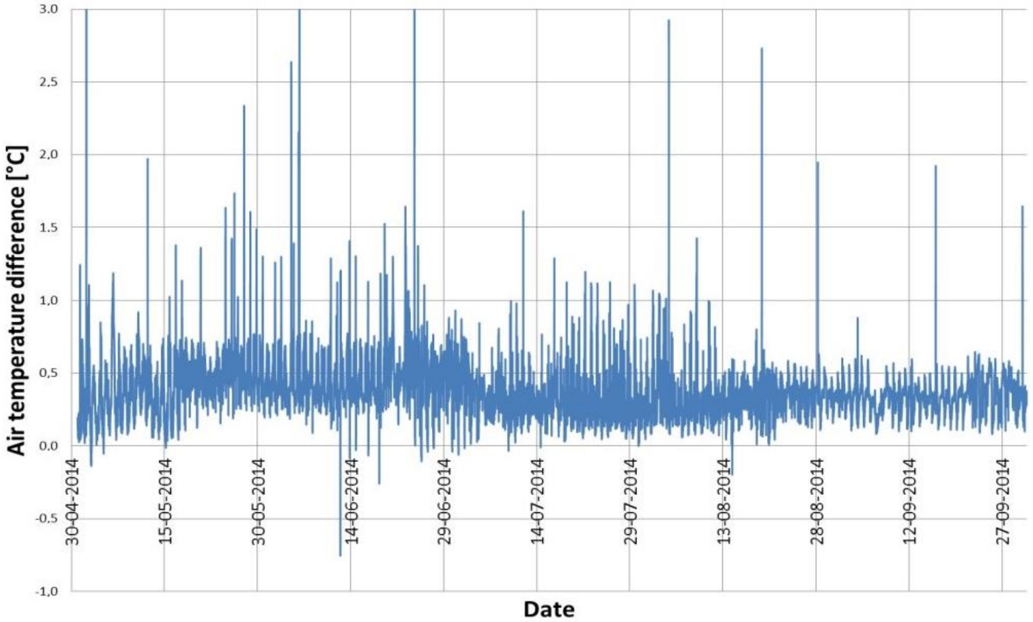

Figure 8. *Vertical air temperature difference between head and ankles during cooling season*

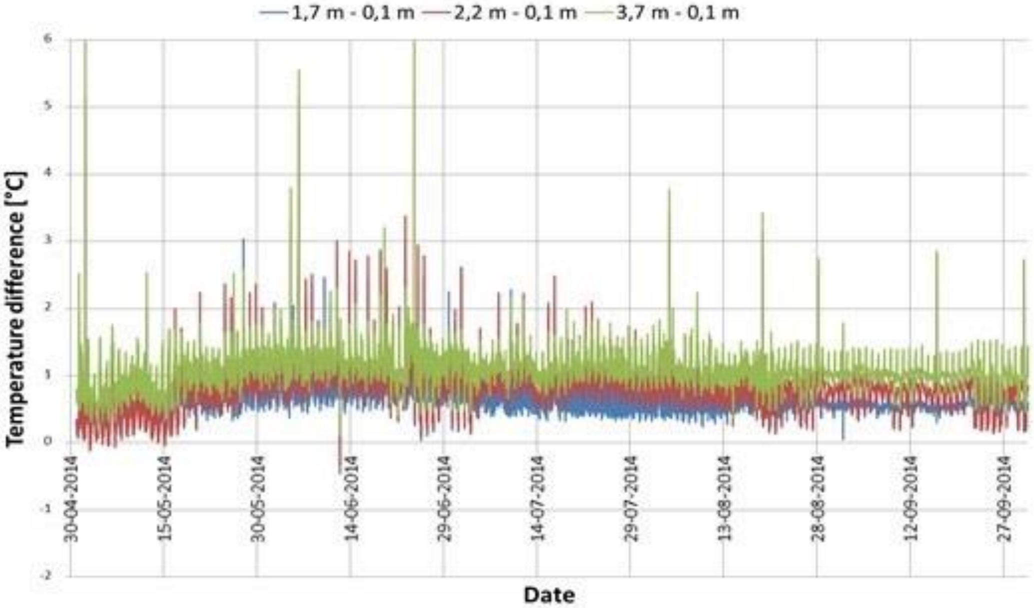

Figure 9. *Air temperature difference between the selected heights, cooling season*

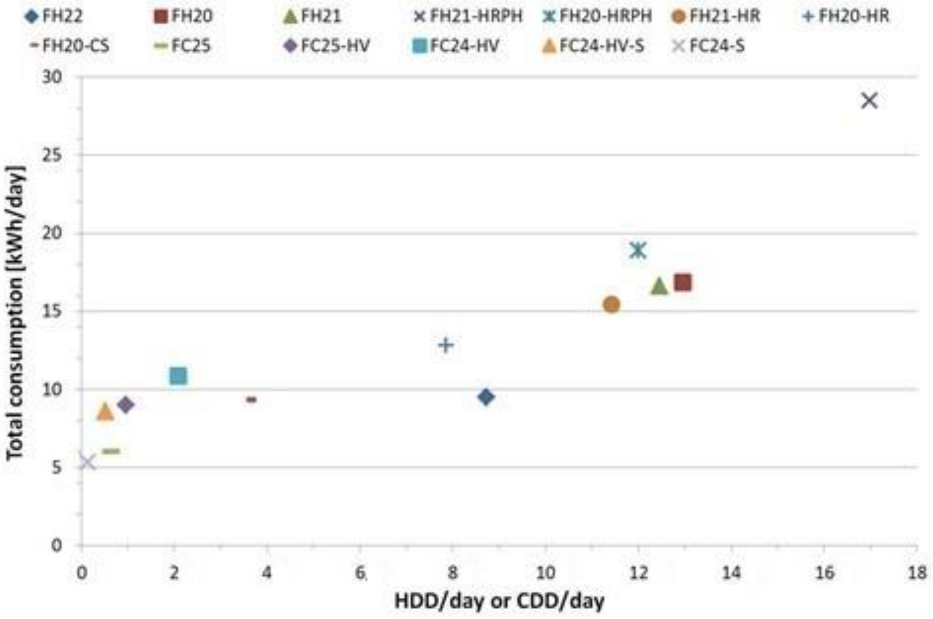

Figure 10. *Energy consumption per day versus heating or cooling degree days per day*

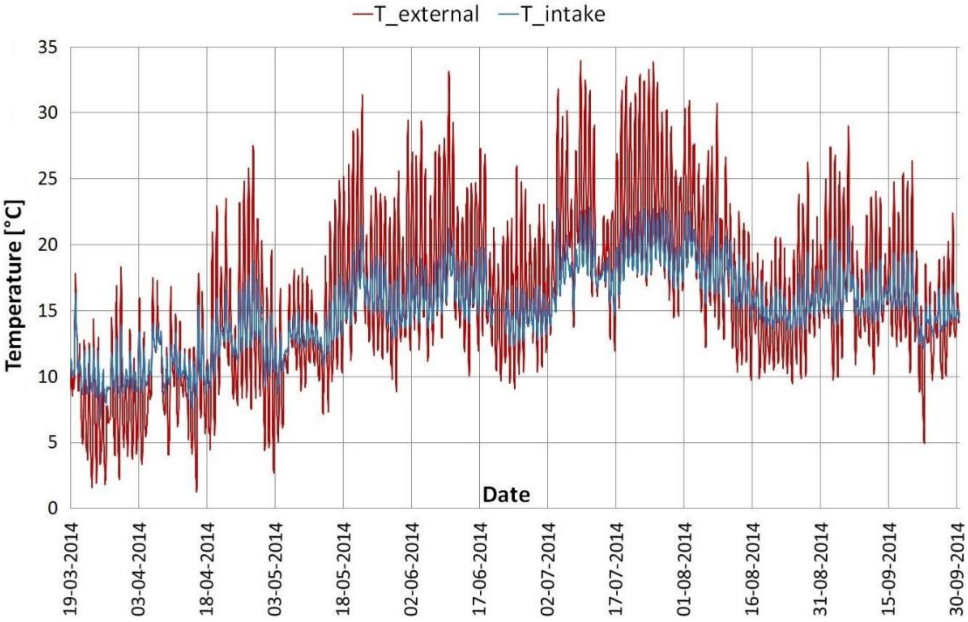

Figure 11. *The external air temperature and the intake air temperature to the AHU*

Tables:

Table 1. *Thermal properties of the envelope*

	North	**South**	**East**	**West**	**Floor**	**Ceiling**
Walls, Area, [m^2]	-	-	37.2	19.3	66.2	53
Walls, U-value, [W/m^{2}K]	-	-	0.09	0.09	0.09	0.09
Windows, Area, [m^2]	36.7	21.8	-	-	-	0.74
Windows, U-value, [W/m^{2}K]	1.04	1.04	-	-	-	1.04

Table 2. *Periods and experimental settings of the different cases, heating season*

Period	***Average external air temperature [°C]***	***Floor heating set-point [°C]***	***Ventilation***	***Case abbreviation***
26th of Sep to 21st of Nov	8.2	22	Off	FH22
21st of Nov to 18th of Dec	4.0	20	Off	FH20
18th of Dec to 16th of Jan	4.6	21	Off	FH21
16th of Jan to 10th of Feb	0.0	21	On, heat recovery and pre-heating**	FH21-HRPH
10th of Feb to 10th of Mar	5.0	20	On, heat recovery and pre-heating**	FH20-HRPH
10th of Mar to 3rd of Apr	5.5	21	On, heat recovery	FH21-HR
3rd of Apr to 1st of May*	9.0	20	On, heat recovery	FH20-HR

*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period.

**: Heat recovery refers to the passive heat recovery and pre-heating refers to the active heat recovery (warm air heating) in AHU. The supply air temperature was between 30 to 34°C, except for the periods with low outside air temperatures when it dropped to 27°C.

Table 3. *Periods and experimental settings of the different cases, cooling season*

Period	***Average external air temperature [°C]***	***Floor cooling set-point [°C]***	***Ventilation type and ventilation rate***	***Solar shading***	***Case abbreviation***
1st of May to 27th of May*	14.7	20**	Heat recovery, 0.5 ach	No	FH20-CS
27th of May to 19th of June	18.7	25	Heat recovery, 0.5 ach	No	FC25
19th of June to 13th of July	18.7	25	Heat recovery, 0.8 ach	No	FC25-HV
13th of July to 30th of July	22.7	24	Heat recovery, 0.8 ach	No	FC24-HV
30th of July to 21st of Aug	18.1	24	Heat recovery, 0.8 ach	Yes	FC24-HV-S
21st of Aug to 1st of Oct	16.0	24	Heat recovery, 0.5 ach	Yes	FC24-S

*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period.

**: Floor system was in heating mode, transition period.

Table 4. *The category of indoor environment based on operative temperature at 0.6 m height, heating season*

Indoor environment category/case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
Category 1 (21.0-25.0°C)	92%	2%	37%	22%	11%	67%	35%	45%
Category 2 (20.0-25.0°C)	97%	44%	92%	72%	61%	98%	77%	80%
Category 3 (18.0-25.0°C)	100%	95%	100%	93%	99%	100%	100%	98%
Category 4*	0%	5%	0%	7%	1%	0%	0%	2%

*: Category 4 represents the values outside Categories 1, 2, and 3.

Table 5. *Time-averaged vertical air temperature difference between head and ankles, heating season**

Case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
Temperature difference [°C]	0.4	0.4	0.3	0.7	0.9	0.3	0.3	0.5

*: Vertical air temperature between head and ankles should be less than 2 K, in order to be within the limits of Category A of EN ISO 7730.

Table 6. *Time-averaged air temperature at the selected heights and the difference between highest and lowest measurement points, heating season*

Height/case	*FH22*	*FH20*	*FH21*	*FH21-HRPH*	*FH20-HRPH*	*FH21-HR*	*FH20-HR*	*Total, average*
0.1 m [°C]	21.7	19.2	20.3	19.5	19.5	20.8	20.4	20.4
1.7 m [°C]	22.3	19.7	20.7	20.7	20.7	21.2	20.9	21.1
2.2 m [°C]	22.3	19.6	20.6	20.9	21.0	21.1	20.8	21.1
3.7 m [°C]	22.6	20.0	21.0	22.3	22.3	21.5	21.2	21.7
Temperature difference between 3.7 m and 0.1 m [°C]	0.9	0.8	0.8	2.8	2.8	0.7	0.8	1.3

Table 7. *The category of indoor environment based on operative temperature at 0.6 m height, cooling season*

Indoor environment category/case	*FH20-CS*	*FC25*	*FC25-HV*	*FC24-HV*	*FC24-HV-S*	*FC24-S*	*Total, average*
Category 1 (23.5-25.5°C)	52%	56%	36%	54%	39%	22%	41%
Category 2 (23.0-26.0°C)	73%	72%	49%	72%	58%	36%	57%
Category 3 (22.0-27.0°C)	87%	87%	75%	91%	84%	72%	81%
Category 4	13%	13%	25%	9%	16%	28%	19%
Hours above 26°C	48	129	79	87	7	0	350*
Hours above 27°C	19	71	38	34	0	0	162*

*: Although the overheating hours cannot be directly added for the different cooling strategies, their total is given to indicate the duration of overheating during the cooling season.

Table 8. *Time-averaged vertical air temperature difference between head and ankles, cooling season*

Case	*FH20-CS*	*FC25*	*FC25-HV*	*FC24-HV*	*FC24-HV-S*	*FC24-S*	*Total, average*
Temperature difference [°C]	0.4	0.5	0.4	0.3	0.3	0.3	0.4

Table 9. *Time-averaged air temperature at the selected heights and the difference between highest and lowest measurement points, cooling season*

Height/case	***FH20-CS***	***FC25***	***FC25-HV***	***FC24-HV***	***FC24-HV-S***	***FC24-S***	***Total, average***
0.1 m [°C]	21.7	24.7	23.6	24.7	23.1	22.3	23.2
1.7 m [°C]	22.3	25.6	24.4	25.3	23.6	22.9	23.8
2.2 m [°C]	22.3	25.8	24.6	25.5	23.8	23.1	24.0
3.7 m [°C]	22.7	26.0	24.8	25.7	24.1	23.3	24.2
Temperature difference between 3.7 m and 0.1 m [°C]	1.0	1.3	1.2	1.1	1.1	1.0	1.1

Table 10. *Monthly electricity production from the PV/T panels (month/year)* [kWh]*

10/13	**11/13**	**12/13**	**01/14**	**02/14**	**03/14**	**04/14**	**05/14**	**06/14**	**07/14**	**08/14**	**09/14**	**Sum**
214.6	143.0	61.9	59.7	168.8	310.2	507.3	621.1	665.1	519.7	405.0	308.1	4043.9

*: Electricity production from the PV/T panels between 26-30/09/13 was 59.3 kWh.

Table 11. *Energy consumption of the HVAC system components*

Case	***HDD***	***CDD***	***Heat pump [kWh]***	***Mixing station [kWh]***	***Controller, radiant system [kWh]***	***AHU [kWh]***	***Total [kWh]***	***Total, average [kWh/day]***
FH22	496	-	518.9	15.5	5.3	0.0	539.7	9.5
FH20	350	-	438.3	11.3	3.8	0.0	453.4	16.8
FH21	361	-	460.6	15.0	5.0	0.0	480.6	16.6
FH21-HRPH	425	-	463.2	10.4	3.5	236.6	713.7	28.5
FH20-HRPH	337	-	307.2	2.2	0.8	221.2	531.4	18.9
FH21-HR	275	-	321.8	7.2	2.5	39.3	370.7	15.4
FH20-HR	220	-	304.6	4.3	1.5	47.5	358.0	12.8
FH20-CS	97	-	206.4	1.3	0.4	42.6	250.7	9.3
FC25	-	15	95.4	5.4	1.8	36.0	138.7	6.0
FC25-HV	-	20	110.1	3.2	1.4	75.2	189.8	9.0
FC24-HV	-	36	114.8	6.7	2.0	60.9	184.3	10.8
FC24-HV-S	-	12	105.6	3.8	1.2	78.8	189.3	8.6
FC24-S	-	6	145.9	0.6	0.2	65.7	212.4	5.3
Total	-	-	3592.9	86.7	29.3	903.8	4612.7	-

Table 12. *Overall energy balance of the house (yearly values)*

Heat pump [kWh/m^2]	54.3
Mixing station [kWh/m^2]	1.3
Controller, radiant system [kWh/m^2]	0.4
AHU [kWh/m^2]	13.7
Energy consumption of the HVAC system, total [kWh] and per floor area [kWh/m^2]	4613 / 69.7
Electricity produced by the PV/T panels [kWh]	4044
Overall energy balance (production-consumption) [kWh]	-569