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Final Report

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Sustainable Plus-energy Houses

(Projektnummer: 344-060)

Slutrapport – Final Report

af/by

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Summary

This study is an outcome of Elforsk, project number 344-060, Bæredygtige Energi-Plus huse (Sustainable plus-energy houses).

The focus of this report is to document the approach and the results of different analyses concerning a plus-energy, single family house. The house was designed for an international student competition, Solar Decathlon Europe 2012 and after the competition it was used as a full-scale experimental facility for one year. During this period, different heating and cooling strategies were tested and the performance of the house regarding the thermal indoor environment and energy was monitored.

This report is structured as follows. Chapter 1 presents the project and briefly explains the different phases of the project. The details of the house's construction and its HVAC system are explained in Chapter 2, along with the energy efficiency measures and innovations. Chapter 3 introduces the investigations carried out in detail, with respect to different phases of the project. The investigations presented are divided into four phases: design phase and pre-competition period, competition period, year-round measurements in Denmark, and improvement suggestions for building and HVAC system. The results of the investigations, measurements, and the experiences from one year of operation are presented in Chapter 4. Chapter 5 presents the main conclusions derived from the project and Chapter 6 presents a look into future research. In Appendix A, all publications and dissemination activities over the course of the project are presented. In Appendix B, the measured parameters and the measuring equipment are given.

Acknowledgements

Table of Contents

Abbreviations

AHU: Air handling unit

COP: Coefficient of performance

DHW: Domestic hot water

DTU: Danmarks Tekniske Universitet (Technical University of Denmark)

EPS: Embedded pipe system

GCHP: Ground coupled heat pump

GHEX: Ground heat exchanger

HP: Heat pump

HVAC: Heating, ventilation and air conditioning

HWC: Heating water circuit

nZEB: Nearly zero-energy building

PCM: Phase change material

PLC: Programmable logic controller

PV: Photovoltaic

PV/T: Photovoltaic/thermal

SDE: Solar Decathlon Europe

1. 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 almost every sector that has a relation to energy and energy use. Buildings sector is one of these sectors and a broad range of research activities are being carried out to find ways to decrease the energy demand and consumption of buildings. One of the main reasons behind this is that the buildings are responsible for 40% of the energy consumption in the member states of the European Union, European Commission (2010).

The building energy codes are becoming tighter and nZEB (nearly zero-energy building) levels are being dictated for new buildings by 2020 in the European Union, European Commission (2010). The improvements are so great that nZEB levels are not enough to achieve anymore and building designers are striving to design plus-energy houses: a house that produces more energy from renewable energy resources than it imports from external resources, on a yearly basis, European Commission (2009). Plus-energy houses could play a significant role in the energy system in different ways; they can compensate for the old buildings that are too expensive to upgrade to nZEB levels, and the plus-energy houses can act as small power plants in the energy system.

People spend most of their time indoors, Olesen & Seelen (1993), therefore buildings are built for people to live in and to have a comfortable, healthy and productive indoor environment and not to save energy, i.e. with fewer buildings there would be higher energy savings. Therefore, energy savings shouldn't be achieved at the cost of occupant thermal discomfort. This makes designing an energy-efficient, comfortable, healthy, and aesthetically appealing building a complicated task and it should be noted that it is a goal not only for engineers but for architects too.

One possible way to classify buildings is to divide them into residential and non-residential buildings. These two groups differ in occupancy period, size, expectations of the occupants from the building, user activities and so forth. Nevertheless, similar energy efficiency and energy saving measures could be applied to both types of buildings. Examples of these measures could be innovative building components, efficient heating, cooling and ventilation strategies and more. The house considered in this study, Fold, belongs to the category of residential buildings and the experiences derived from this project are intended to provide recommendations on the design and operation of the building envelope and building's systems (heating, ventilation and air conditioning system, control system, etc.) that are also applicable for different buildings.

This report presents the results obtained from various studies and analyses related to Fold, the house that was designed by the students of Technical University of Denmark to compete in an international student competition, Solar Decathlon Europe 2012, which took place in Madrid, Spain in September 2012. Fold was a detached, one-story, single family, plus-energy house.

In order for a house to be appealing, it should combine various features such as being aesthetically appealing, energy efficient, affordable and so forth. These aims are parallel with the rationale behind the competition, Solar Decathlon. The competition consists of 10 categories where teams are evaluated either by a jury or by measurements or task completion. These 10 categories are architecture, engineering and construction, energy efficiency, electrical energy balance, comfort conditions, house functioning, communication and social awareness, industrialization and market viability, innovation, and sustainability.

The house was first constructed at the campus of DTU in Kongens Lyngby, during the spring of 2012. During this period, the operation of the different systems of the house was tested and optimized. After this period the house was disassembled, loaded into trucks and transported to the competition location, Madrid. The house was

assembled again in Madrid and it competed in the competition. When the competition period was over, the house was disassembled and loaded into trucks and it came back to Denmark.

The house was erected again in the summer of 2013 in Bjerringbro, Denmark. The house was used as a full-scale experimental facility (without any occupants living in the house) where different heating, cooling and ventilation strategies were tested. Year-round measurements of indoor climate, energy production and consumption and various physical parameters in the HVAC system were taken from 26th of September 2013 to 1st of October 2014. The house was also used as a meeting room and as a showcase for energy efficient technologies by Grundfos.

The results are divided into four parts:

- The results obtained during the design phase and pre-competition period (results from experiments with particular technologies used in the house, results from simulation softwares, and results from calculations);
- The results of the competition period (17th-28th of September 2012);
- The results from the year-round measurements in Bjerringbro over the period 26th of September 2013 – 1st of October 2014 (heating season, cooling season, annual results, and notes on the operation of the house);
- Possibilities for improvements in the building and HVAC system design (investigated by means of a dynamic building simulation software).

In order to get further information on the project and various analyses carried out, please consult the following theses and deliverables:

- Skrupskelis, M., & Kazanci, O. B. (2012). *Solar sustainable heating, cooling and ventilation of a net zero energy house.* Kgs. Lyngby.
- Ševela, P. (2012). *Energy management in DTU Solar Decathlon house.* Kgs. Lyngby.
- Grigužauskas, D. (2012). *HVAC System Automation in Solar Decathlon Europe 2012 FOLD House.* Kgs. Lyngby.
- Andersen, M. E., & Schøtt, J. (2014). *Analyse af et plus-energi hus for optimering af HVAC system.* Kgs. Lyngby.
- Børgesen, J., & Nielsen, K. W. (2012). *Test af PVT-panel.* Kgs. Lyngby.
- Team DTU. (2012). *Project Manual #7.* Kgs. Lyngby.
- Team DTU. (2012). *Project Drawings #7.* Kgs. Lyngby.
- Team DTU. (2012). *Press Release December 19, 2012.* Kgs. Lyngby.

In addition to these documents, there have been numerous scientific publications based on the work carried out regarding the house. These scientific publications are referred to throughout the report and a full list is given in Appendix A.

2. Details of the house

When designing an energy efficient house, the first goal should be to minimize the demand for heating and cooling and then the demand should be addressed with most environmentally friendly and energy efficient systems. In this case, designing a system that provides optimum thermal comfort and a healthy indoor environment for the occupants and consumes lowest possible energy becomes the greatest challenge. This challenge extends further to find a feasible way of replacing the fossil resources by integrating renewable energy resources into the HVAC system. There is not a single way of achieving this and therefore innovation becomes a key parameter in achieving these goals.

The construction details of the house, the details of the HVAC system, and implemented energy efficiency measures are presented in this chapter.

2.1 Construction details

The name of the house, Fold, stems from the structural shape of the house. The idea behind the shape of the house was to take a piece of paper and fold it in such a way, around the occupants, that will give the optimum inclination and orientation for the photovoltaic/thermal panels on the roof and at the same time it will minimize the heat losses and heat gains from the ambient (i.e. solar gains). The folding strategy (inclination of the walls, inclination and angle of the roof, length of the overhangs, orientation and so forth) is a function of the geographical location. An example of the folding procedure is shown in Figure 1:
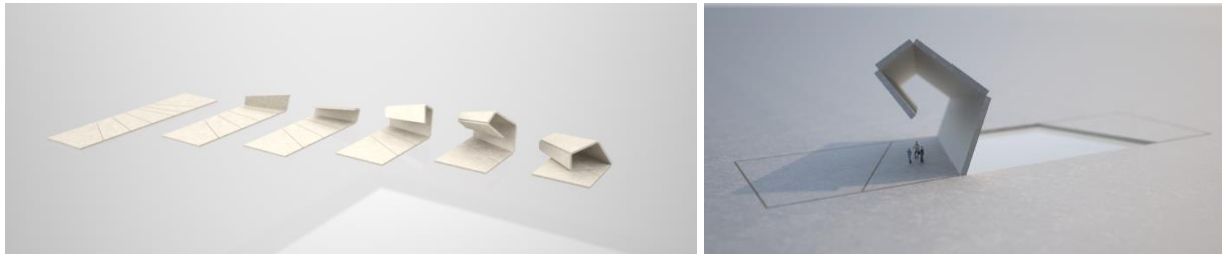
Figure 1. An example of the folding strategy

Fold 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 wooden elements. Pre-fabricated wooden elements were made from layers of Kerto board (laminated veneer lumber), which in combination with I beams in between formed the structural part. The house was insulated with a combination of two types of insulation: 20 cm of conventional mineral wool (in between the boards of the structural element) and 8 cm of compressed stone wool fibers and Aerogel, Aerowool (4 cm on each side). The walls, roof and floor structures were formed by installing prefabricated elements in a sequential order and sealing the joints. The North and South glazed façades were inserted later and the joints between the glazing frame and the house structure were sealed. The house was supported on 20-30 cm concrete blocks.

Inside the house, there was a single space combining kitchen, living room and bedroom areas. Shower and toilet areas were separated by partitions. The technical room was completely isolated from the main indoor space, having a separate entrance. The wall between the technical room and the indoor space was insulated with the same level of insulation as the exterior walls. The technical room was partly exposed to the outdoor air, by the implemented natural ventilation concept. The effect of the natural ventilation in this area was created by an opening in the floor and an opening (with installed grills) on the door.

The glazing façades in the South and North sides of the house were partly shaded by the overhangs. No solar shading was installed in the house except for the skylight window. The largest glazing façade was oriented to the North with a 19° turn towards the West.

The exterior and the interior of the house are shown in Figure 2 and Figure 3:

Figure 2. Outside views of the house, seen from North-West and South-West

Figure 3. Inside views of the house, competition (left) and measurement (right) configurations

The surface areas and corresponding thermal properties of the structural parts of the house are given in Table 1:

Table 1. Thermal properties of the walls

External walls	South	North	East	West	Floor	Ceiling
Area [m²]	-	-	37.2	19.3	66.2	53
U-value [W/m²K]	-	-	0.09	0.09	0.09	0.09
Windows	South	North	East	West	Floor	Ceiling
Area [m²]	21.8	36.7	-	-	-	0.74
U-value [W/m²K]	1.04	1.04	-	-	-	1.04
Solar transmission	0.3	0.3	-	-	-	0.3

2.2 Details of the HVAC system

The design of the house's HVAC system exploited the advantages of well-known and proven technologies combined with those of less mature technologies in order to achieve an innovative, efficient and sustainable solution. During the design phase of the HVAC system, main goals were to provide optimum thermal comfort for the occupants and to achieve this with lowest possible energy consumption.

In the actual operation of the house, some differences occurred compared to the initially designed system. These differences are identified and explained.

2.2.1 Designed system

Fold's HVAC system consisted of these main parts: embedded pipes in the floor and in the ceiling (dry radiant system), photovoltaic/thermal panels (PV/T), domestic hot water (DHW) tank, mechanical and natural ventilation, ground heat exchanger and ground coupled heat pump (GHEX and GCHP). The HVAC system had no direct fossil fuel consumption. Only indirect consumption of fossil fuel was associated with the electricity imported from the grid when the produced electricity was not enough.

The main heat source and heat sink of the house was designed to be the ground, realized by means of a borehole (single U-tube ground heat exchanger). During the heating season, the ground was used as a heat source, if space heating was needed then the heat pump was activated. In the cooling season, when the ground was acting as a heat sink, the heat pump was by-passed and free cooling was obtained via a circulation pump that circulates the return water from the embedded pipes. In this mode, only energy consumption is due to the circulation pump.

The main sensible heating and cooling strategy of the house relied on the low temperature heating and high temperature cooling principle via the hydronic radiant system. There were pipes embedded in the floor and in the ceiling structure. The embedded pipes in the ceiling were designed to be used for cooling purposes only while the embedded pipes in the floor could be used for heating as well as cooling during the peak loads.

The floor heating and cooling system was a dry radiant system, consisting of a piping grid installed in the wooden layer, with aluminum profiles on the pipes for better thermal conductance. The details of the floor system were: chipboard system, with aluminum heat conducting profiles (thickness was 0.3 mm and length was 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. In total there were four loops in the floor. The details of the ceiling system were: foam-board system, with aluminum heat conducting profiles (thickness was 0.3 mm and length was 0.12 m), PE-X pipe, 12x1.7 mm. Pipe spacing was 0.125 m. In total there were six loops in the ceiling.

A mixing station (and a controller), that links the indoor terminal unit with the heat source and sink, was installed in the system to control the flow to the individual loops, flow rate, and the supply temperature to the embedded pipes. The operation of the radiant system was based on the operative temperature set-point that was adjusted from a room thermostat with 0.5 K intervals and on the relative humidity inside the house (to avoid condensation).

PV/T part (67.8 m^2) was intended to produce electricity (by photovoltaic cells), and produce heat for the domestic hot water and domestic appliances' use (dishwasher, washing machine and tumble dryer). Extraction of heat from the PV/T panels also cools the panels, which helps keeping the electrical efficiency close to the maximum. Based on this approach, the PV/T area was divided into two parts; Part A (45.4 m^2) and Part B (22.4 m^2). It was possible for the Part B to interact directly with the ground.

Part A was only intended to charge DHW tank when there was a need (no interaction with the ground). If there was flow in Part A, this meant that there was a DHW need and the flow can only be directed to the DHW tank, including Part B. Part B served two purposes; charging the DHW tank and cooling the PV/T panels. When there was a DHW need, Part B contributed to the charging of the DHW tank. Initial simulations and calculations showed that the ground (one borehole) was not capable of providing necessary supply temperature to the embedded pipes when house cooling and PV/T cooling were active simultaneously. Therefore PV/T cooling option was only applicable when house didn't need space cooling. There was a drain-back tank between the PV/T loops and the DHW tank which made it possible to drain all the water from the PV/T loops, when necessary, in order to avoid boiling or freezing of the water in the circuits.

The DHW tank, 180 liters, was equipped with two spiral heat exchangers and an electric heater. One of the spiral heat exchangers was connected to the PV/T panels via the drain-back tank and the other one to the active heat recovery system of the air handling unit. The top part of the tank (54 liters) was heated by the electric heater, when necessary.

It was possible to ventilate the house mechanically (by means of an air handling unit, AHU) and naturally (by window openings in the façades). Mechanical ventilation gives a higher degree of control over indoor environmental quality but at the expense of energy consumption. This energy consumption can be eliminated with the use of natural ventilation. It was intended that the natural ventilation will overrule the mechanical ventilation system when the outside conditions are suitable, to take advantage of the passive means. The mechanical ventilation was only used to provide fresh air to the house since the main sensible heating and cooling terminal of the house was the radiant system. This also enables to have lower ventilation rates compared to a case where space heating and cooling is mainly obtained by mechanical ventilation.

Fresh air was provided into the house by an AHU which had passive and active heat recovery possibilities. The passive heat recovery was obtained by means of a cross-flow heat exchanger and it had an efficiency of 85% (sensible heat). The active heat recovery was obtained by means of a reversible air-to-water (or water-to-air, depending on the operation mode) heat pump that was coupled to the AHU and the DHW tank. The AHU could supply fresh air at a flow rate up to 320 m^3/h at 100 Pa. The design ventilation rate was determined to be 0.5 ach. Humidification of the supply air was not possible due to the limitations of the AHU.

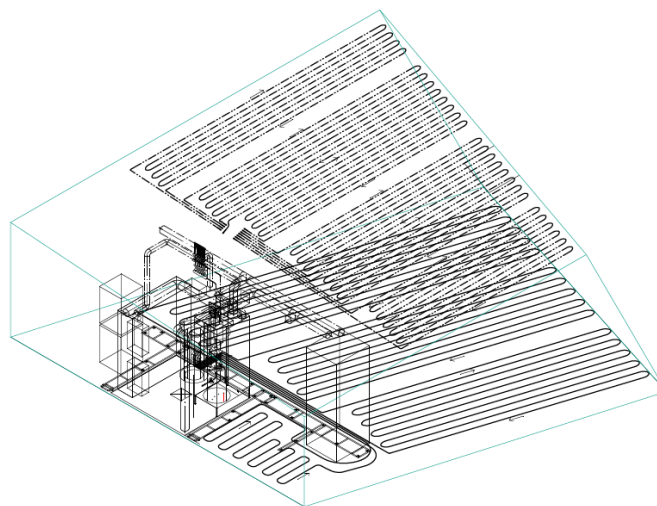Mechanical installations in the house may be seen in Figure 4:

Figure 4. Mechanical installations in the house

2.2.1.a Control

The initial ambition in the control system design was to have one control system that controls every component in the house, from lights to pumps, valves and so forth. This strategy proved to be too complicated to be realized due to the time constraint. Therefore some components of the system (which had its own sensors, control units etc.) were left to operate independently from the rest of the system (the ones that had their own control algorithm, e.g. control of radiant system), while some of the components were controlled by the main control system (programmable logic controller, PLC). For example, the lights of the house were controlled by the home automation system, the ventilation system was partly controlled by the PLC, the PV/T system, the valves, and the pumps were controlled by the PLC. The details of the HVAC control system can be found in Grigužauskas (2012) and Skrupskelis & Kazanci (2012).

Further details of the system and its components (dimensioning, annual performance, and so forth) can be found in Skrupskelis & Kazanci (2012).

2.2.2 Implemented system

Due to the limitations in the practical implementation and chosen experimental conditions, some differences occurred compared to the initially designed system. These differences were:

- The heat pump (GCHP) was intended to be used during the experiments in Denmark but it was not possible due to the lack of heat source (the ground heat exchanger was not installed);

- It was not possible to install a ground heat exchanger during the competition, due to the competition regulations. Therefore the ground heat exchanger (GHEX) was simulated by a reversible air-to-water heat pump that was coupled to a 500 L buffer tank;

- Before the experiments in Denmark, the buffer tank was taken out of the system. A flat-plate heat exchanger was installed between the house's space heating and cooling system and the air-to-water heat pump (the main heat source and sink of the house for the space heating and cooling was a reversible air-to-brine heat pump). The part between the heat exchanger and the air-to-water heat pump was filled with an anti-freeze mixture (40% ethylene glycol) in order to avoid frost damage during winter;

- The cooling of the PV/T panels via the ground heat exchanger was not realized (PV/T Part B never interacted with the ground). This was due to two reasons: the cooling capacity of the designed GHEX was not enough to provide space cooling to the house and PV/T cooling at the same time, and the hydronic system of the house would become too complicated in order to implement this strategy;

- Before the activation of the thermal part of the PV/T, the piping leading to the ground was eliminated. The drain-back strategy was not implemented due to the problems with getting the required flow rate, and problems with the air in the system. Therefore, the system was filled with an anti-freeze mixture and pressurized, and it operated as a regular solar thermal installation;

- During the experimental period, natural ventilation was not used;

- Ceiling heating or cooling was not used during year-round measurements in Denmark;

- Inner solar shading (manually operated) was installed on the North façade (covering 20 m^2) on 30th of July 2014 and it was used in fully down position until the end of the experiments. The installed solar shading is shown in Figure 5:

Figure 5. Installed inner solar shading

2.3 Energy efficiency measures and innovations

Energy efficiency was one of the key aspects of the design phase and the overall project. It was realized by means of choosing energy efficient products and strategies, integration of renewable energy resources into the HVAC system, and product development. A summary of energy efficiency measures and innovations are as follows:

- Very low U-value of the envelope;
- Geometry of the house (optimized inclination of the roof, orientation of the house, overhangs, smaller South façade than North façade, etc.);
- Low temperature heating and high temperature cooling system for sensible heating and cooling;
- Radiant system has its own control system with its own sensors, learns the behavior of the building and controls the pumps and the loops based on the learned behavior;
- Ground as the heat source (GCHP) and sink (GHEX) of the house (high COP of the heat pump and free cooling via by-passing the heat pump in the cooling season);
- Mechanical ventilation was only used to provide fresh air (low ventilation rate, low energy consumption);
- Natural ventilation, when ambient conditions are suitable;
- Passive and active heat recovery in the AHU (AHU is coupled with the DHW tank);
- PV/T and DHW tank combination (keeping the electrical efficiency of PVs close to optimum, utilizing the waste heat to charge DHW tank);
- DHW tank is also heated with ventilation coupled heat pump (air-to-water heat pump);
- PV/T cooling with ground heat exchanger as an option;

- Utilization of surplus heat from the PV/T panels in Heating water circuit (HWC) appliances instead of electricity (energy- and exergy-wise efficiency);

- Appliances and all the lights were the most energy efficient ones available at the design stage;

- A slim structural ceiling element that incorporates custom-made PV/T panels, insulation (conventional insulation and a new, more effective and thinner type), and embedded pipes (radiant heating/cooling system) was developed. This element and its features are shown in Figure 6:
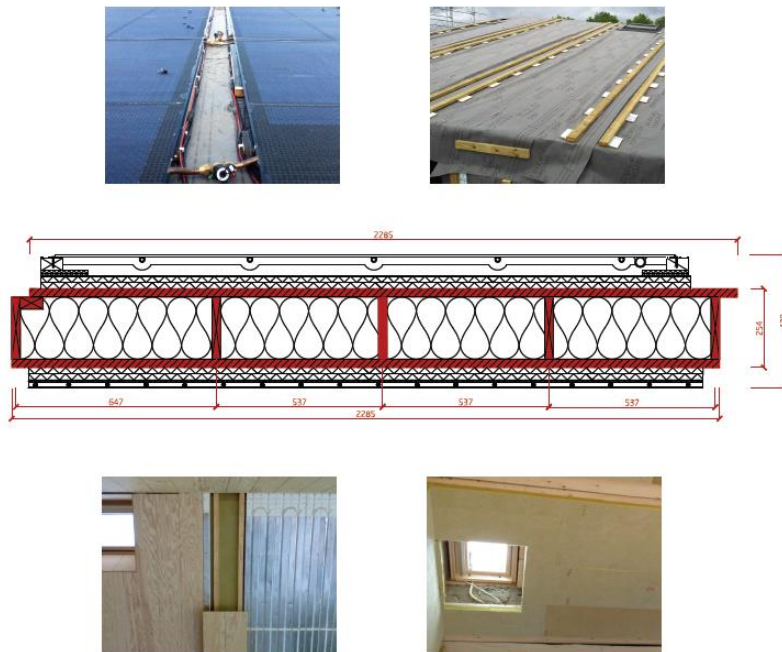

Figure 6. Innovative ceiling element

3. Investigations

This chapter explains the investigations carried out with respect to the different phases of the project. The results and discussion of the results are given in the following chapter.

3.1 Design phase and pre-competition period

The design phase and the pre-competition period consisted of the work carried out in order to design the house and its systems. It included the different tests carried out on different components of the house and on the house on full-scale when it was at DTU's campus in Kgs. Lyngby.

During the design phase, different alternatives were considered regarding the choice of system components, combinations, operation strategy and building structure (envelope). Various analyses were carried out by means of calculations (based on guidelines, standards and so forth), simulation softwares (simulation of components and whole building simulations), experiments to investigate the applicability of different technologies in the house (experiments regarding the cooling performance of PCM, test of PV/T panels) and to investigate the performance of different components (heat output from the radiant floor structure, and full-scale tests of different mixing stations for the radiant cooling system).

The obtained results from these analyses guided the design process, the choice of system components, and the operation of the system. A summary of the results obtained during the design phase and pre-competition period is given in Chapter 4.1.

3.2 Competition period

The evaluation of the teams' performance in the competition was based on 10 categories. Some of these categories were evaluated by juries consisting of three experts from that particular field and some of the categories were evaluated by measured parameters and task completion. The categories were architecture, engineering and construction, energy efficiency, electrical energy balance, comfort conditions, house functioning, communication and social awareness, industrialization and market viability, innovation, and sustainability.

During the competition period, the house was supposed to function as a regular house with systems such as computer, DVD player, washing machine, tumble dryer, dishwasher, oven and so forth. Therefore the functionality of the house as a real house was evaluated.

The overall results of the competition together with the measurements of the indoor climate (temperature, relative humidity and CO_2 concentration in this context) and the energy consumption, production (and hence the balance) are presented in Chapter 4.2.

3.3 Year-round measurements in Denmark

After the competition was completed, the house was disassembled and loaded into trucks. The house had to wait in trucks until a final decision about its location was reached. The house was assembled again and it became fully functional again in September 2013.

Once the house was functional, the measurements regarding the thermal indoor environment and energy performance were initialized. In addition to these aspects, various physical parameters were measured in the house and in its systems. The measurements continued from 26th of September 2013 to 1st of October 2014. A

full list of the measured parameters and information regarding the measuring equipment can be found in Appendix B.

During the experimental period, various physical measurements were taken from the house. The temperature (air and globe) measurements were taken at the 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 representative location in the house. The reason to measure at the heights above the occupied zone was to evaluate the effects of thermal stratification based on the different heating and cooling strategies. The stratification is particularly important for Fold because of its high and inclined ceiling. It was aimed to use thermal stratification as an indicator for the performance of the heating strategy regarding heat loss from the conditioned space.

The globe temperatures were measured by a gray globe sensor, 4 cm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person, Simone et al. (2008), and will thus at 0.6 m and 1.1 m heights represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded to avoid heat exchange by radiation, Simone et al. (2013). The output from the sensors was logged via a portable data logger. The measurement location, the sensors and a close-up of the sensors are shown in Figure 7:

Figure 7. The location of the measurements (left) and the measurement equipment (middle and right)

In its final location (Bjerringbro, Denmark), the house was occasionally used as a meeting room and as a showcase of various energy efficiency measures. There were no occupants living inside the house but the occupancy and equipment schedules (internal heat gains) were simulated by means of heated dummies. A dummy is 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. Dummies had an adjustable heat output up to 180 W, Skrupskelis & Kazanci (2012). Their locations were based on where the occupants and the equipment were expected to be in the house.

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

3.3.1 Heating season

Different heating strategies were tested during the heating season (October 2013 to April 2014, both months included). A total of seven different experimental conditions were studied.

For the first part of the experiments, the floor heating was operated, without ventilation, with different operative temperature set-points following a previous study by, Kazanci & Olesen (2013). In the second part, floor heating was supported with warm air heating by the ventilation system, and during the last part of the heating season, floor heating was operated with heat recovery on the ventilation system. 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 determined to be 0.5 ach.

The most important boundary conditions regarding different case studies are given in Table 2:

Table 2. Periods and experimental settings of the case studies, heating season

Period	Average external air temperature [°C]	Floor heating set-point [°C]	Ventilation	Case study 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 the dummy, equipment #2, were OFF during this experimental period.
**: Heat recovery refers to the passive heat recovery in the AHU. Pre-heating refers to the active heat recovery in the AHU.

The results of the analyses are given in Chapter 4.3.1.

3.3.2 Cooling season

The operation of the HVAC system during the cooling season (May to September 2014, both months included) had a similar approach to the heating season. The house was cooled by floor cooling and it was ventilated with the mechanical ventilation system (heat recovery on ventilation). Different operative temperature set-points (to control the operation of the radiant system) and different ventilation rates were implemented. At a certain point during the measurements, overheating proved to be a problem and internal solar shading was installed to tackle this problem. The internal solar shading was installed on the North façade of the house on 30th of July 2014.

The most important boundary conditions regarding different case studies in cooling season are given in Table 3 (HV stands for higher ventilation rate and S stands for solar shading):

Table 3. *Periods and experimental settings of the case studies, cooling season*

Period	Average external air temperature [°C]	Floor cooling set-point [°C]	Ventilation type and ventilation rate	Solar shading	Case study abbreviation
1st of May to 27th of May*	14.7	20**	Heat recovery, 0.5 ach	No	FH20
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 October	16.0	24	Heat recovery, 0.5 ach	Yes	FC24-S

*: The dummies simulating the occupants and the dummy, equipment #2, were OFF during this experimental period.
**: Floor heating was active, transition period.

The results of the analyses are given in Chapter 4.3.2.

3.3.3   Annual

Various other measurements were taken from the house, such as relative humidity, noise, energy consumption, energy production and so forth. The results of these measurements and experiences from one year of operation are provided in Chapter 4.3.3.

3.4 Improvement suggestions for building and HVAC system

Despite being designed and constructed as a competition house, the house could still be improved in different ways. Some of the reasons underlying these investigations are as follows:

- Previous studies about the indoor environment and energy performance of the house showed that the large glazing façades created high heating and cooling demands and affected the energy performance of the house in a negative way;

- The house had been transported and it had been assembled (three times) and disassembled (two times). The house had been stored in containers for several months, hence it is likely that the air-tightness and thermal bridges changed from the original values, resulting in a lowered thermal performance of the building envelope.

In order to quantify the effects of possible improvement options regarding the building envelope and the HVAC system, parametric studies were carried out by means of IDA ICE. The results of the different analyses are presented in Chapter 4.4.

4. Results and discussion

The results obtained from different analyses regarding the house are presented in this chapter. These analyses include calculations, simulations, and measurements.

4.1 Design phase and pre-competition period

Design phase and pre-competition period includes all the analyses carried out during the design and test phase operation of the house in campus of DTU in Kgs. Lyngby, Denmark. The following results are obtained from Skrupskelis & Kazanci (2012) and Ševela (2012):

- Regarding the heat output from the radiant heating and cooling system, calculations based on two standards, EN 15377-1 (2008) and EN 1264-2 (2008), simulations with HEAT2, and full-scale experiments were performed. The results of heating and cooling outputs were in good agreement, except for the values obtained from EN 15377-1 (2008), which were too low compared to the other values and this is currently under investigation;

- Two mixing station were tested (one of the solutions was a commercially available product and the other one was an outcome of the collaboration between the HVAC design team and one of the sponsors). Both of them had its advantages and disadvantages and both of them showed potential to be improved;

- Calculations, simulations, and experiments were performed in order to evaluate the applicability of phase change materials (PCM) in the house. The simulations showed that a combination of embedded pipes and PCM enables energy savings up to 30% in the early and late cooling season and 20% in the peak month, in Madrid. The results of the experiments showed a better performance than the calculations and it was possible to discharge the PCM panels in 5 hours, but further development and testing were needed (due to corrosion, unexpected behavior of melting and solidifying, etc.) in order to fully employ the tested PCM panels, therefore PCM was not used in the final design of the house;

- Free cooling concept with the GHEX enables the same cooling output to be obtained with 8% of the energy consumption of a chiller (air-to-water heat pump). Capacity of one borehole was not enough to provide space cooling and PV/T cooling simultaneously, hence the space cooling was prioritized. GCHP operates with a high coefficient of performance (COP), 3.3 and 3.1 for Copenhagen and Madrid, respectively during the heating season. The results showed that for both locations (Madrid and Copenhagen) the heat absorbed from the ground was higher than the heat rejected to the ground and this resulted in a temperature decrease around the borehole in long term (i.e. 10 years). This is an undesirable effect, and it could be addressed with PV/T cooling via the ground in order to balance the heat rejected and absorbed from the ground;

- The simulations showed that the PV/T panels produced more electricity than the house consumed, on a yearly basis, for both of the locations (Madrid and Copenhagen), enabling the house to be a plus-energy house. The thermal part of the PV/T panels helped to keep the electrical efficiency of the PV cells close to the maximum, and the thermal part of the PV/T panels yielded a solar fraction of 63% and 31% in Madrid and Copenhagen, respectively;

- The PV/T panels proved to be an efficient combination, compared to having the electrical part (PV cells) and the thermal part (solar thermal collectors) separately (by increasing the surplus energy). The electrical efficiency of the PV cells was increased from 13.5% to 15.5% when the cells were cooled actively;

- Annual simulations of the house in different simulation softwares (TRNSYS and Be10) showed that the current orientation of the house was the optimal in terms of thermal indoor environment and energy consumption. In a later stage of the project this was also shown by another software, IDA ICE;
- The house has a high heating and cooling demand, due to the glass façades of the house. This drastically decreases the energy performance of the house, therefore active elements (PV/T panels) are needed for the house to become a plus-energy house;
- Implementation of a drain-back tank could be a good option but it was not fully realized due to poor design and implementation;
- When there was surplus heat from the PV/T panels, this heat was used in the heating water circuit (HWC) appliances (dishwasher, washing machine and tumble dryer) which proved to be a beneficial solution;
- Control system has a very high share in the total electricity consumption, 33% and 39% depending on if the energy consumption of the chiller (air-to-water heat pump) is included or not, for Madrid.

4.2 Competition period

The results obtained during the competition period (17th-28th of September 2012) of Solar Decathlon Europe 2012 in Madrid are presented with a focus on the comfort conditions (air temperature, relative humidity and CO_2 concentration, in this context) and on the power and energy values (production, consumption and balance). Certain limits were defined by the organizers regarding comfort conditions; indoor air temperature should be between 23.0ºC and 25.0ºC, indoor relative humidity should be between 40% and 55%, and indoor CO_2 concentration should be lower than or equal to 800 ppm. These physical parameters were measured by a SCR110-H sensor from Schneider Electric, provided by the organizers.

The air temperature, relative humidity, and CO_2 concentration from 00:00:00 on 17th of September 2012 until 23:59:59 on 28th of September 2012 are presented in Figure 8 to Figure 10:
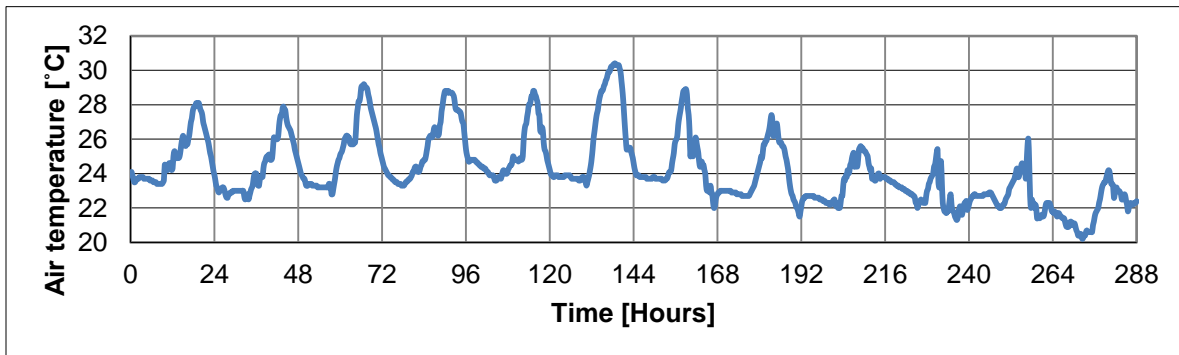
Figure 8. *Air temperature versus time*
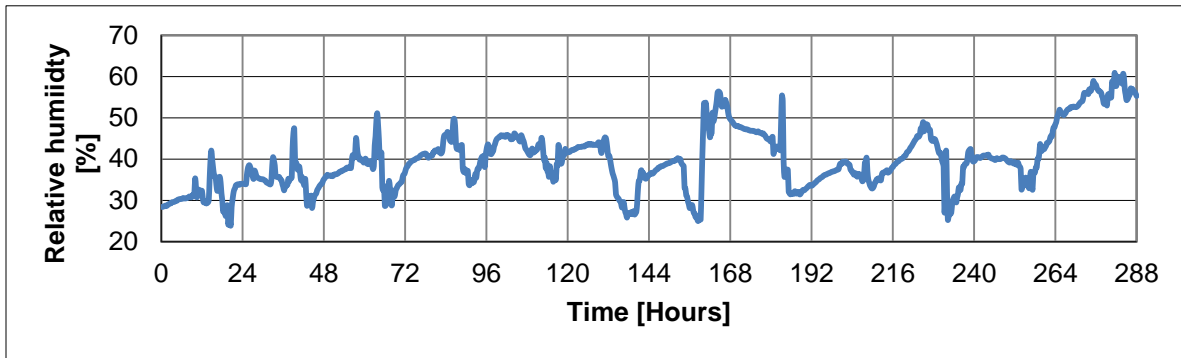
Figure 9. Relative humidity versus time
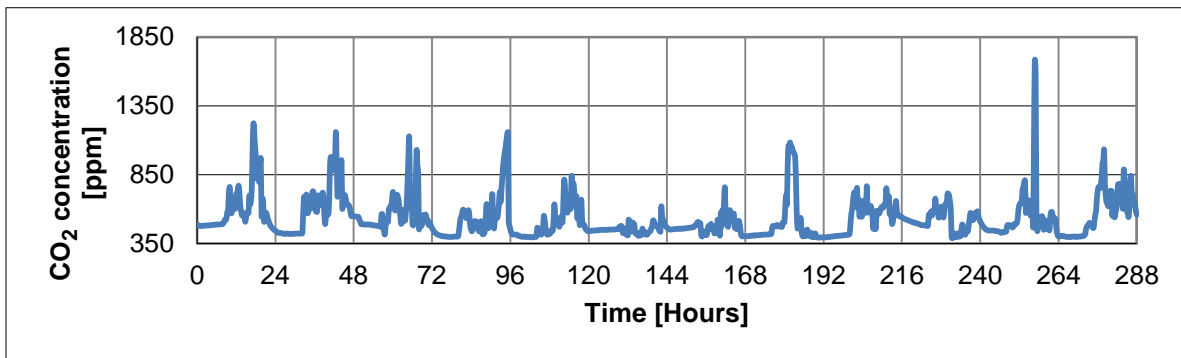
Figure 10. CO_2 concentration versus time

The power production, consumption, and balance are presented in Figure 11. Negative values indicate that the electrical load of the house was greater than the power being produced by the house, at that instant.
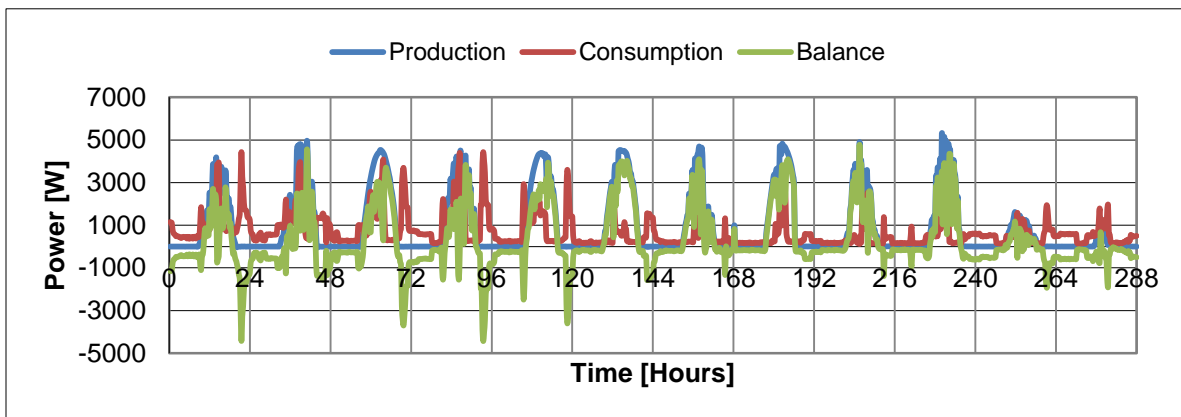
Figure 11. Power measurements (minus represents electricity taken from the grid)

Due to the competition regulations, it was not possible to install a real GHEX. The rationale behind having a chiller (a reversible air-to-water heat pump) and a buffer tank was to simulate the GHEX. Therefore, it is worthwhile to analyze how chiller consumption affected the overall consumption and how the consumption would have been if the chiller didn't exist. Figure 12 illustrates the effect of the chiller on the power consumption:
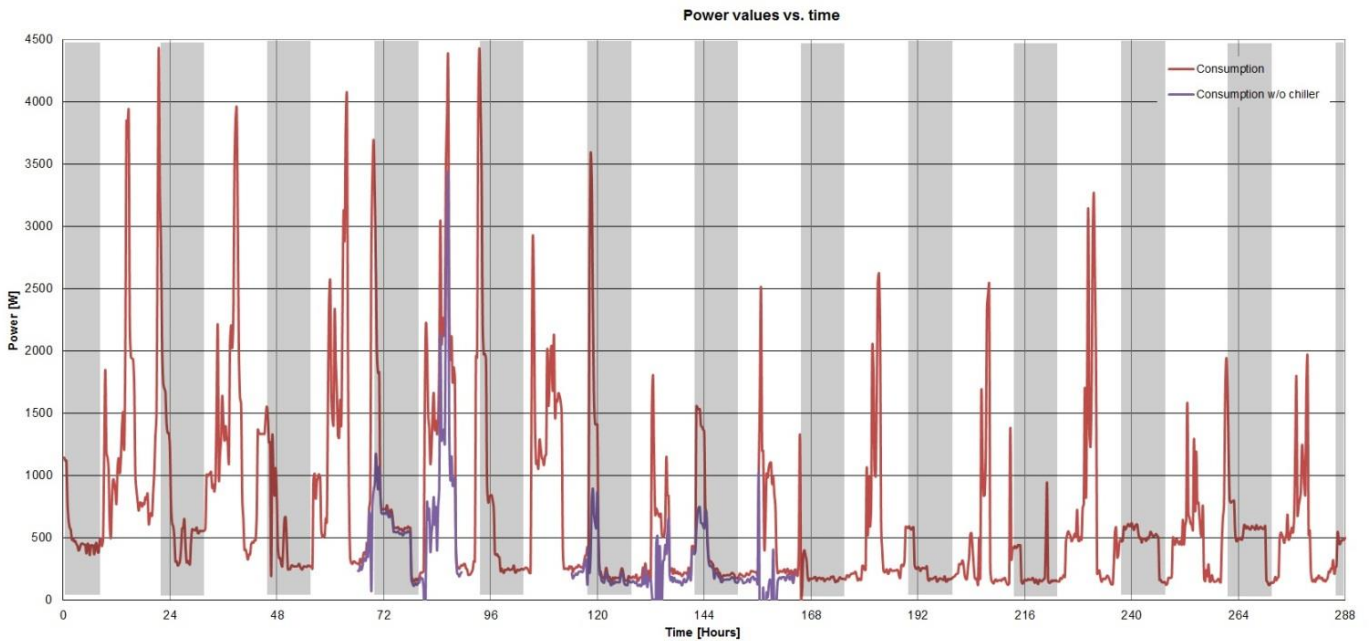
Figure 12. *Instantaneous consumption values, with and without the chiller*

It can be observed from the above figure that chiller had a significant effect on the consumption and on the peak power needed. It is worth mentioning that for the last 5 days of the competition the chiller was not activated and there was a loss of data from 18:01 on 20th of September to 18:23 on 21st of September 2012.

In addition to the previous figures, an energy analysis was made for the competition duration. Overall analysis is shown in Table 4:

Table 4. *Energy values during the competition*

Production [kWh]	275.6
Consumption [kWh]	196.9
Consumption without chiller [kWh]*	129.4
Balance with chiller [kWh]	78.7
Balance without chiller [kWh]*	146.2

*Chiller consumption was 67.5 kWh

The results regarding the comfort conditions show that the necessary conditions were met most of the time and high scores were obtained 63.18/70, 8.37/10, and 4.91/5 points for temperature, relative humidity and CO_2 concentration, respectively, Solar Decathlon Europe (2012).

The results also show that the house produced more energy than it consumed during the competition, 1.4 to 2.1 times more than it needed (with and without the chiller, respectively). It is also possible to observe from the above table that the chiller had a significant effect on the energy consumption and, hence, the energy balance. Results also indicate that the energy consumption of the chiller corresponded to 34% of the total consumption. At this point it should be noted that this chiller was used to simulate the ground heat exchanger and it was not a part of the initial system design.

The Fold completed the competition 10th among 20 teams. The final scoring is shown in Table 5:

Table 5. Total scoring of Fold in Solar Decathlon Europe 2012

Category	Rank	Obtained score	Possible score
Architecture	12	60	120
Engineering and construction	10	65	80
Energy efficiency	9	75	100
Electrical energy balance	9	83.93	120
Comfort conditions	7	96.80	120
House functioning	10	106.36	120
Communication and social awareness	12	51.80	80
Industrialization and market viability	5	64.90	80
Innovation	10	32.90	80
Sustainability	11	71.40	100
Total bonus/penalties	7	7.50	
Total scoring	10	715.59	1000

In addition to the competition categories given in the above table, there were different out-of-contest awards. One of these awards was "Solar Systems Integration Award". The focus of this award was that the solar systems of the house were well integrated into different systems of the house (heating, cooling, ventilation, control, electrical systems and so forth) including the aesthetical aspects. Team DTU won this award, indicating that a perfect integration of the solar system was achieved.

The results obtained from the competition show the importance of a holistic approach to the design process of the house. Overall, the house had a good performance regarding the comfort conditions, electrical energy balance, and industrialization and market viability. The overall results could have been improved with slight changes in the design phase and in the operation of the house.

4.3 Year-round measurements in Denmark

In its final location (Bjerringbro, Denmark), the house was occasionally used as a meeting room and as a showcase of various energy efficiency measures. The data presented in this study include the irregularities and disturbances that took place during the experimental duration such as meetings, various visits, door openings, the experimenter going in and out of the house and so forth.

In the following analyses, 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 of local thermal discomfort but human thermal comfort depends also on other factors such as radiant temperature asymmetry, draught and so forth. All of these factors should be considered for a definitive conclusion on the occupant thermal comfort.

4.3.1 Heating season

The performance of the different heating strategies were compared based on the achieved indoor climate category according to EN 15251 (2007), and temperature stratification at the given measurement location. The temperature stratification was also used as an indicator of heat loss, hence the energy efficiency. The indoor environment category was analyzed for the different heating strategies and for the entire heating season.

Categories are given according to EN 15251 (2007) for sedentary activity (1.2 met) and clothing of 1.0 clo. The results are shown in Table 6:

Table 6. 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.

The operative temperature (at 0.6 m height) and the external air temperature during the heating season are shown in Figure 13:
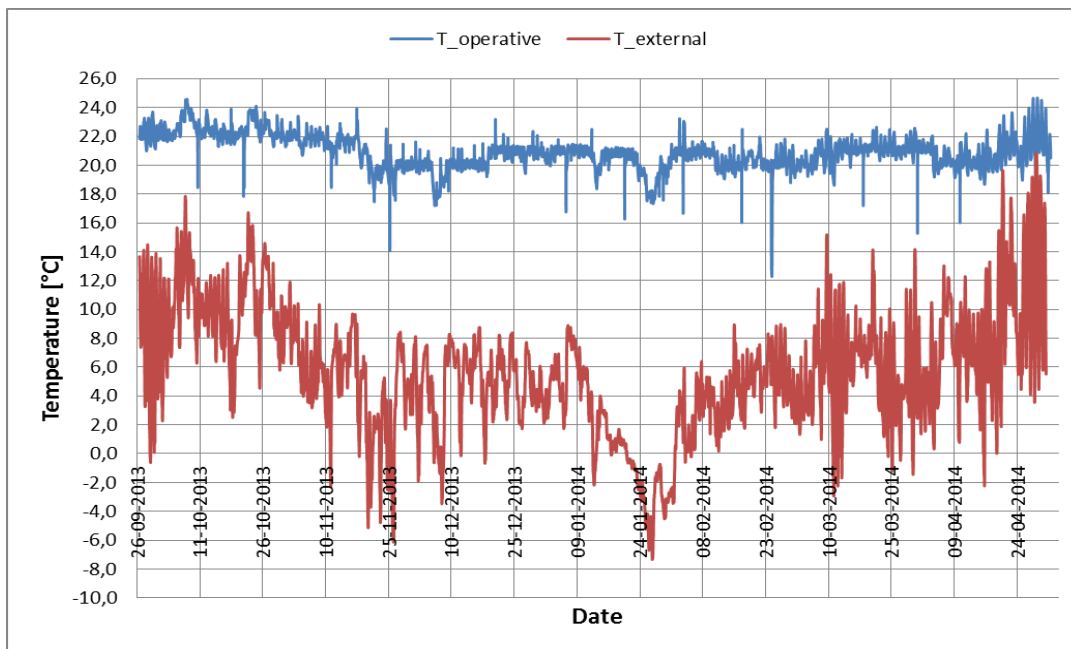
Figure 13. Operative temperature and external air temperature during the heating season

It may be seen from Table 6 and Figure 13 that even though different heating strategies were tested, the overall performance regarding the indoor environment was satisfactory, i.e. 80% of the time in category 2 according to EN 15251 (2007). It may also be seen that there were durations where the indoor environment was out of category 3, during 2% of the time in category 4. This is an undesirable situation however these instances might correspond to the previously mentioned disturbances.

The results showed that it was possible to keep the indoor operative temperature close to the set-point however the systems struggled to achieve this when the outside temperatures got relatively low. In addition to the increased heating demand, one possible explanation to this behavior is that both the air-to-brine heat pump and the AHU are affected by the lowered outside air temperatures.

The operative temperature set-point of 20°C is too low. This is because even though the ventilation system would be heating, the floor heating system (which is the main sensible heating terminal) would start the water circulation in the loops when the operative temperature drops below 20°C. This resulted in several periods with room temperatures below 20°C.

Vertical air temperature difference between head and ankle levels (1.1 m and 0.1 m above the floor, respectively) at the measurement location was evaluated according to EN ISO 7730 (2005), as an indicator of local thermal discomfort. The average temperature differences with respect to the heating strategy are given in Table 7 and the temperature difference during the entire heating season may be seen in Figure 14:

Table 7. 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
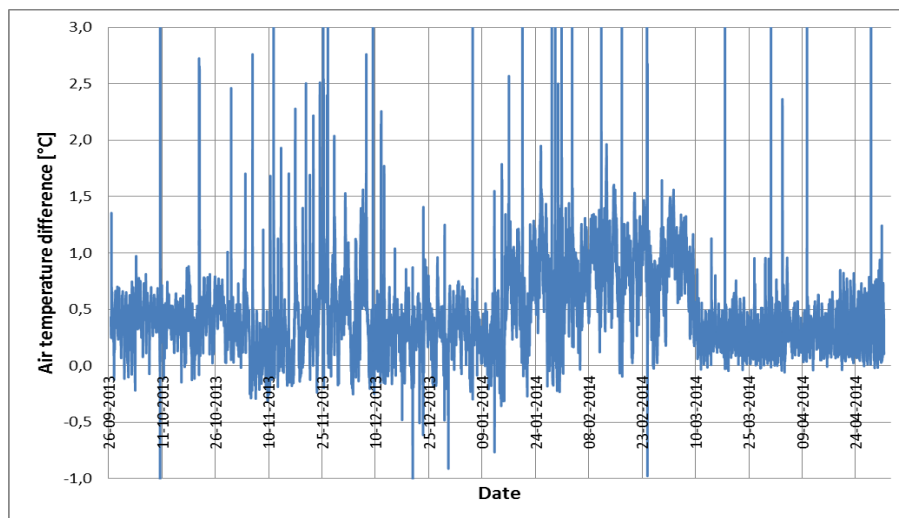
Figure 14. Vertical air temperature difference between head and ankles during heating season

It may be seen from Table 7 and Figure 14 that the vertical air temperature difference was the highest for the cases where the floor heating was supported with warm air heating by the ventilation system. For each heating strategy and for the overall heating season the average temperature difference was less than 2 K indicating that Category A is met according to EN ISO 7730 (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 (hence energy efficiency). In Table 8, average air temperatures at selected heights are presented based on the heating strategy:

Table 8. *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

*: For this height, globe temperature was used due to a problem with the air temperature sensor.

In Figure 15, air temperature differences (globe temperature is used for 1.7 m) between the selected heights are presented for the heating season:
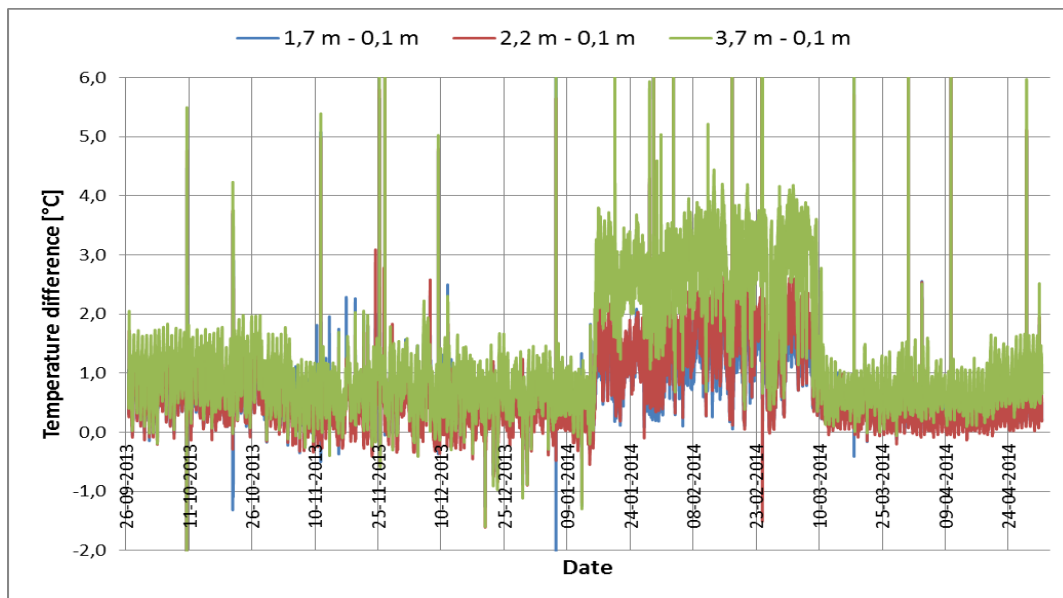
Figure 15. *Air temperature difference between the selected heights, heating season*

The results presented in Table 8 and Figure 15 indicate that the thermal stratification inside the house is greatest when the floor heating is supported by warm air heating by the ventilation system. Because of the lower density of the supplied warm air compared to the room air, the supply air tends to flow along the ceiling and not to mix with the room air. Due to this phenomenon and the thermal stratification, in the cases where the floor heating is supported by warm air heating with ventilation, the space above the occupied space is being heated. This increases the heat loss from the indoor space and especially where there are glass façades with lower U-values. Increased thermal stratification is a phenomenon to avoid, especially in a house with a high and tilted ceiling as the present one.

4.3.2 Cooling season

The performance of different cooling strategies were compared based on the indoor environment categories given in EN 15251 (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 (2013). According to DS 469 (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). It should be noted that according to DS 469 (2013), mechanical cooling would normally not be installed in residential buildings.

The obtained indoor environment categories, and hours above 26°C and 27°C with respect to the cooling strategy are given in Table 9, and the operative temperature and external air temperature over the cooling season are presented in Figure 16:

Table 9. The category of indoor environment based on operative temperature (at 0.6 m height), cooling season

Indoor environment category/case	FH20	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

*: The house was not cooled from 20th of June 11:00 to 23rd of June 08:00 (the floor cooling and the AHU were OFF).
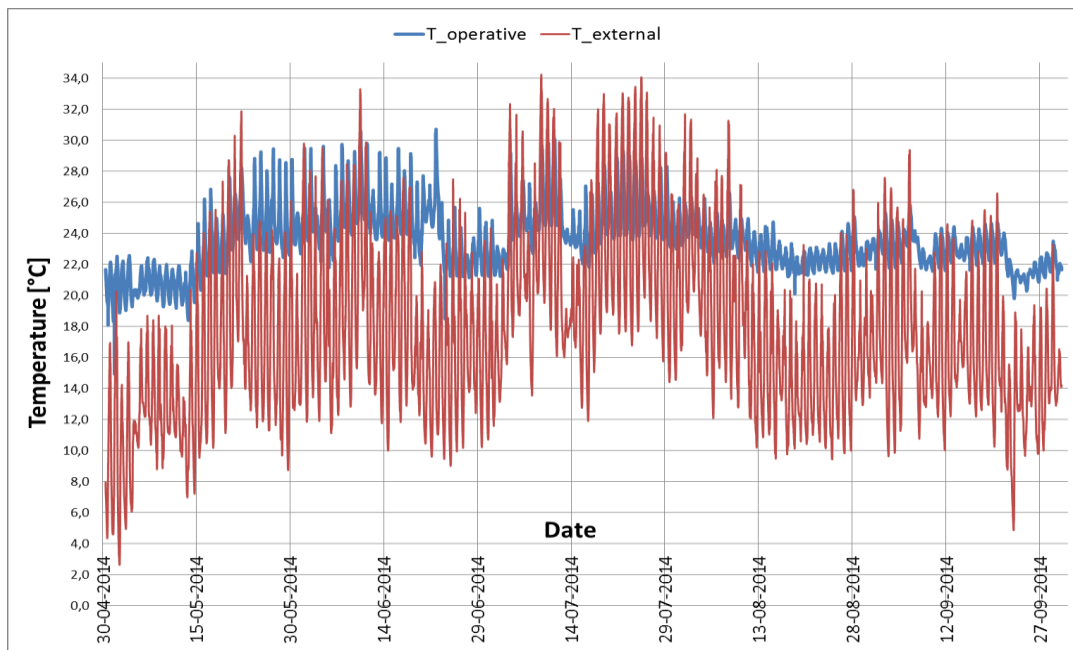
Figure 16. Operative temperature and external air temperature during the cooling season

It could be seen from Table 9 and Figure 16 that the house performed worse in the cooling season than the heating season; 57% of the time in category 2 and 19% of the time outside the recommended categories in EN 15251 (2007). This was mainly due to the transition periods inside the cooling season and due to overheating, which proved to be a problem during the cooling season, except for the last two months, i.e. August and September. The total hours above 26°C and 27°C exceeded the values recommended in DS 469 (2013).

28

Decreasing the operative temperature set-point and increasing the ventilation rate proved to be effective ways to deal with the increasing cooling load. This is mainly due to the longer operation of the floor cooling and increased cooling obtained from the supply air into the house.

The results also show that even though the floor heating was active during most of May (transition month), 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 performance regarding indoor environment.

The most of the overheating hours were in the late afternoon hours (i.e. from 18:00 until the sunset); during this period of the day, there was direct solar radiation into the house, coming in from the North façade. Another observed effect was the strong reflection from the PV panels placed 150 m across (on the North-West side, which is the direction of North façade of the house) from the house, and this was an unexpected external factor that contributed to the cooling load.

The most significant problems of the house were the large glazing façades (including the lack of solar shading) and the lack of thermal mass in order to buffer the sudden thermal loads. In the current positioning of the house, the direct solar radiation from the South façade was not a significant problem, because of the longer overhang and because of the trees that created shadows, on the South façade.

The vertical air temperature difference between head and ankles was evaluated according to EN ISO 7730 (2005) as an indicator of local thermal discomfort. The average temperature differences with respect to the cooling strategy are shown in Table 10 and the temperature difference during the cooling season may be seen in Figure 17:

Table 10. Time-averaged vertical air temperature difference between head and ankles, cooling season

Case	FH20	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
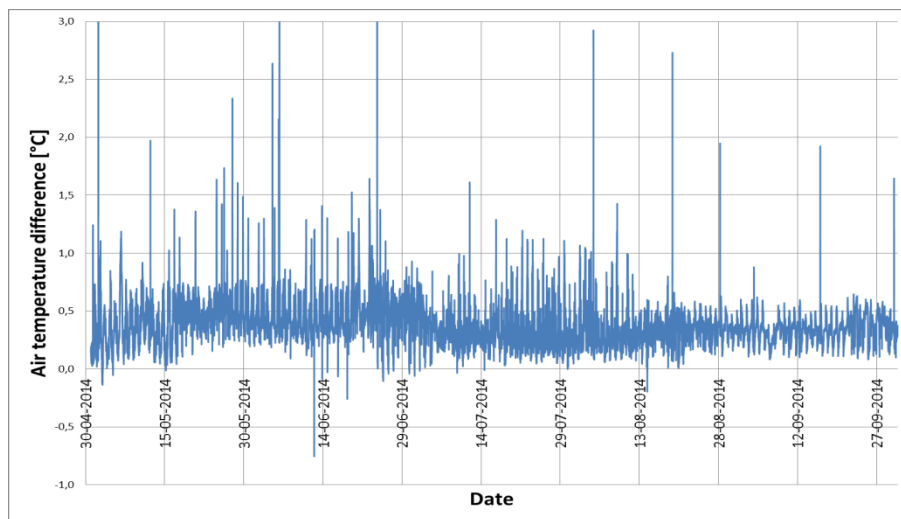
Figure 17. Vertical air temperature difference between head and ankles during cooling season

It may be seen from Table 10 and Figure 17 that for each cooling strategy and in average, the vertical air temperature difference was lower than 2 K indicating that Category A was met according to EN ISO 7730 (2005) at the measurement location. The high values of fluctuation may be attributed to the direct solar radiation on the sensor at 1.1 m height (even though the sensor was shielded against radiation).

The thermal stratification at the measurement location was also evaluated. The average temperature at chosen heights with respect to the cooling strategy and the temperature difference between the lowest and highest measurements points are given in Table 11. The air temperature difference between the selected heights over the cooling season is shown in Figure 18:

Table 11. Time-averaged air temperature at the selected heights and the difference between highest and lowest measurement points, cooling season

Height/case	FH20	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
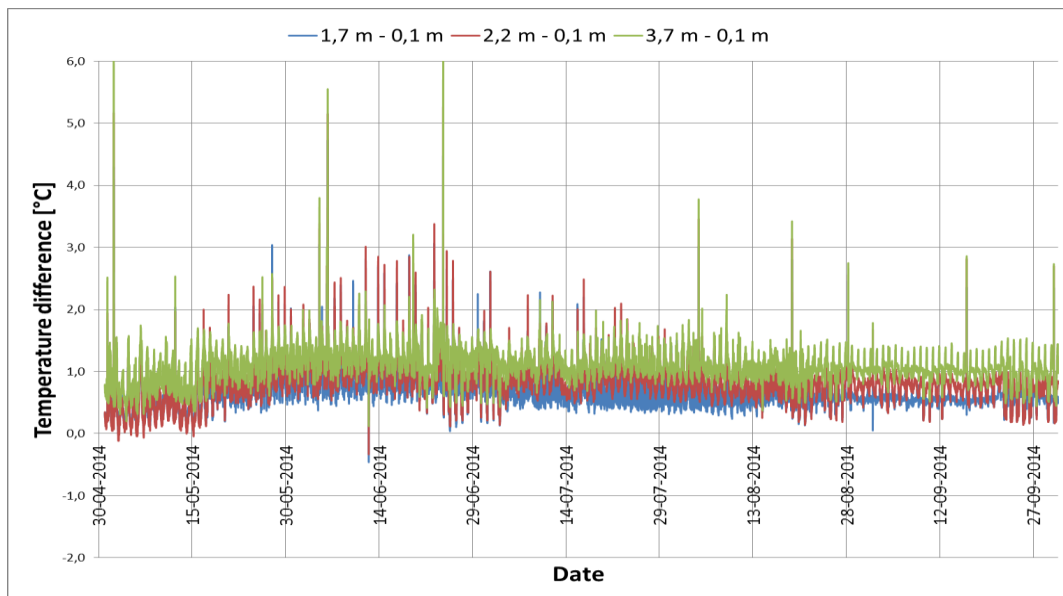
Figure 18: Air temperature difference between the selected heights, cooling season

It may be seen from Table 11 and Figure 18 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 the floor heating supported by warm air heating). This effect could be explained with the floor cooling. The sudden increases in the temperature difference could be due to direct solar radiation on the sensors.

Even though different simulation softwares showed that the current orientation of the house was optimal in terms of thermal indoor environment and energy consumption, based on the measurement results, it could have been a better option if the house had a 180° reversed orientation, i.e. the façade with the longer overhangs was towards the North, this might also increase the solar heat gains during the winter.

In addition to the previously described measurements, horizontal temperature distribution inside the house was measured. Since the house consisted of a single space interior, the control of indoor environment in this single space could be problematic. Also, due to the large glazing façades, operative temperature can be influenced significantly, and radiant temperature asymmetry could be encountered. In order to address these concerns, the measurement locations were increased and air, globe, and operative temperatures were measured in different locations inside the house. The analysis of these measurements is currently under process and the results will be presented at ASHRAE's Annual Conference in Atlanta, GA, USA in 2015, Kazanci & Olesen (2015a).

4.3.3 Annual

4.3.3.a Other measurements

The relative humidity was measured throughout the year. Even though the relative humidity was not controlled by the ventilation system, it is important to consider its long term values. Long term high humidity could cause microbial growth, condensation, mould, and long term low humidity could cause irritation of eyes and airways, EN 15251 (2007).

The measured relative humidity values (at 1.1 m height) were not classified according to EN 15251 (2007) since it was not controlled. Minimum, maximum and average relative humidity values were 23%, 68%, and 44%, respectively. Relative humidity during the measurement period is shown in Figure 19:

Figure 19. *Relative humidity during the measurement period in Bjerringbro*

It could be seen from Figure 19 that the relative humidity was within the range of 20-70% according to EN 15251 (2007) during the measurement period, indicating that there was no significant problem related to humidity indoors.
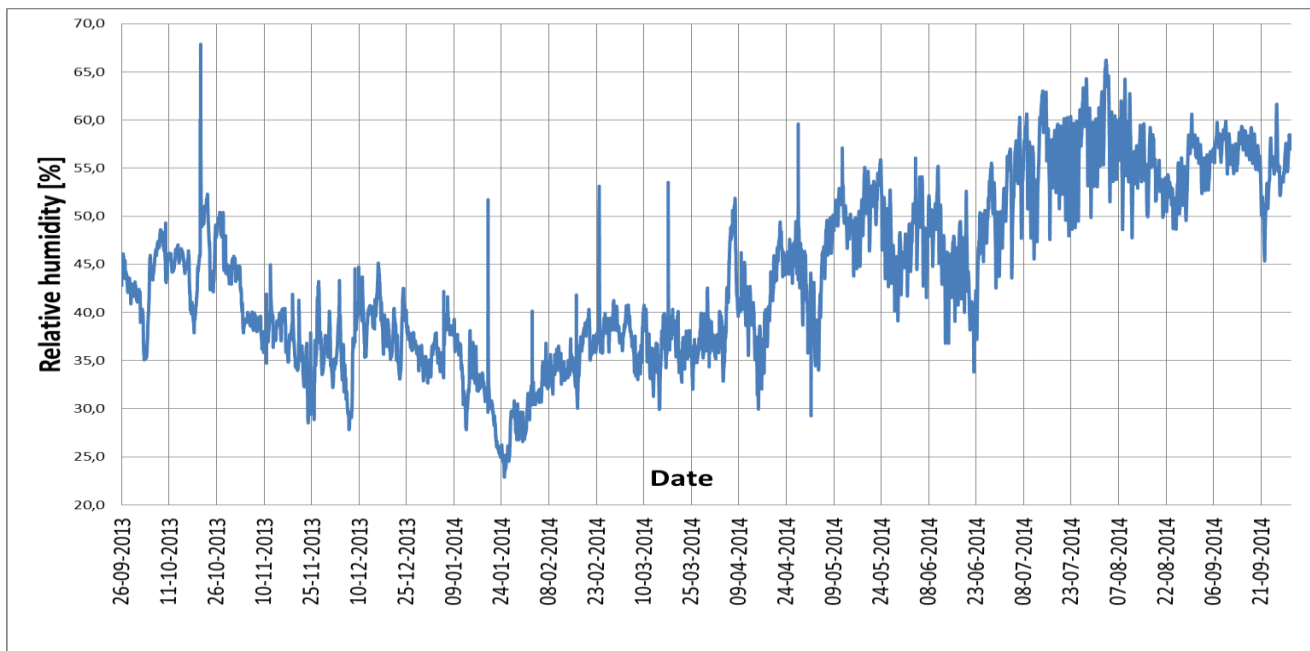
Subjective evaluations and measurements showed that the noise produced by the ventilation system was too high. Measurements showed that the sound pressure levels inside the house were 41.4 dB(A) and 44.6 dB(A), for 0.5 ach and 0.8 ach, respectively. These values are above the default design value of 32 dB(A) and the typical range of 25 to 40 dB(A), given for living rooms in residential buildings, according to EN 15251 (2007). This problem could have been solved with the installation of silencers in the ventilation system.

4.3.3.b Energy production and consumption

During the measurement period in Bjerringbro, the energy production (from the PV/T panels) and energy consumption were measured. A few sensor (or computer) failures have happened and the data lost during these periods were estimated by means of calculations. The annual electricity production with respect to months is shown in Table 12:

Table 12. Annual electricity production from the PV/T panels

Date	Electricity produced [kWh]
26-30th September 2013	59.3
October 2013	214.6
November 2013	143.0
December 2013	61.9
January 2014	59.7
February 2014	168.8
March 2014	310.2
April 2014	507.3
May 2014	621.1
June 2014	665.1
July 2014	519.7
August 2014	405.0
September 2014	308.1
Total	4043.9

The annual electricity production from the PV/T panels was lower compared to the simulation results from TRNSYS (for Copenhagen), 7434.3 kWh. This was already expected; it was known from the competition period that the output of the PV/T panels was lower than the expected values, also the climate is different from the weather files used in simulations (and also the location is different). In addition to these factors, some of the PV/T panels were damaged (during disassembly/assembly and transportation of the house). In the house's current location, some trees have been creating undesired shading on the PV/T panels.

For the HVAC system's consumption, air-to-water heat pump, mixing station and its controller (controls the flow into the radiant systems' loops), and AHU were considered. An extra pump before the mixing station was also in operation (it was ON from 23rd of June 2014) but the consumption of this pump is not included since it would not be installed in a regular installation (in this particular case, it was installed in the system as a brine pump for the possible GCHP).

32

During the heating season, the set-point of the heat pump was 35°C until 21st of November 2013 and after this date, it was 40°C. During the cooling season, the set-point of the heat pump was 15°C. It should be noted that there was a certain heat loss/heat gain from the heat pump until the technical room.

The consumption of the components with respect to the case studies is presented in Table 13:

Table 13. *Energy consumption of the HVAC system components*

	Case	Heat pump [kWh]	Mixing station [kWh]	Controller, radiant system [kWh]	AHU [kWh]	Total [kWh]
Heating season	FH22	518.9	15.5	5.3	0.0	539.7
	FH20	438.3	11.3	3.8	0.0	453.4
	FH21	460.6	15.0	5.0	0.0	480.6
	FH21-HRPH	463.2	10.4	3.5	236.6	713.7
	FH20-HRPH	307.2	2.2	0.8	221.2	531.4
	FH21-HR	321.8	7.2	2.5	39.3	370.7
	FH20-HR	304.6	4.3	1.5	47.5	358.0
Cooling season	FH20	206.4	1.3	0.4	42.6	250.7
	FC25	95.4	5.4	1.8	36.0	138.7
	FC25-HV	110.1	3.2	1.4	75.2	189.8
	FC24-HV	114.8	6.7	2.0	60.9	184.3
	FC24-HV-S	105.6	3.8	1.2	78.8	189.3
	FC24-S	145.9	0.6	0.2	65.7	212.4
	Total	3592.9	86.7	29.3	903.8	4612.7

In Table 13, heat pump's consumption includes the heat pump cycle's consumption, an integrated pump and the heat pump's control system. The mixing station's consumption includes a pump, a motorized mixing valve and the control unit. The controller of the radiant system is the device that controls the flows into the different loops and decides when the pump in the mixing station should be ON (master/slave). The AHU's consumption includes fans (supply and exhaust), control system, by-pass dampers, heat pump cycle and its related equipment.

It is possible to increase the energy performance of the house with simple modifications, e.g. 1051 kWh (29%) of the consumption of the heat pump is due to the pump (120 W) 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 with synchronizing the mixing station pump and this pump (since there is no storage in between). It should be noted at this point that in the initial design of the HVAC system, the heat source and sink of the house was a ground heat exchanger. A similar approach regarding the synchronization of the pumps can be employed for the control of the brine pump (even though its consumption is not included), lower ventilation rates can be employed when the house is unoccupied, natural ventilation can be employed when the outside conditions are suitable, and so forth.

4.3.3.c General notes on the house's operation

The house was supported on concrete blocks and the space between the ground and the house's floor structure was covered. The fresh air into the AHU was taken from 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, therefore it slightly buffered the

variations in the external air temperature (in Madrid and in Bjerringbro). Though, the effects on the heat loss should be considered for a final conclusion on this (comparison of heat loss to the ground versus heat loss to the space between the ground and the house).

During the summer of 2014, the thermal part of the PV/T panels started to operate. It was observed that the thermal part of the PV/T panels contributed significantly to the DHW needs of the house during the summer period but it was not so beneficial outside the summer months (mid-October to mid-March). This is due to the low levels of incoming solar radiation and high heat loss from the PV/T panels. The analyses also revealed a potential for night radiative cooling with the PV/T panels but this application would require thermal storage (either in form of thermal mass in the building or in form of a storage tank).

The transition periods (i.e. September and May) require special attention regarding the operation of the heating and cooling system and regarding the switchover between heating and cooling operation. Though, increased thermal mass could address some of the concerns regarding thermal indoor environment and energy consumption during the transition periods.

The results of the blower-door tests and thermal camera imaging of the house showed that the house's envelope was not as tight as it was intended during the initial design stage; this was due to the transportation, storage of the house in containers, and several assembly processes.

The results of the year-round measurements will be disseminated in, Kazanci & Olesen (2015b) and Kazanci & Olesen (2015c).

4.4 Improvement suggestions for building and HVAC system

This chapter is based on Andersen & Schøtt (2014) and Andersen et al. (2014). Further details can be found in these publications.

4.4.1 Background and methodology

Experiences from the different stages of the project led to the conclusion that even though the house was designed for a competition and it is classified as a plus-energy house, there was potential for improvement regarding the energy consumption and indoor environment. Therefore, in addition to the previous dynamic simulations of the house in Be10 and TRNSYS, further simulations were carried out in IDA ICE.

The main goal of the simulations was to provide improvement suggestions for lowered energy consumption and improved indoor environment. The effects of different building and HVAC system parameters (orientation of the house, positioning and areas of the windows, thermal bridges, infiltration, exterior solar shading, natural ventilation, thermal mass, and increased embedded pipe system area) were studied. Operative temperatures from the simulation model and from the house were compared, as well as the energy consumption of the chosen components of the HVAC system, to validate the simulation model. The measurement period considered was from 26th of September 2013 to 3rd of April 2014.

4.4.2 The results of operative temperature comparison

The measurements of the operative temperature (at a height of 1.1 m) were used for the comparison of the measurements with the simulation results.

Figure 20 shows the operative temperature from the measurements and from the simulation results:
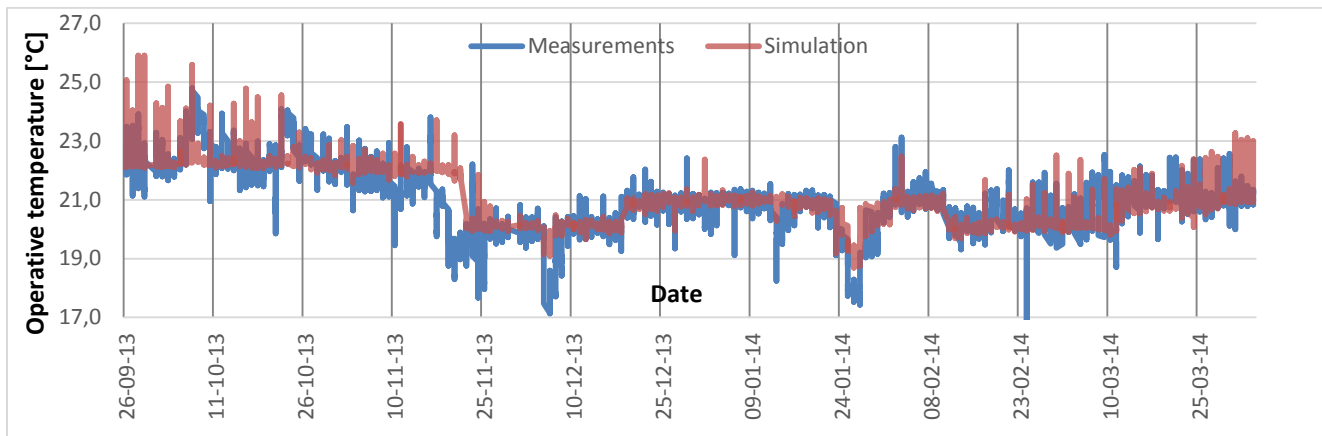
Figure 20. *Comparison of operative temperature at 1.1 m*

It may be seen in Figure 20 that the operative temperature predicted by the simulations has a tendency to be higher than the measurements. The relative difference between measurements and simulation results was 2.7% during the measurement period. The difference was higher when there was direct solar radiation. When this contribution was higher than 100 W/m^2, the relative difference between the two temperatures increased to 4.6%.

4.4.3 The results of energy consumption comparison

A comparison of energy consumption for the heat pump and the ventilation system was made for the simulations and measurements. The simulation results showed lower energy consumption than the measurements. The relative difference in energy consumption for the heat pump was 14% and for the ventilation system was 23%.

4.4.4 Improvements

In order to compare the different improvement options, the thermal indoor environment was evaluated according to EN 15251 (2007), based on the operative temperature. The energy consumption was also considered when comparing the different improvements.

The improvements with the highest impact regarding both thermal indoor environment and energy consumption were reducing the window area, reducing the infiltration and minimizing the thermal bridges. The results of the investigations on these three improvements are presented in Table 14, Table 15, and Table 16. In these tables, the reference case refers to the current state of the house, and the values were obtained from the IDA ICE model.

Table 14. *Results of reduced window area*

Window area reduction		Reference	5%	10%	15%	20%	25%	38%	58%
Indoor environment category	I	71%	74%	76%	79%	81%	84%	89%	94%
	II	27%	24%	22%	20%	17%	16%	11%	5%
	III	2%	2%	2%	1%	1%	1%	1%	0%
	IV	0%	0%	0%	0%	0%	0%	0%	0%
Energy consumption	kWh/ year	6371	6151	5943	5729	5519	5311	4742	4125

When the window areas were reduced, the daylight in the house was also considered in order to assure that the daylight levels abided the regulation of 200 lux, based on the Danish Building Regulations, Energistyrelsen (2014). The investigations showed that the reference case abided the regulations 93% of the time. The case with the smallest window area abided the regulations 82% of the time.

In Table 15 the values for the infiltration are given at an induced pressure of 50 Pa:

Table 15. Results of reduced infiltration

Infiltration (L/s/m²)		Reference (5.3)	1.5	1.0	0.5
Indoor environment category	I	71%	80%	81%	81%
	II	27%	19%	18%	18%
	III	2%	1%	1%	1%
	IV	0%	0%	0%	1%
Energy consumption	kWh/ year	6371	5552	5438	5323

In IDA ICE, it is possible to quantify the thermal bridges (e.g. for the connection between a window and a wall: very poor-0.40 W/mK, poor-0.06 W/mK, typical-0.03 W/mK, good-0.02 W/mK, and none-0.00 W/mK). For the simulation of the effects, every building part was varied corresponding to different thermal bridges. The results of the varying thermal bridges are presented in Table 16:

Table 16. Results of thermal bridges

Thermal bridges		Very Poor	Poor	Typical	Good	None
Indoor environment category	I	42%	68%	79%	80%	83%
	II	29%	29%	19%	18%	16%
	III	21%	3%	1%	1%	0%
	IV	8%	1%	0%	0%	1%
Energy consumption	kWh/ year	9993	6626	5520	5359	4982

In Table 17 the results for different orientations of the house are presented:

Table 17. Results of different orientations

Orientation		Reference	North West	West	South West	South	South East	East	North East
Indoor environment category	I	71%	69%	64%	66%	69%	69%	67%	69%
	II	27%	25%	26%	23%	22%	21%	24%	28%
	III	2%	5%	6%	6%	5%	5%	7%	3%
	IV	0%	2%	4%	4%	5%	5%	1%	0%
Energy consumption	kWh/ year	6371	7184	7870	7579	7123	7290	7203	6626

Regarding the orientation, the current orientation is the best solution both regarding thermal indoor environment and overall energy consumption.

Different improvement alternatives have been investigated as an addition to the previously mentioned parameters:

- Automatically controlled exterior solar shading;
- Natural ventilation. Natural ventilation was provided from 10% of the window area in the glazing façades that could open and it was controlled based on the temperature set-points in the house;
- Thermal mass was simulated by adding 0.1 m concrete in the walls;
- An increased embedded pipe system (EPS) area was simulated with EPS installed in the walls.

The respective results of these variations are presented in Table 18:

Table 18. Results of other improvements

Other parameters		*Reference*	*Exterior solar shading*	*Natural ventilation*	*Thermal mass*	*Increased EPS area*
Indoor environment category	I	71%	74%	74%	72%	88%
	II	27%	23%	23%	26%	11%
	III	2%	3%	3%	3%	1%
	IV	0%	0%	0%	0%	0%
Energy consumption	kWh/ year	6371	6104	6053	6192	6467

Regarding the thermal indoor environment, the increased EPS area, the exterior solar shading, and the natural ventilation had the biggest impact. The last two primarily made an impact in the cooling season by counteracting the cooling loads due to solar radiation.

4.4.5 Optimized Fold

An optimized version of the house was proposed based on the simulations. In the optimized house, the area of the glazing façades were reduced by 25% and the U-value for the glass was lowered to 0.5 W/m²K. The infiltration was set according to the requirements for Danish houses in 2020, Energistyrelsen (2014), and the thermal bridges were reduced to make it more appropriate for a modern house. In the optimized house, there was also natural ventilation. The results of the thermal indoor environment and total energy consumption for the reference case and the optimized cases are presented in Table 19:

Table 19. Results of the optimized house

		Reference	*Optimized*
Indoor environment category	I	71%	97%
	II	27%	3%
	III	2%	0%
	IV	0%	0%
Energy consumption	kWh/ year	6371	2023

The optimized model significantly improved the thermal indoor environment and there was no duration when the operative temperatures were outside the range of category 2 according to EN 15251 (2007). Furthermore, the temperature never exceeded 26°C, indicating that there was no overheating. The energy consumption was reduced by 68% when the proposed improvements were implemented.

The simulations showed that the most important improvement was to reduce the heating demand of the building by reduction of the window area, infiltration and thermal bridges. The improved house design performed better in both thermal indoor environment and energy consumption than the reference case. The duration in thermal indoor environment category 1, according to EN 15251 (2007), was increased from 71% to 97% and the annual energy consumption was reduced by 68% compared to the reference building (both results are based on IDA ICE simulations).

5. Conclusion

During the entire course of the project, various calculations, simulations and experiments were carried out. The conclusions and experiences obtained from the entire course of the project are listed below:

- In order to achieve energy efficiency, it is crucial to minimize the heating and cooling demand of the building and to address the demand with the most energy efficient and environmentally friendly technologies and system;

- The house envelope is not efficient due to the glass façades (high heating and cooling demand). This drastically decreases the energy performance of the house, therefore active elements (PV/T panels) are needed for the house to be a plus-energy house;

- During the competition, indoor climate conditions fulfilled the requirements most of the time and the house performed as a plus-energy house;

- With the variation and optimization of different building and HVAC system parameters it was possible to increase the performance of the house regarding thermal indoor environment and energy consumption: the duration in thermal indoor environment category 1, according to EN 15251 (2007), was increased from 71% to 97% and the annual energy consumption was reduced by 68% compared to the reference building;

- It was shown that the control system's energy consumption can correspond to up to 39% of the total energy consumption. Control system should be kept simple, in order to avoid the backfiring effect: the increased energy consumption while trying to decrease the energy consumption with advanced control strategies;

- The ground was initially intended to be the heat source and sink of the house for space heating and cooling, but it was never implemented. Simulations showed that, free cooling concept with the GHEX enables 92% energy saving compared to an air-to-water heat pump. GCHP operates with a high COP. It is possible to cool the PV/T panels with the GHEX and balance the heat absorbed from the ground;

- The simulations showed that the PV/T panels produced more electricity than the house consumed, on a yearly basis, and this enabled the house to be a plus-energy house. The thermal part of the PV/T panels yielded a solar fraction of 63% and 31% in Madrid and Copenhagen, respectively;

- The year-round measurements showed that the thermal part of the PV/T panels contributed significantly to the DHW needs of the house during the summer period but it was not so beneficial outside the summer months (mid-October to mid-March). The measurements also revealed a potential for night radiative cooling with the PV/T panels but this application would require thermal storage (either in form of thermal mass in the building or in form of a storage tank);

- The PV/T panels proved to be an efficient combination, compared to having the electrical part (PV cells) and the thermal part (solar thermal collectors) separately. The thermal part of the PV/T panels helped to keep the electrical efficiency of the PV cells close to the maximum; the electrical efficiency was 15.5% when the cells were cooled actively and it dropped to 13.5% when there was no cooling;

- The annual electricity production from the PV/T panels (4043.9 kWh) was lower compared to the simulation results from TRNSYS (for Copenhagen), 7434.3 kWh. Several factors caused this difference, lower peak power values obtained compared to the simulations, different climatic conditions, damaged PV/T panels, shadows on the PV/T panels;

- It is possible to increase the energy performance of the house with simple modifications in the operation strategies of the components and by passive means (e.g. natural ventilation);

- Different heating strategies were tested. The overall performance regarding the indoor environment was satisfactory, i.e. 80% of the time in category 2 according to EN 15251 (2007). Among the investigated cases, floor heating with heat recovery on the ventilation was the optimal heating strategy concerning occupant thermal comfort, and thermal stratification (heat loss, hence energy efficiency);

- The house performed worse in the cooling season than the heating season; 57% of the time in category 2 according to EN 15251 (2007). Overheating was a significant problem and the total hours above 26°C and 27°C exceeded the values recommended in DS 469 (2013). The most significant problems of the house were the large glazing façades (including the lack of solar shading) and the lack of thermal mass in order to buffer the sudden thermal loads;

- Even though the relative humidity was not regulated, it was within the range of 20-70%, indicating that there was no significant problem related to humidity indoors;

- The transition periods (i.e. September and May) require careful consideration regarding the operation of the heating and cooling system;

- Innovation and university-industry partnership resulted in custom-made PV/T panels and a prototype of a new mixing station.

Based on the above points, it could be concluded that it is possible to build plus-energy houses that are aesthetically appealing, energy efficient, environmentally friendly and have a healthy and comfortable indoor environment. Though, this requires careful and detailed design, operation, and good execution of the ideas (air-tightness, building envelope, lowered thermal bridges, etc.). Even though it might be possible to improve the energy performance of the house with some changes after the construction, this is not the optimal situation. The current house diverged from the above-described ideal situation, due to the high heating and cooling demand. It should be noted that with less heating and cooling demand, it will be possible to achieve plus-energy targets with less area of active systems (i.e. PV/Ts).

6. Further investigations

The experience from the house yielded to further ideas and possibilities to be investigated. These investigations are as follows:

- Space heating and night radiative cooling possibilities with the PV/T panels;
- Experimental validation of the performance of the ground heat exchanger coupled to a heat pump with the by-pass possibility for free cooling;
- Consideration of the house's (or several plus-energy houses') role in the energy system;
- Energy saving potential of natural ventilation;
- Operation of the 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?
- Effects of increased building thermal mass on the thermal indoor environment and energy consumption;
- Simplified but improved control algorithm, that either controls all of the components or assures the optimal inter-play between different components;
- Heating and cooling control based on a predictive control algorithm.

7. References

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Kazanci, O. B., & Olesen, B. W. (2015a). Horizontal Temperature Distribution in a Plus-Energy House: Cooling Season Measurements. *2015 ASHRAE Annual Conference.* Atlanta: ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Abstract accepted.*

Kazanci, O. B., & Olesen, B. W. (2015b). Indoor Environment and Energy Consumption Measurements in a Plus-Energy House. *6th International Building Physics Conference, IBPC 2015.* Torino. *Abstract accepted.*

Kazanci, O. B., & Olesen, B. W. (2015c). Year-round measurements of thermal indoor environment and energy consumption in a plus-energy house. *In preparation to be submitted to Energy and Buildings*.

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Appendix A – List of publications, presentations and other activities related to Fold

In addition to the theses and deliverables mentioned in the main report, there have been other publications and dissemination activities based on the work regarding Fold.

The list of scientific publications and publications in professional journals are given below (this list consists of the publications that the authors of this report were a part of):

Publications in refereed international journals

2. Kazanci, O. B., & Olesen, B. W. (2015). Year-round measurements of thermal indoor environment and energy consumption in a plus-energy house. *In preparation to be submitted to Energy and Buildings.*

1. Kazanci, O. B., Skrupskelis, M., Sevela, P., Pavlov, G. K., & Olesen, B. W. (2014). Sustainable heating, cooling and ventilation of a plus-energy house via photovoltaic/thermal panels. Energy and Buildings 83, 122-129. doi:http://dx.doi.org/10.1016/j.enbuild.2013.12.064.

Publications in conference proceedings

9. Kazanci, O. B., & Olesen, B. W. (2015). Horizontal Temperature Distribution in a Plus-Energy House: Cooling Season Measurements. 2015 ASHRAE Annual Conference. *Abstract accepted.*

8. Kazanci, O. B., & Olesen, B. W. (2015). Indoor Environment and Energy Consumption Measurements in a Plus-Energy House. 6th International Building Physics Conference, IBPC 2015. *Abstract accepted.*

7. Andersen, M. E., Schøtt, J., Kazanci, O. B., & Olesen, B. W. (2014). Analysis of a Plus-Energy House for Improved Building and HVAC System Design. Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms (pp. 377-384). Sao Paulo: Institute for Technology Research - IPT and Jovem Benedicto de Moraes.

6. Kazanci, O. B., & Olesen, B. W. (2014). Air and Operative Temperature Measurements in a Plus-Energy House under Different Heating Strategies. Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms (pp. 312-319). Sao Paulo: Institute for Technology Research - IPT and Jovem Benedicto de Moraes.

5. Kazanci, O. B., & Olesen, B. W. (2013). The Effects of Set-Points and Dead-Bands of the HVAC System on the Energy Consumption and Occupant Thermal Comfort. In Proceedings of the 7th Mediterranean Congress of Climatization.

4. Sevela, P., & Olesen, B. W., (2013). Development and benefits of using PVT Compared to PV. Paper presented at Clima 2013, Prague, Czech Republic.

3. Kazanci, O. B., Skrupskelis, M., Olesen, B. W., & Pavlov, G. K. (2013). Solar Sustainable Heating, Cooling and Ventilation of a Net Zero Energy House. Paper presented at Clima 2013, Prague, Czech Republic.

2. Olesen, B. W., Skrupskelis, M., Kazanci, O. B., & Sevela, P. (2012). Sustainable Heating, Cooling and Ventilation of an Energyplus House. Paper presented at 43rd International Congress & Exhibition on Heating, Refrigeration and Air Conditioning, Belgrade, Serbia.

1. Pavlov, G. K., Olesen, B. W., Skrupskelis, M., & Kazanci, O. B. (2012). Ground source heat pump combined with thermo-active building system with incorporated PCM for low-energy residential house. In Proceedings of Innostock 2012: The 12th International Conference on Energy Storage.

Publications in professional journals

5. Andersen, M. E., Schøtt, J., Kazanci, O. B., & Olesen, B. W. (2014). Analysis of a plus-energy house. HVAC Magasinet, (12), 28-34.

4. Kazanci, O. B. (2014). Low temperature heating and high temperature cooling in buildings. HVAC Magasinet, (6), 26-32.

3. Sevela, P., & Olesen, B. W., (2013). Development and Benefits of Using PVT Compared to PV. Sustainable Building Technologies, e-magazine, Fall, 90-97, (in Russian).

2. Kazanci, O. B., Skrupskelis, M., Olesen, B. W., & Pavlov, G. K. (2013). Net Zero Energy Building. FOLD Project. Sustainable Building Technologies, e-magazine, Summer, 24-34, (in Russian).

1. Olesen, B. W., & Kazanci, O. B. (2013). Bæredygtig opvarmning, køling og ventilation af et plusenergihus. HVAC Magasinet, (7), 20-26, (in Danish).

The list below consists of various presentations and dissemination activities carried out by the authors of this report (this list consists of the activities that the authors of this report were a part of and there have been other presentations by other people involved in the project):

2011

- The project was featured on TV2 Lounge, 15th of June 2011.

2012

- A movie (which followed the different phases of the project from different team members' points of view) was shot. It was shown to different audiences in different occasions, including a two episode view under the name, FOLD – Fremtidens bolig and FOLD – Plusenergihuset, on Danskernes Akademi on DR K (in 2013);
- Fold was featured in one of the Post Danmark flyers in the summer of 2012;
- The minister of climate, energy and building of Denmark opened Fold, among many industry partners and sponsors of the project;
- A presentation was given at Energy Mondays organized by Energy Crossroads Denmark, 12th of November 2012, Copenhagen, Denmark;
- A presentation was given at 43rd International Congress & Exhibition on Heating, Refrigeration and Air Conditioning, 5th – 7th of December 2012, Belgrade, Serbia, based on the paper:

  Olesen, B. W., Skrupskelis, M., Kazanci, O. B., & Sevela, P. (2012). Sustainable Heating, Cooling and Ventilation of an Energyplus House. 43rd International Congress & Exhibition on Heating, Refrigeration and Air Conditioning, Belgrade, Serbia.
- Many presentations were given to different sponsors in different events, including a presentation at Rockwool on 14th of December 2012, a presentation for Grundfos and representatives from Samsung C&T on 27th of April 2012, a presentation for Grundfos on 26th of June 2012, and many more.

2013

- A presentation was given in DTU course, 11982 Integrated Functional Project, 25th of February 2013, Kgs. Lyngby, Denmark;
- A presentation was given at DANVAK Dagen 2013, 10th of April 2013, Copenhagen, Denmark;
- A presentation was given at the 6th Sino-Danish Workshop, 15th of April 2013, Kgs. Lyngby, Denmark;
- A presentation was given at ATIC (the Belgian HVAC society) Workshop which was organized under the IEA, EBC Annex 59, 3th Expert meeting, 18th of April 2013, Liege, Belgium;
- A presentation was given at the department breakfast at DTU BYG, 2nd of May 2013, Kgs. Lyngby, Denmark;
- The project was exhibited on Energiens Topmøde 2013, 6th of June 2013, Copenhagen, Denmark;
- A presentation was given at DTU, 40 year's alumni day (DTUs 40 års alumne dag), 6th of June 2013, Kgs. Lyngby, Denmark;
- A presentation was given at the EuroTech meeting, 10th of June 2013, Lausanne, Switzerland;

- A presentation was given at CLIMA 2013,16[th] – 19th of June, Prague, Czech Republic, (11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings), based on the paper:

  Kazanci, O. B., Skrupskelis, M., Olesen, B. W., & Pavlov, G. K. (2013). Solar Sustainable Heating, Cooling and Ventilation of a Net Zero Energy House. Clima 2013, Prague, Czech Republic.

- A poster regarding Solar Decathlon Europe 2012 was presented at DTU BYG Innovation Day, 12th of September 2013, Kgs. Lyngby, Denmark;

- A presentation was given to the representatives from Uponor (Germany), 16th of September 2013, Kgs. Lyngby, Denmark;

- A presentation was given at Climamed'13, 3rd - 4th of October, Istanbul, Turkey, (The 7th CLIMAMED Mediterranean Congress of Climatization), based on the paper:

  Kazanci, O. B., & Olesen, B. W. (2013). The Effects of Set-Points and Dead-Bands of the HVAC System on the Energy Consumption and Occupant Thermal Comfort. In Proceedings of the 7th Mediterranean Congress of Climatization.

- An exhibition regarding energy (En verden af energi) at Energimuseet in Bjerringbro was attended and Fold was presented within the framework of Dansk Naturvidenskabsfestival (week 39), Bjerringbro, Denmark;

- A presentation was given at IEA, EBC Annex 59, 4th Expert meeting, 16th – 17th of October 2013, Beijing, China;

- A presentation was given regarding Solar Decathlon Europe 2012 and 2014 at Schneider Electric's Rådgiverdag 2013, 29th of October 2013, Copenhagen, Denmark;

- A presentation was given at COWI, 8th of May 2013, Kgs. Lyngby, Denmark.

2014

- Some of the results regarding the ground heat exchanger was included in the course material in DTU course, 11127 Sustainable Heating and Cooling of Buildings;

- A presentation was given at Building Energy Research Center, Tsinghua University, 5th of March 2014, Beijing, China;

- A presentation was given at DANVAK Dagen 2014, 9th of April 2014, Copenhagen, Denmark;

- Fold was visited and its features were presented during Carbon War Room meeting at Grundfos Headquarters, 5th of June 2014, Bjerringbro, Denmark (the authors of this report was not present during this event but prepared the visual material for it);

- Presentations were given at Tokyo University, Tokyo City University and Waseda University, October 2014, Tokyo, Japan;

- Two presentations were given at ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms, 19th – 22nd of October 2014, São Paulo, Brazil, based on the papers:

  Andersen, M. E., Schøtt, J., Kazanci, O. B., & Olesen, B. W. (2014). Analysis of a Plus-Energy House for Improved Building and HVAC System Design. Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms (pp. 377-384). Sao Paulo: Institute for Technology Research - IPT and Jovem Benedicto de Moraes.

  Kazanci, O. B., & Olesen, B. W. (2014). Air and Operative Temperature Measurements in a Plus-Energy House under Different Heating Strategies. Proceedings of ROOMVENT 2014, 13th SCANVAC

International Conference on Air Distribution in Rooms (pp. 312-319). Sao Paulo: Institute for Technology Research - IPT and Jovem Benedicto de Moraes.

2015

- There will be conference presentations in Turin, Italy (June) and in Atlanta, GA, USA (June or July) based on the publications (respectively):

Kazanci, O. B., & Olesen, B. W. (2015). Indoor Environment and Energy Consumption Measurements in a Plus-Energy House. IBPC 2015, 6th International Building Physics Conference. *Abstract accepted.*

Kazanci, O. B., & Olesen, B. W. (2015). Horizontal Temperature Distribution in a Plus-Energy House: Cooling Season Measurements. 2015 ASHRAE Annual Conference. *Abstract accepted.*

Appendix B – Measured parameters and measuring equipment

The measured parameters and the equipment used to measure these parameters are given in this appendix. First, the measured parameter is given and then the measuring equipment is indicated in the parentheses.

The following parameters were measured or logged with HOBO data loggers:

- Air and globe temperatures at 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 heights, at a representative location inside the house (shielded air temperature sensor and gray globe sensor connected to HOBO U12-013);

- Relative humidity inside the house (HOBO U12-013);

- Outside temperature and relative humidity (HOBO U12-013);

- Additional air and globe temperature measurements at 0.1 m, 0.6 m, 1.1 m and 1.7 m heights, in two locations, one close to the North and one close to the South façade (shielded air temperature sensor and gray globe sensor connected to HOBO U12-013);

- Additional air and globe temperature measurements on the East wall, at 1.7 m height (shielded air temperature sensor and gray globe sensor connected to HOBO U12-013);

- Measurements of light intensity in the above locations (in order to determine the direct solar radiation on the sensors) (HOBO U12-012).

Measured or logged via the programmable logic controller (PLC):

- Air temperature, relative humidity and CO_2 concentration, placed on the technical room wall (WindowMaster, WET 112 KNX Room Air Sensor);

- Rain (rain/no rain) and wind speed, outdoor temperature (WindowMaster WLA 340 and WOT100).

From the Nilan Compact P+JVP (based on the information available from the manufacturer):

- Supply and exhaust fan speeds;

- Temperatures in the top and bottom of the DHW tank (CTS600 NTC sensor JM103C1R1);

- Condenser and evaporator temperatures (in the AHU) (CTS600 NTC sensor JM103C1R1);

- Supply, exhaust, fresh and discharge air temperatures (in the AHU) (CTS600 NTC sensor JM103C1R1).

PV/T part:

(VFS: Vortex Flow Sensor)

- Surface temperatures (three in Part A and one in Part B) (PT100 resistance thermometer);

- Flow rates and temperatures, supply to Part A (after the pump of Part A), supply to Part B (after the pump of Part B), before the drain-back tank (after the return flows from Part A and B are merged) and before the DHW tank (after the drain-back tank, before the spiral heat exchanger in the DHW tank) (Grundfos VFS 2-40 QT).

Energy consumption and production:

- Energy consumption of the mixing station and the controller of the radiant system (JO-EL wattmeter);
- Energy consumption of the air-to-water heat pump (Kamstrup wattmeter);
- The rest of the energy consumption, and production were measured by Schneider Electric, Branch Circuit Power Meter (BCPM), power and energy meter.

The following parameters were logged by an Agilent 34972A LXI Data Acquisition/Switch Unit:

Multiplexer #1:

(VFS: Vortex Flow Sensor, RPS: Relative Pressure Sensor)

- Supply to the ceiling loops of the radiant system, flow rate and temperature (Grundfos VFS 1-20);
- Return from the ceiling loops of the radiant system, flow rate and temperature (Grundfos VFS 1-20);
- Supply to the floor loops of the radiant system, flow rate and temperature (Grundfos VFS 1-20);
- Return from the floor loops of the radiant system, flow rate and temperature (Grundfos VFS 1-20);
- Supply to the heat exchanger (from the air-to-water hat pump), flow rate and temperature (Grundfos VFS 5-100 QT);
- Return from the heat exchanger (to the air-to-water hat pump), pressure and temperature (Grundfos RPS 0-2.5).

Multiplexer #3:

- Surface temperatures on the floor at four points corresponding to different loops under the floor (Astra Meditec, Craftemp sensor);
- Surface temperatures on the ceiling at six points corresponding to different loops above the ceiling (Astra Meditec, Craftemp sensor);
- Surface temperatures on the East and West walls, and South and North façades (Astra Meditec, Craftemp sensor);
- An extra surface temperature on the North façade (Astra Meditec, Craftemp sensor);
- Air temperature in one of the supply diffusers (PT1000 resistance thermometer).

Not logged but measured:

- Tap in the kitchen (on the hot water connection), flow rate and temperature (Grundfos VFS 2-40 QT).

Other measurements:

- To determine the air-tightness of the building, the blower door test (Retrotec Model Q46: aluminum frame, automated fan, 2000 series door fan, and digital gauge, DM-2, with automatic fan control);
- To determine the thermal bridges (FLUKE Ti20 Thermal Imager);
- To measure flow rates in the ventilation system (Alnor CompuFlow CF8571M thermo-anemometer);
- To measure noise (sound pressure level) (Extech Instruments, 407735 dual range sound level meter);
- Rest of the weather parameters were obtained from a weather station, Davis Vantage Pro2 Plus, located in another location in Bjerringbro (used by Grundfos).