Project acronym: GEOTABS

Project title: Towards optimal design and control of geothermal heat pumps combined with thermally activated building systems in offices

Deliverable 4.1: Report of energy performance and control strategy evaluation for each detailed case

Due date of deliverable: 30-April 2012

Actual submission date: 30-Januari 2013

Start date of project: 01-February 2011

Duration: 48 months

Organization name of lead contractor for this deliverable: University of Liège, Belgium

Dissemination Level		
PU	Public	v
CO	Confidential, only for the members of the consortium	

GEOTABS

WP 4: Monitoring of real GEO-HP-TABS

Energy performance and control evaluation

Author: Vincent Lemort

Contributors: Clément Gantiez, François Randaxhe, Jan Hoogmartens, Franziska Bockelmann, Geeraart Franck

1 Introduction

This report presents the analysis of measurement data collected on five different buildings in the frame of WP4 (“Monitoring of real GEO-HP-TABS”) of GEOTABS project. These office buildings are located in Germany (buildings A and B) and in Belgium (buildings C, D and E). First of all, the buildings architecture will be presented. The control strategies of the HVAC systems used in these buildings will also be described. Then the energy performance of each building system will be assessed and discussed (on seasonal, daily and monthly bases). The evaluation of the energy performance will be based on monitoring data collected on the geothermal heat pump – TABS systems and other HVAC components. An analysis of the long-term thermal comfort will be presented. Finally, an economic and environmental analysis will be performed for two of the buildings. The analysis of the energy and thermal comfort performance of buildings A and B, presented in this report, has been largely conducted by Bockelmann et al. (2010 and 2011).

2 Architecture of each building system

2.1 Building A

The energy concept of building A is presented in Figure 2-1. The net floor area of this building is 20,693 m² and the geothermal system is composed of 196 energy piles of 9 m length.

In winter, the geothermal brine-to-water heat pump (106 kW) extracts heat from the ground in order to supply the TABS. As shown in Figure 2-1, the rest of the heat consumption is provided by district heating through radiators, floor heating and ventilation devices (terminal units).

In summer, the entire cooling load is provided by geothermal energy through the TABS (free chilling mode (150kW)). Operation in free chilling mode (or “geocooling”) is made possible by integrating a heat exchanger between the geothermal loop and the TABS (Figure 2-2). There is no active cooling system.

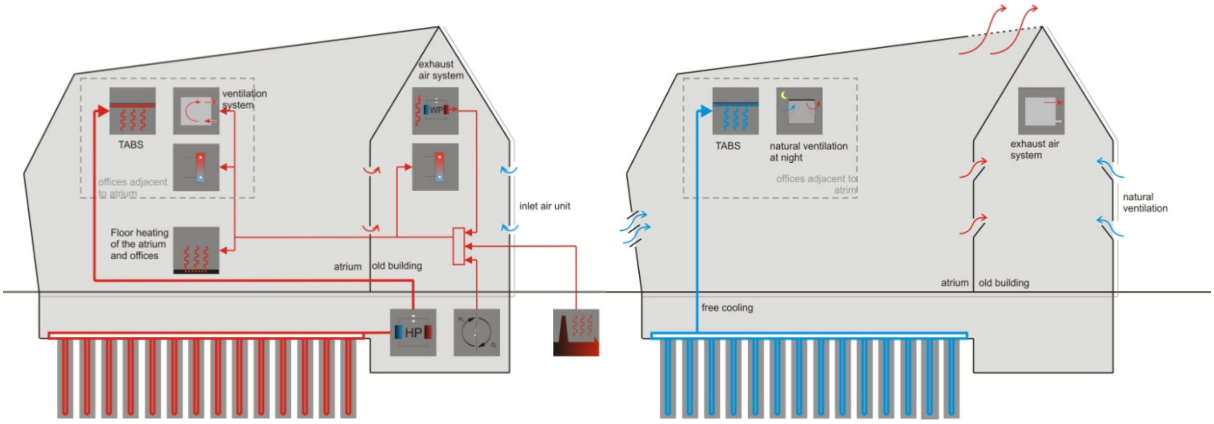


Figure 2-1: Energy concept of building A for heating (right) and cooling (left)

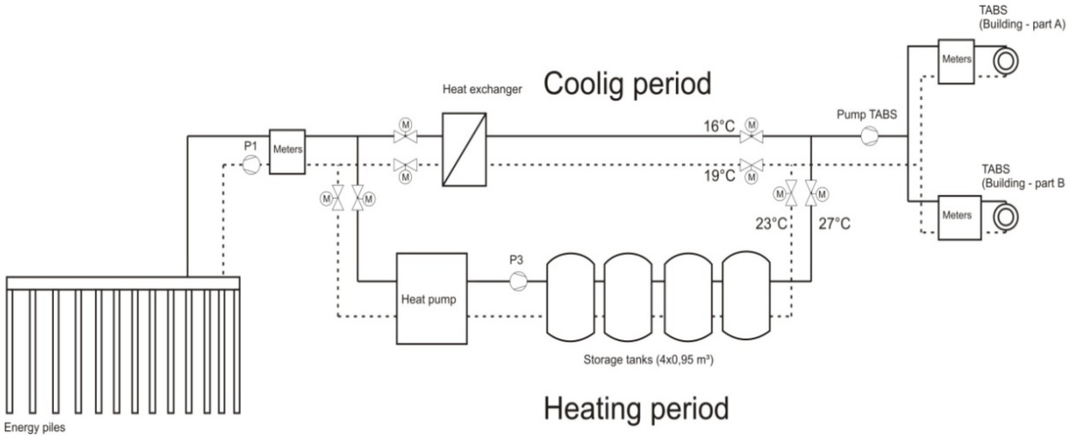


Figure 2-2: Hydraulic scheme of the geothermal heat pump system of building A

2.2 Building B

Building B (Figure 2-3) has a net floor area of round 4,000 m². There are 100 energy piles, with length from 17 to 22 meters. In winter, a ground-coupled brine to water heat pump (82 kW) extracts heat from the ground and supplies it into the building. During the day it is used to preheat the incoming air to the entrance hall (through “HVAC” components as shown in Figure 2.5) and the training rooms; whereas at nighttime it supplies heat to the TABS (approximately 1,500 m²) in the offices and training rooms. The geothermal energy covers the base load of the building. In case of an increased heat demand during the day, the additional heat from district heating is supplied to conventional radiators in the offices and floor heating in the entrance hall. Moreover, the district heating can be used for preheating the air supplied to the ventilation systems.

In summer, two cooling modes are used. As long as the conditions in the ground are cold enough, the free chilling mode (80 kW) is used. When the ground temperature rises notably, the reversible heat pump is used as a chiller (89 kW). As in winter, the ground is used to pre-cool the air supplied to the ventilation system during the day and to cool down the TABS in the office and training rooms at night.

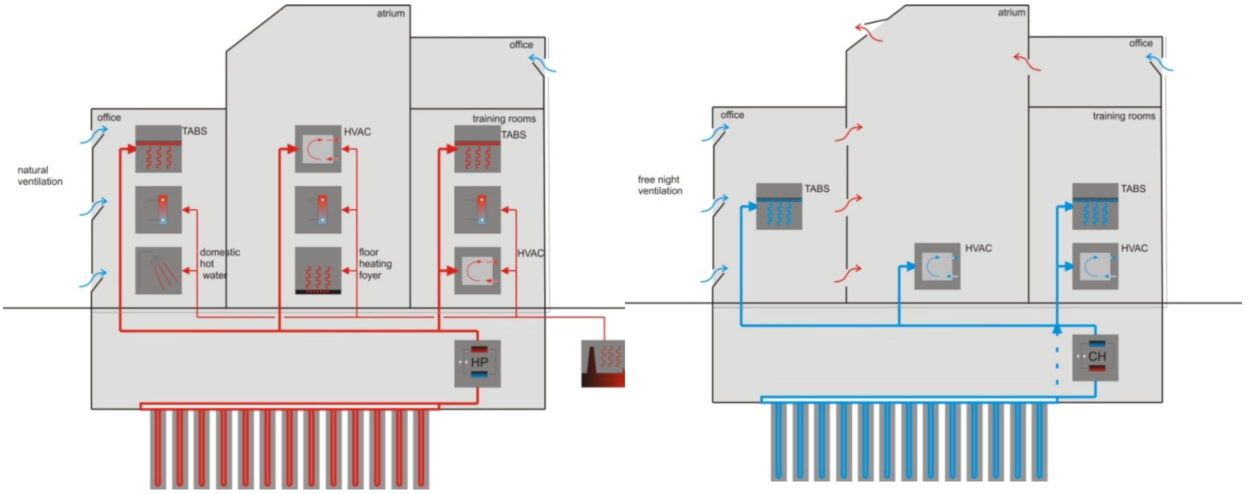


Figure 2-3: Energy concept of building B for heating (right) and cooling (left)

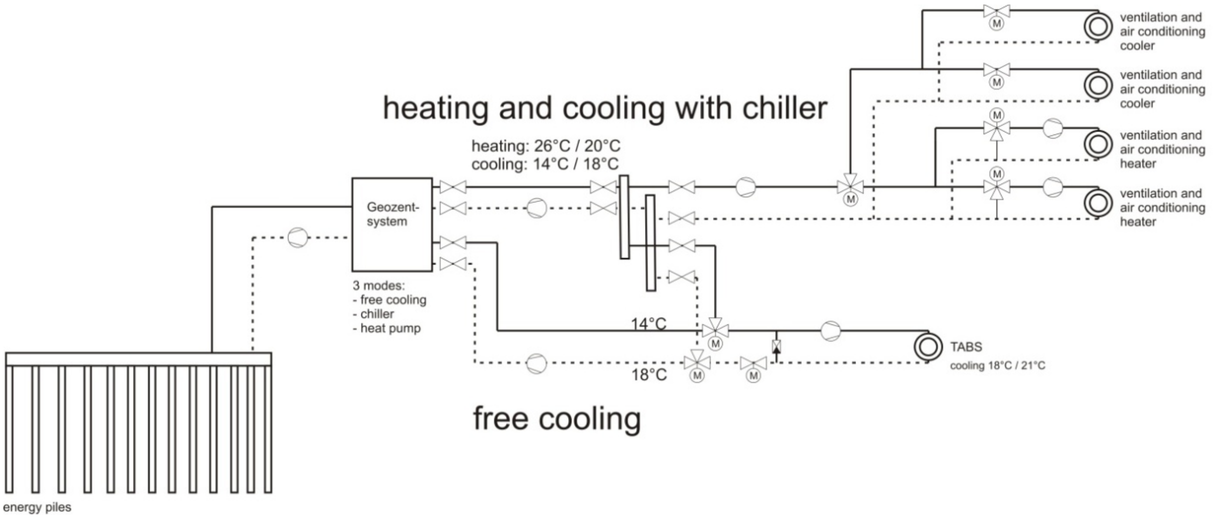


Figure 2-4: Hydraulic scheme of the geothermal heat pump system of building B

2.3 Building C

Building C is located close to Hasselt (Flemish Region of Belgium). This building has a net floor area of round 4,600 m². Its geothermal system comprises 22 borehole heat exchangers of 75 m depth.

The heating and cooling energies for the TABS, the main AHU (for the offices) and the floor heating on the ground floor is generated in the main production unit (Figure 2-8). It consists of a heat pump (156 kW in nominal conditions), cold and hot storage tanks and three heat exchangers. It can operate in heating (156 kW in nominal conditions) and active cooling mode (142 kW in nominal conditions), in which cases the ground-coupled heat pump is active. So-called ‘free cooling’ or (also called geocooling or passive cooling) is a third possible mode of operation (72 kW in nominal conditions), in which cooling energy is extracted from the ground through a direct heat exchanger between the brine and the cold storage tank.

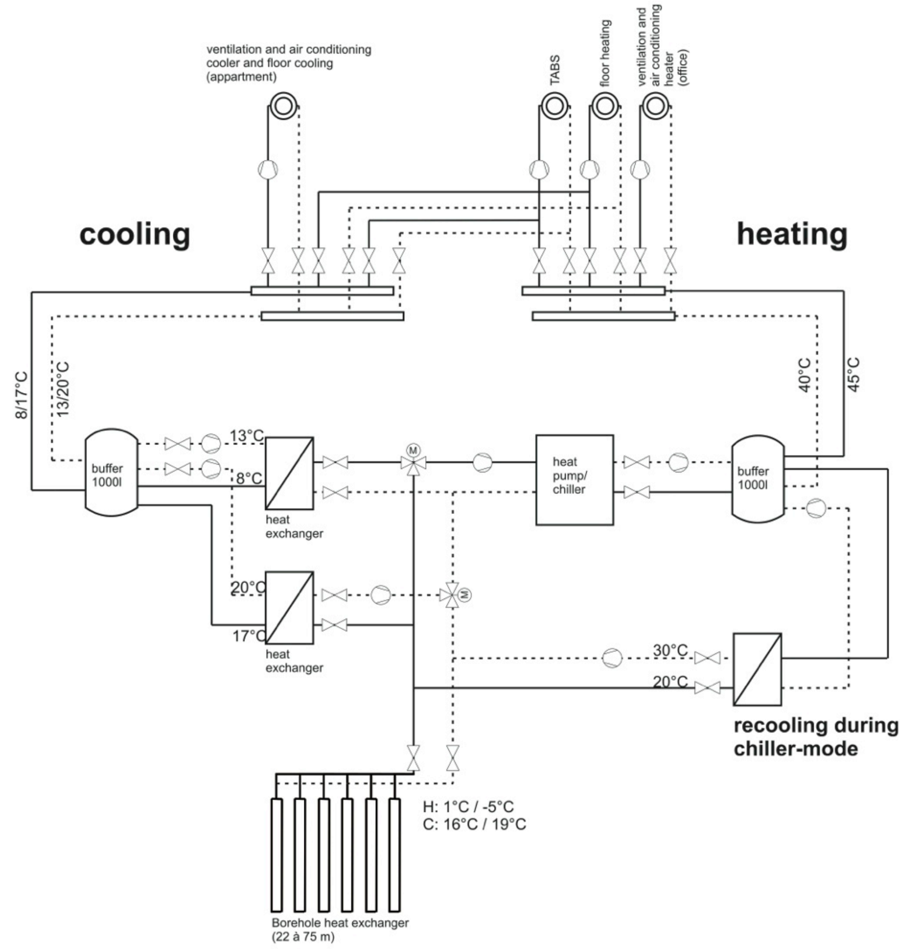


Figure 2-5: Hydraulic scheme of the geothermal heat pump system of building C

In addition to this, two modulating gas-fired boilers are present in the building. One boiler with a rated thermal output of 35 kW provides heat to a second and smaller AHU used for the apartment and also to the apartment floor heating. The other boiler, with a rated thermal output of 60 kW, is the back-up heat production for the main AHU.

The TABS system is represented in Figure 2-6. The apartment and the ground floor are equipped with heating floor. The heating floor of the apartment is connected to a separate boiler and not to the geothermal heat pump system. In a TABS element, the upper and lower water piping circuits can be separately controlled.

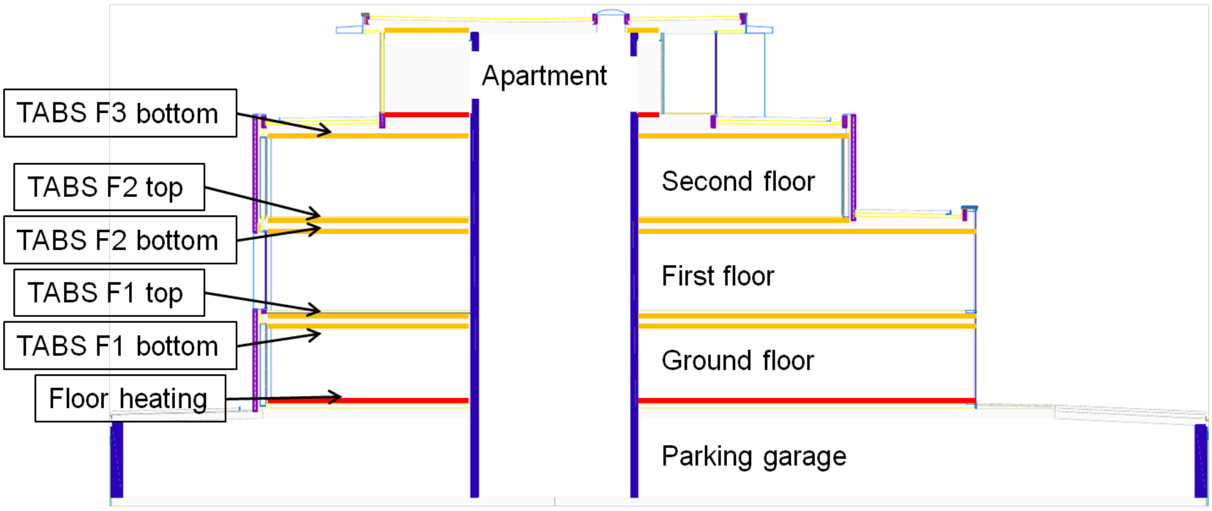


Figure 2-6: Scheme of thermally activated building components (floor heating: red, TABS: orange)

2.4 Building D

Building D is located close to Brussels, in the Flemish Region of Belgium. Construction of the building was achieved in 2009 and the gross floor surface is around 10,000 m².

The basis of the heating and cooling loads is theoretically provided by a TABS. This TABS is fed, in winter, by 2 ground-coupled heat pumps (70 kWth each). The geothermal system consists of 60 boreholes of around 100 m deep. In summer, the geothermal loop (coupled with TABS) allows cooling the building without additional energy consumption (free chilling), provided that indoor thermal comfort in summer is maintained.

The rest of the heating and cooling load is satisfied by 2 condensing boilers (383 kW each) and a chiller (430 kW). The condensing boilers seem to have been sized in the eventuality that the TABS does not work.

The production of domestic hot water is provided by a third ground coupled heat pump (51 kW) and a back-up boiler (60 kW). Also radiators are used in archives rooms.

The ventilation system is connected to a ground-air heat exchanger that allows pre-heating the air in winter or pre-cooling in summer. There is also a heat recovery system (regenerative wheel) between fresh air and exhaust air of the building.

Moreover, individual needs for heating and cooling are provided by fan-coil units on the floor, controlled room per room.

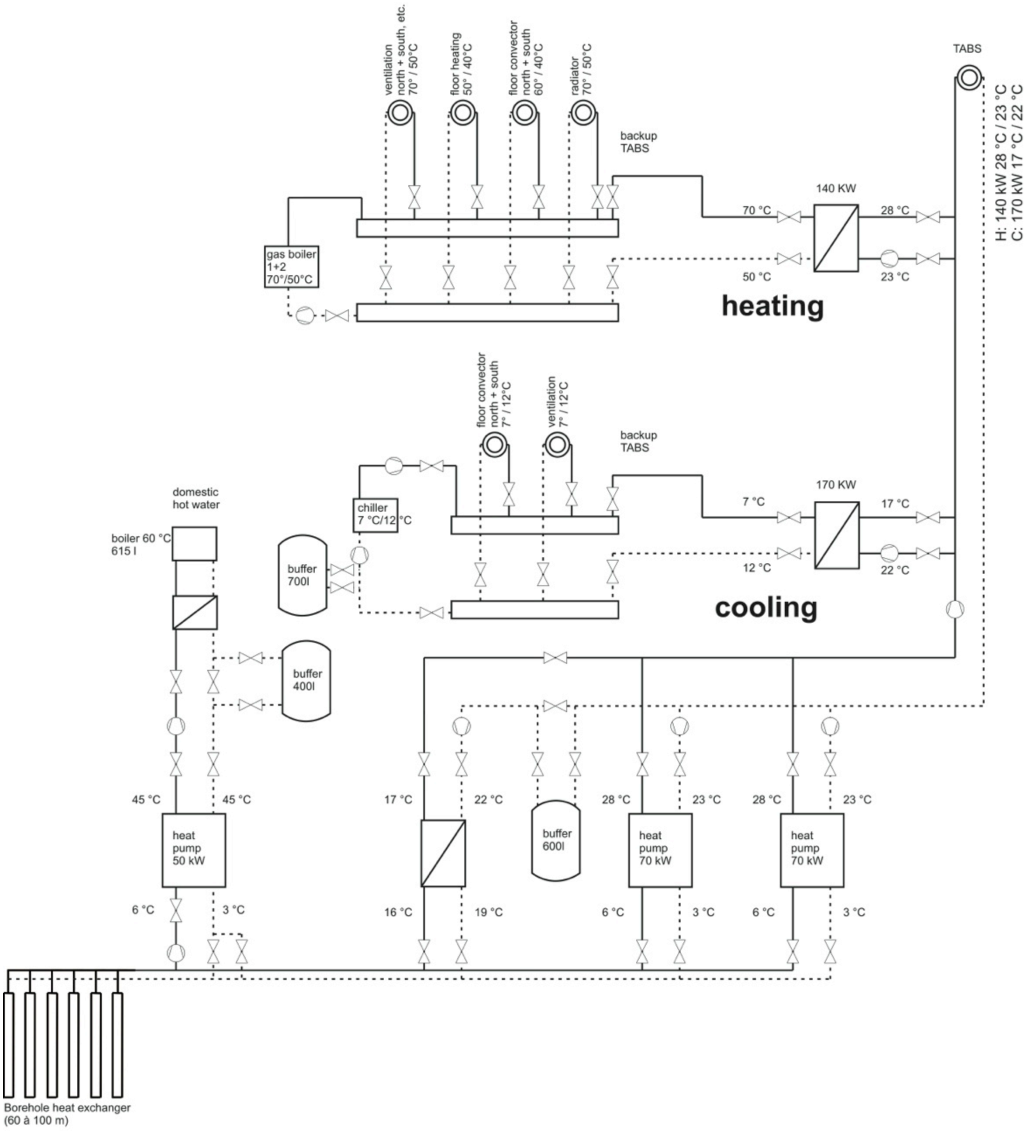


Figure 2-7: Hydraulic scheme of the HVAC plant of the building D

2.5 Building E

Building E is located at Torhout, in Belgium. The building was finished in 2009 and the net floor area is round 4,000 m².

The installation of building E (Figure 2-8) consists, for the heating part, of 2 ground coupled reversible heat pumps (130 kW each) combined to a TABS (1^{st} and 2^{nd} floor) and floor heating (ground level). There is also a gas boiler (391 kW) that provides heat to floor convectors (at each floor level). Finally the AHU is pre-and reheated by both the heat pumps and the boiler. For cooling there are 3 possible ways to get sufficient cooling capacity. The first method is the free chilling mode through the TABS and floor cooling. The second method is to use the heat pumps in reverse (through TABS and floor cooling). The last method is to use a chiller (221 kW) in combination with the AHU.

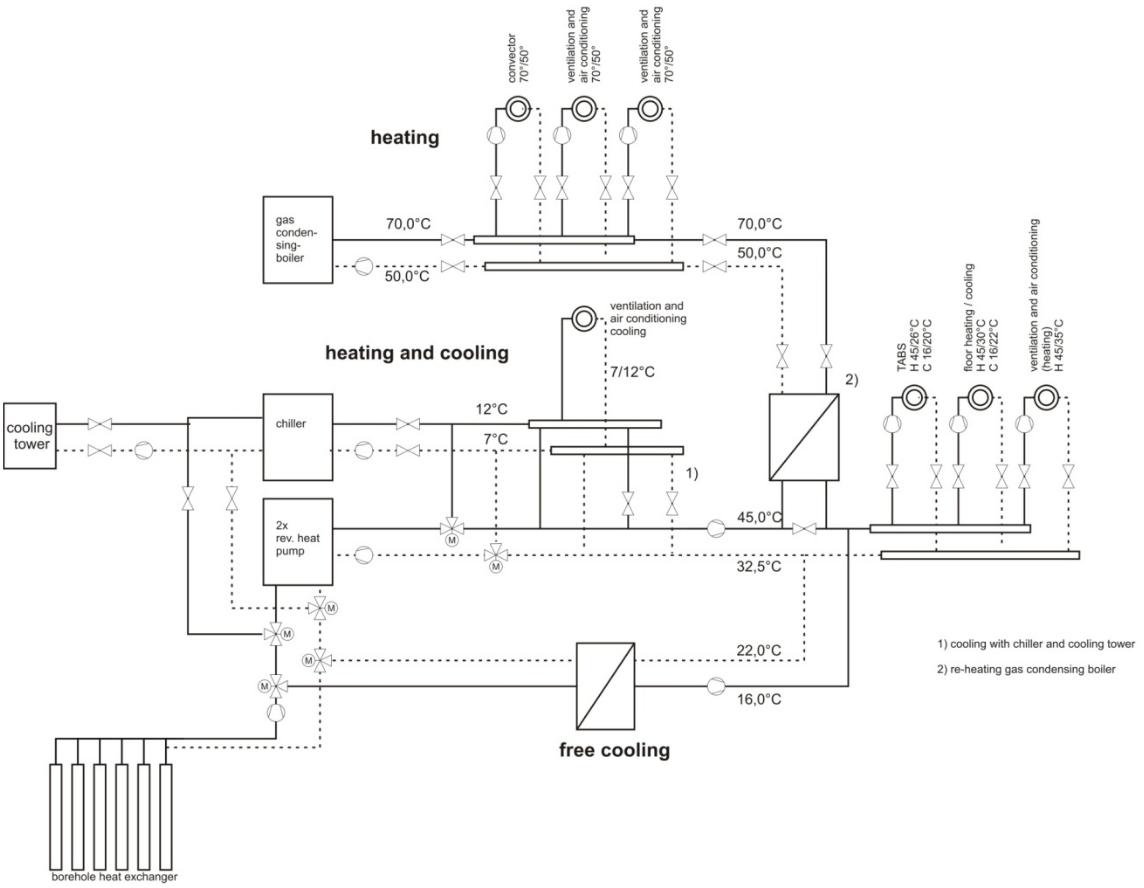


Figure 2-8: Hydraulic scheme of the HVAC plant of building E

2.6 Summary

Table 2-1 summarizes the different building characteristics. The heating and cooling loads will be computed latter in this report.

Table 2-1: Summary of the different buildings characteristics

			A	B	C	D	E
	Country		De	De	Be	Be	Be
	Net floor area	[m^2]	20693	3957	4600	10000	4000
Energy consumption	Year		2010	2009	2011	2011	2011
	Total heating consumption	[kWh/m^2/y]	57,99	88,75	18,33	46,12	125,57
	Total cooling consumption	[kWh/m^2/y]	2,25	4,92	13,14	9,27	17,07
HVAC plant	Primary systems	Geothermal heat pump	✔	✔ (rev)	✔ (rev)	✔	✔ (rev)
		Boiler			✔	✔	✔
		District heating	✔	✔			
		Chiller				✔	✔

		Geocooling	✔	✔	✔	✔	✔
	Secondary systems	TABS	✔	✔	✔	✔	✔
		Radiant floor	✔	✔	✔	✔	✔
		Fancoils units				✔	✔
		Radiator	✔	✔		✔	
		Ventilation	✔	✔	✔	✔	✔

3 Control strategies

3.1 Building A

In this building, there was only information concerning the applied control strategies of the TABS. TABS (geothermal source) operates in heating mode, when continuous average outdoor temperature measured over the last 24h is lower than 14°C. The cooling mode is turned on, if continuous average outdoor temperature measured over the last 24h is higher than 20°C. Figure 4-1 shows quarter-hourly values of the supply TABS temperature in function of the average outdoor temperature measured over the last 24h for 2010. It can be seen that the supply water temperature of the TABS is close to the theoretical curve in heating and cooling mode with a difference of 2 K, in average. Furthermore when the average outdoor temperature is between 14°C and 20°C there should be a dead band, where the geothermal system does not operate. It can be seen that, in this time, the circulating pump of the TABS is running. It is inefficient because of no heating or cooling supply for the TABS, it is only recirculation. In summer time, the ground is too hot for cooling mode so that the cooling curve is exceeded by 3K. Moreover, it can be deduced from the measurement that the TABS operate 24h/24h.

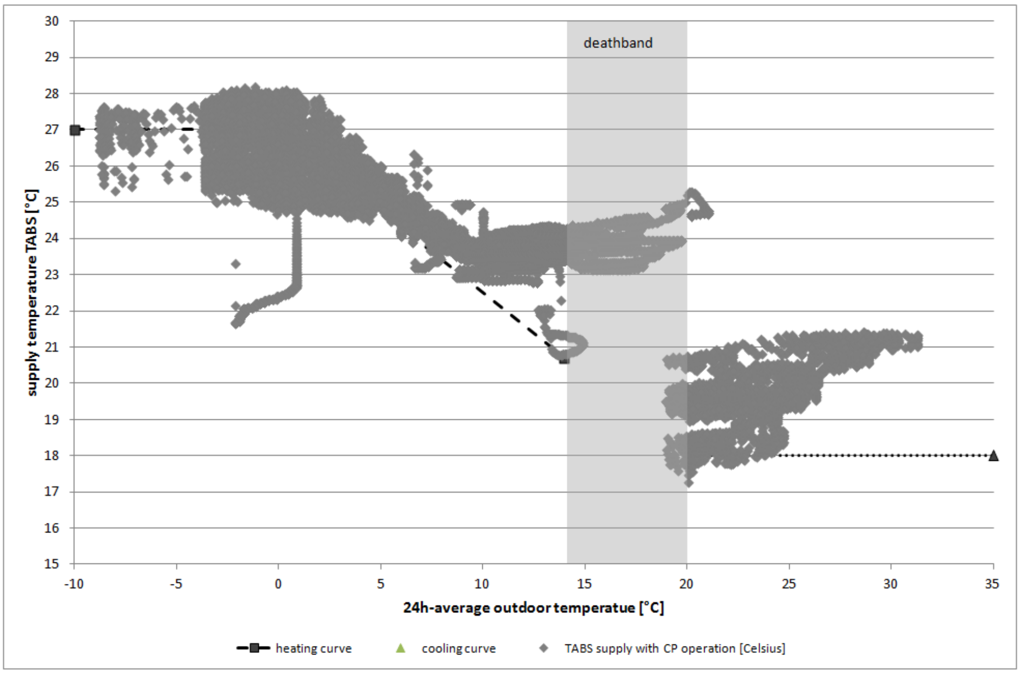


Figure 4-1: Heating/cooling curves of the TABS (building A)

3.2 Building B

The control strategies of the different subsystems of this building are:

- Radiators (district heating source) operate at daytime if the present outdoor temperature is lower than 18°C while they operate at night time if the present outdoor temperature is lower than 5°C.
- TABS (geothermal source) operate only at night time, between 10:00 PM and 6:00 AM. The heating mode is switched on if the average outdoor temperature measured between 6:00 AM and 6:00 PM of the previous day was lower than 17.5 °C. The cooling mode is turned on if the average outdoor temperature measured between 6:00 AM and 6:00 PM of the previous day was higher than 22°C and if the present room temperature is higher than 20°C. If the average outdoor temperature is between 17.5°C and 22°C, the TABS is neither heated, nor cooled.
- Ventilation (geothermal source and district heating) operates only at day time, between 6:00 AM and 10:00 PM. It runs in heating mode if the actual outdoor temperature is lower than 18°C while the cooling mode is turned on if the actual outdoor temperature is higher than 22°C. If the outdoor temperature is comprised between 18°C and 22°C, the ventilation is neither heated, nor cooled, there is only natural ventilation.

In addition to this, the heating and cooling curves of the TABS (only geothermal source) and the ventilation (with geothermal and district heating) are compared to the measurement data of 2009 in Figure 4-2 and Figure 4-3 respectively. Regarding the TABS, the strategy is quite simple: water is injected in the TABS at 26°C in heating mode (average outdoor temperature lower than 18°C) and at 18°C in cooling mode (average outdoor temperature higher than 22°C). It can also be seen that the measurements are close to the theoretical curve in heating mode while it diverges more in cooling mode. Concerning the ventilation, the heating and cooling curves are function of the present outdoor temperature. It is shown in Figure 4-3 that the measurements are close to the theoretical heating curve, but totally different to the cooling curve. These differences can be explained by the fact that first scheduled cooling mode started in spring/summer 2009. Finally, as mentioned previously, if the outdoor temperature is comprised between 18°C and 22°C the building will be, theoretically, neither heated nor cooled. However, Figure 4-2 and Figure 4-3 show that both systems are still running between 18°C and 22°C.

Regarding the control strategy of the TABS, the fact that the supply temperature is constant in heating mode could also explain the lower SCOP of building B compared to building A (what will be shown latter in this report), for which, the supply temperature of TABS decreases with the outdoor temperature (see Figure 4-1).

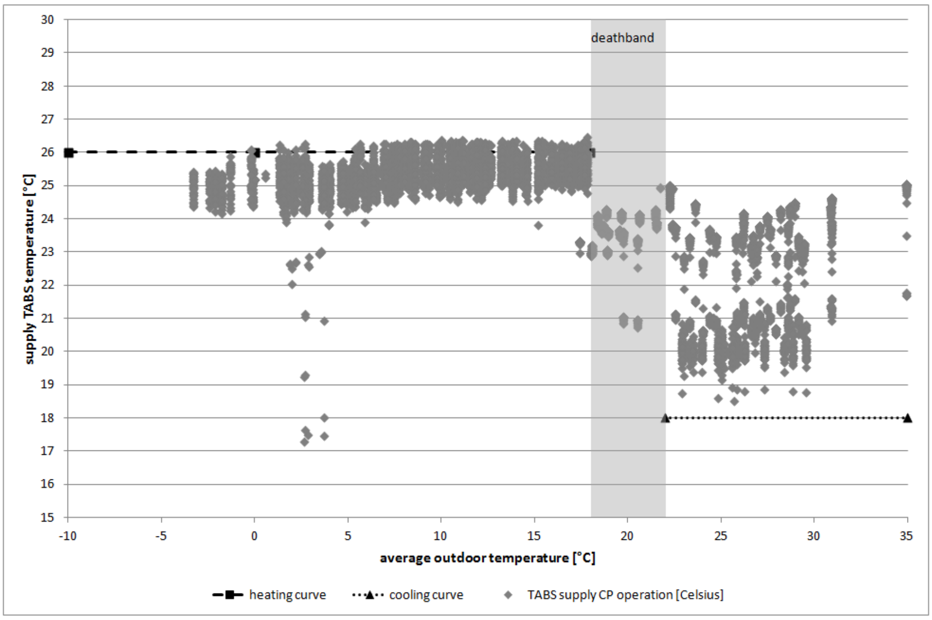


Figure 4-2: Heating/cooling curves of the TABS (building B)

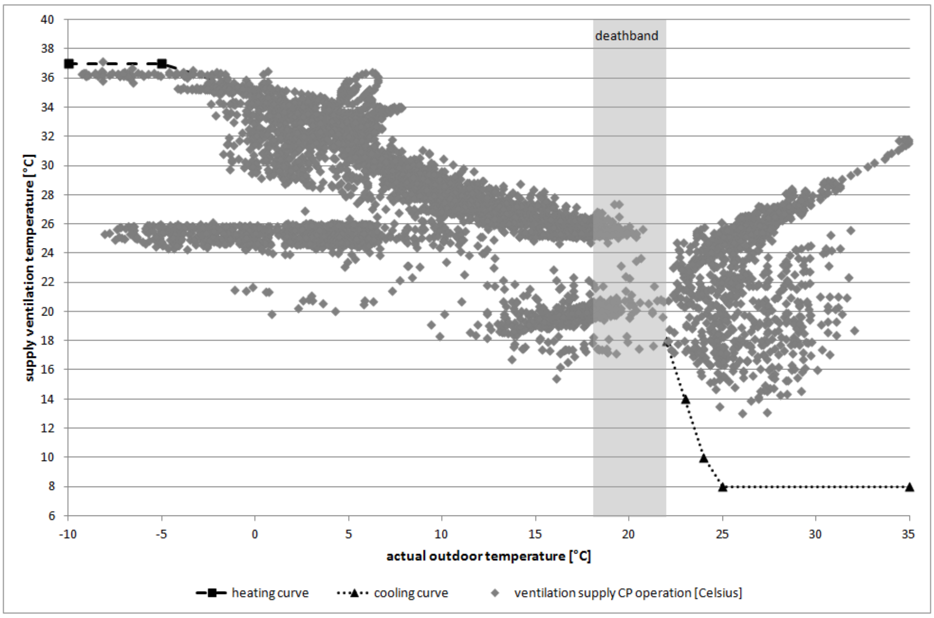


Figure 4-3: Heating/cooling curves of ventilation (building B)

3.3 Building C

The heat pump is a Daikin EWWP145 KAW1M, which consists of 3 modules (2 x EWWP045 KAW1M and 1 x EWWP055 KWA1M) that can be separately controlled.

The internal control of the heat pump decides which modules are switched on and off. The control algorithm is however unknown. According to information supplied by the manufacturer, the minimum time between two starts of a compressor is 240 seconds, the minimum time between a stop and a start of a compressor is 60 seconds and the minimum time between two starts of two different compressors is 1 to 300 seconds.

The combination of the 3-step – thus crude- modulation of the heat pump and the relatively small storage tanks will lead to cycling of the heat pump and of the supply temperature. The lack of hydraulic buffering should not pose problems in the zones, due to the thermal buffer of the TABS. For the air-handling units however, which are also fed by this production unit, it might lead to poor set point tracking.

The switch between heating and cooling mode depends on the running average outdoor temperature of the three previous days. The switching point is set at 14°C with a hysteresis of ±1°C.

When in heating mode, the production unit is controlled based on the temperature of the water leaving the hot storage tank. The set point is set to the set point of the TABS plus or minus an offset of 3 K to compensate losses of the distribution system. The supply temperatures of the TABS, AHU and floor heating are controlled separately by means of mixing valves (even if they share the same hot water collector). The set point supply temperature for the heat pump is calculated based on the maximum calculated set point temperature of the TABS, floor heating, AHU. Although the heating coil in the AHU was not sized for such low temperatures, no control problems, neither comfort problems were established.

When in cooling mode, the control is based on the temperature of the water leaving the cold storage tank. The set point is the maximum of the set points of the TABS and AHU. The passive cooling is kept in operation for 30 minutes when the set point is reached. Active cooling is only allowed in specific conditions: the outdoor temperature must be higher than 30°C for 1 hour, the cold storage temperature is at least 10°C higher than its set temperature for 1 hour and manual permission is given.

The back up boiler of the main AHU is switched on when the mixing three-way valve of the AHU coil is opened over 95% in heating mode for 2 minutes.

Concerning the TABS, each floor of the building is divided into four control zones. There are thus 4 floor heating control zones and 21 TABS control zones (including the apartment) (see Figure 2-6). Each of these zones is controlled with a binary two-way valve. This valve will open for approximately 10 minutes every hour of the day. When at the end of this period, the temperature difference between the supply and return temperature for that zone is higher than 2 K, the valve is kept open for another period of approximately 10 minutes, and so on. The controller is programmed in a way that the opening of the valves is spread as much as possible over each hour to avoid high peak loads. The opening- and closing time of each valve is 2 min 30s.

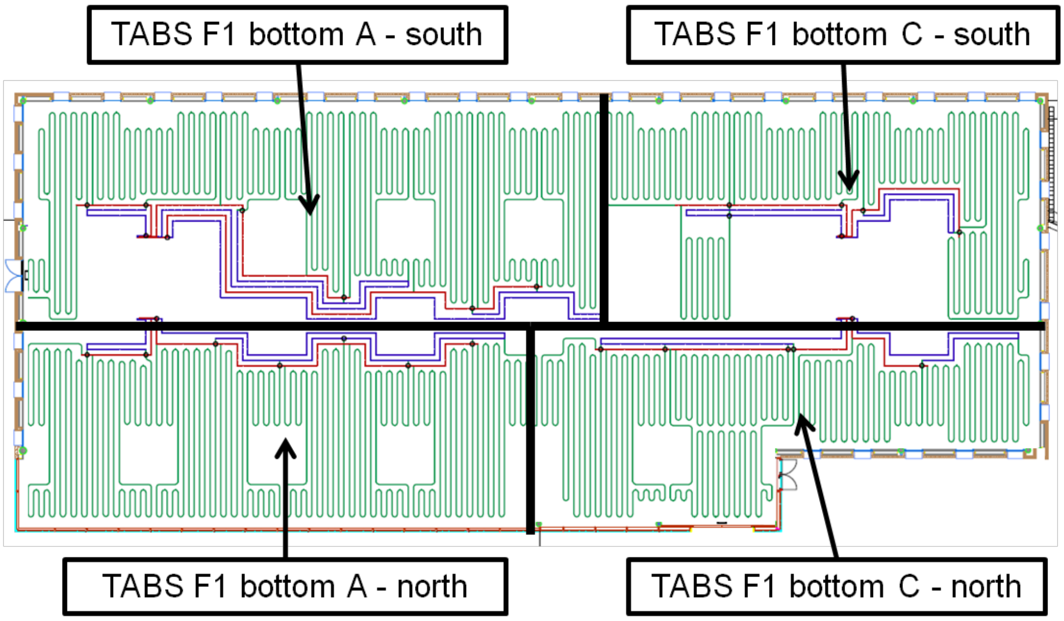


Figure 3-1: Hydraulic scheme of the bottom layer of the TABS elements of the 1st floor (building C)

The supply water temperature set points depend on the running average outdoor temperature of the six previous hours for the TABS and on the running average of the three previous days for the floor heating. Two mixing three-way valves produce the desired water temperatures. The implemented heating- and cooling curve for TABS is shown in Figure 4-4. The ground floor heating system uses the same heating curve as TABS, cooling is not possible via the floor heating system.

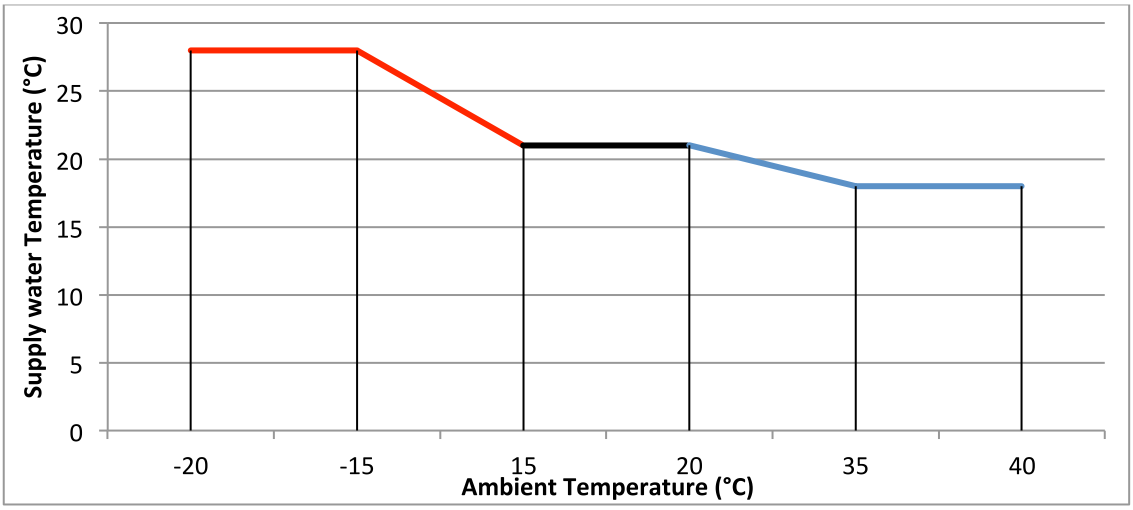


Figure 3-2: Heating/cooling curve of the TABS (building C)

The three office floors are equipped with VAV-boxes to control the ventilation air flow rate, except in the sanitary zones. The VAV-boxes are however on/off controlled based on time schedules. The ventilation system is balanced. The extraction air flow from the sanitary zones (440 m^3/h per floor) is exhausted to the outside, while the rest is sent to the main air handling unit (AHU) for possible recirculation or heat recovery.

The air for the apartment is made up in a separate, smaller AHU. Two extraction fans (38 000 m^3/h total design) ensure a sufficient air renewal rate in the parking garage via a perforated port.

The main AHU (Figure 3-3) consists of a centrifugal variable speed supply fan and extraction fan, a coil for heating and cooling (total cooling power = 83.2 kW and sensible cooling power = 75 kW for 18620 m^3/h air at 30°C and 50% RH and 23.9 m^3/h water at 17°C) and a cross-flow plate air-to-air heat exchanger (effectiveness 60% for air flow rates of 18620 m^3/h).

A fraction of the extraction air can be recirculated. The recirculation valve and complementary fresh air valve are PI controlled based on the supply air temperature and the return air CO_2-level. The latter is only active above a threshold value of 750 ppm and has priority over the temperature control. A minimum level of fresh air can be imposed, which was 50% at the time of this study. In addition, there is a bypass at the air-to-air heat exchanger for the fresh air. It is PI controlled based on the supply air temperature.

The water flow rate to the coil is constant (26.4 m^3/h in design). The water temperature is PI controlled with a mixing 3-way valve, based on the supply air temperature. The supply air set temperature equals 22°C when the outside air temperature is below 19°C and 20°C when the outside air temperature is above 20°C and is linearly interpolated in between.

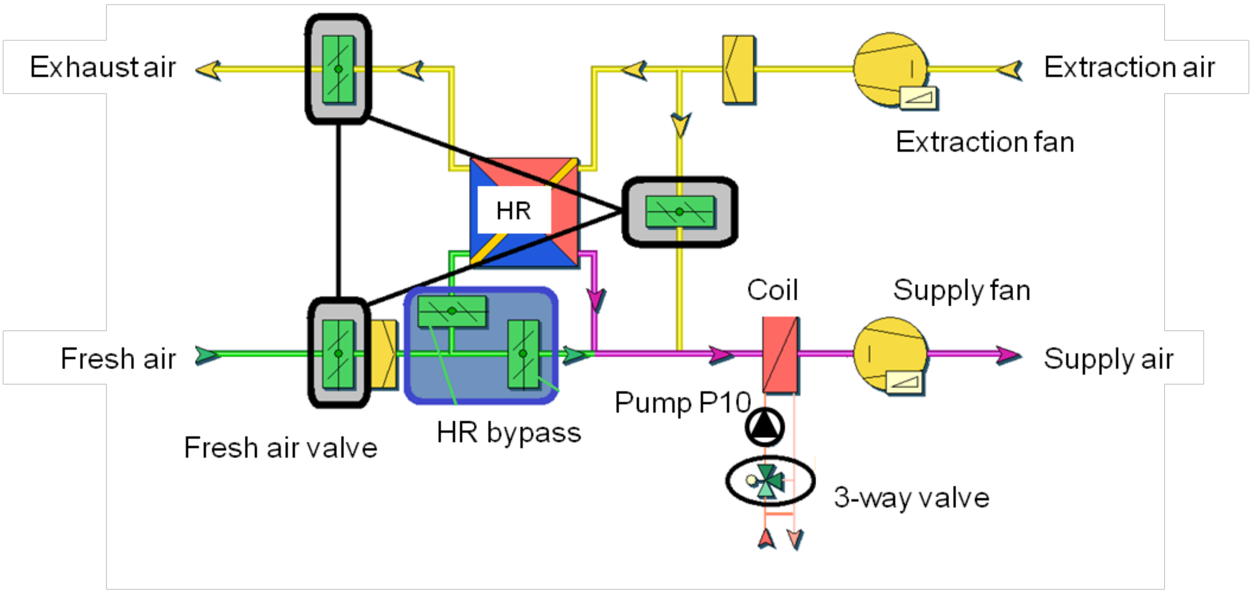


Figure 3-3: Air handling unit scheme (building C)

3.4 Building D

The control strategies of the different subsystems of this building are:

- TABS operates 24h/24h and 7d/7d. According to the situation, the building manager decides whether the TABS operate in heating or cooling mode. There is also use of recirculation to reach the set point. In winter, the water supply temperature is 20°C and in summer this temperature is 21.5°C.
- Fan coils operate during the day (from 5 am to 9 pm), to keep a set point temperature of 22°C all the year. During the night, fan coils are off unless the lower heating limit of 18°C is reached or the higher cooling limit of 28°C is reached.

- Ventilation system operates only during the day according to the temperature law given in Figure 4-5.

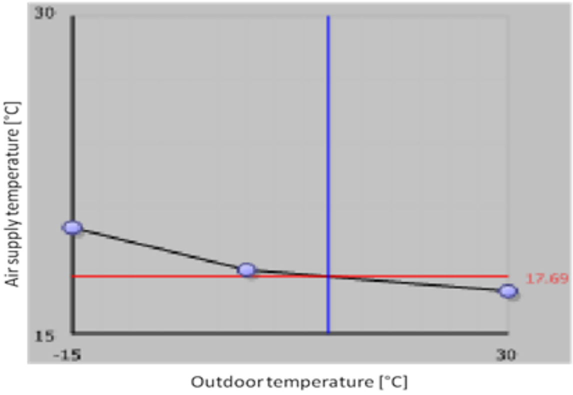


Figure 4-5: Heating/cooling curve of the ventilation system (building D)

Figure 4-6 shows instantaneous (5 min) values of the supply TABS temperature in function of the actual outdoor temperature for 2011. It can be seen that the supply water temperature of the TABS (in blue) is close to the theoretical curve in heating (in red) and cooling (in green) mode with a difference of 2K, in average. Moreover, as it is the building manager that decides whether the TABS operate in heating or cooling mode, the limit of 15°C between heating and cooling is totally arbitrary.

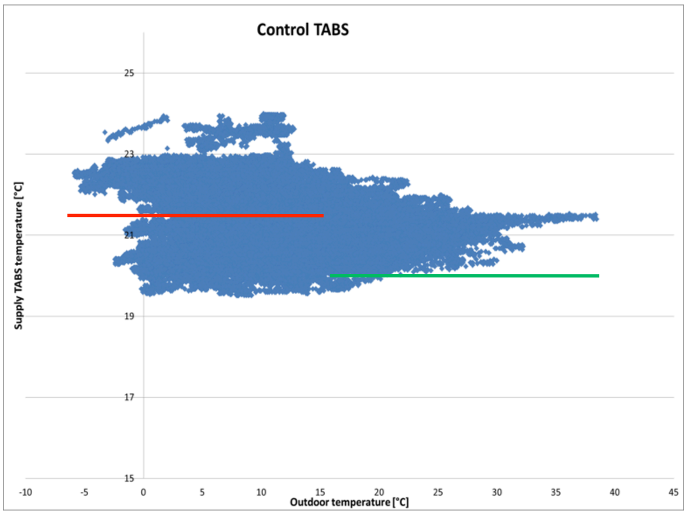


Figure 4-6: Control strategy of TABS (building D)

3.5 Building E

The control strategies of the different subsystems of this building are:

- The TABS has 3 working conditions: heating, cooling and idle. Changing from heating to cooling and vice versa can only be done by passing the idle state. This state lasted minimum 48 hours. Once every 24 hours the control system decides to heat or cool.
  - ✓ Start heating mode:
    - The average outside temperature of the previous day was < 10°C
    - In the last 48 hours, the cooling mode was not active.

- ✓ Start cooling mode:
    - o The average outside temperature of the previous day was > 14°C
    - o In the last 48 hours, the heating mode was not active.
- ✓ In all other cases the idle mode is activated

The supply temperature for heating and cooling modes is fixed and determined as followed.

- ✓ For the heating mode the temperature is set to 28°C.
- ✓ For the cooling mode the temperature is set to 17°C

The TABS is divided in zones and each zone can individually be opened or closed. The activation depends on the energy mode, the inside temperature and the outside temperature.

Heating at a TABS zone is activated under the following conditions:

- ✓ Energy mode is heating
- ✓ The average outside temperature of the previous day (between 8:00 hour and 18:00 hour) was <10°C
- ✓ The average momentary temperature in the zone is < 22.5°C

Cooling at a TABS zone is activated under the following conditions:

- ✓ Energy mode is cooling
- ✓ The average outside temperature of the previous day (between 8:00hour and 18:00 hour) was >16°C OR the average momentary temperature in the zone is (>22,5°C)

- For the convectors the heating and cooling strategy can be described as followed: The convectors are grouped in 4 zones. NO, SW,NW, SO. In each zone there are two temperature transmitters installed. The activation of the zone depends on the average of the 2 temperature sensors and a pre given set point. When there is a temperature difference between the average measured temperature and the set point temperature of the convector group is proportional controlled open. The supply temperature of the convectors depends on the outside temperature. Heating will be shutdown when all the following criteria are fulfilled:
    - ✓ The system status is cooling
    - ✓ The average temperature inside ALL of the open-space offices has reached (22,5°C)
- The ventilation system is controlled with a time schedule, the set point temperature of the supply temperature is set fixed to 17,0°C in winter and in summer conditions. If there is a temperature difference between the set point and the measured value of the exhausted air, a heat wheel will be started. If the heat wheel can't handle the heat load, a low temperature (28°C) reheater will be started. If the capacity is not enough, a two way valve will be send open connecting the high temperature collector, to give additional heat.

  If the measured supply temperature is higher than the set point temperature, and the heat wheel cannot compensate the temperature difference a cooling coil can give extra cooling capacity.

4 Energy balance and performance

4.1 Monitoring data

The period of measurement depends on each building as well as the sampling rate (Table 3-1). However, for each building, the type of data available is quite similar. Measurements comprise thermal data such as temperatures and flow rates, but also electrical consumptions. Hence, based on these data, it will be possible to compute thermal powers and energy performance.

This table also indicates that all buildings are not equipped with measurements of pump electrical consumption and flow rates. In that case, nominal powers and flow rates are considered.

Table 3-1: Type of data for each building

	Period	**Thermal data**			**Electrical data**		
		Temperatures	Flow rates	Sampling rate	HP	Circulating pump	Sampling rate
A	2010	✔	✔	15min	✔	✔	15min
B	2009	✔	✔	15min	✔	X	15min
C	2011	✔	Nominal	32 or 8 min	✔	✔	1 day
D	2011	✔	Nominal	5 min	✔	X	30min
E	2010	✔	Nominal	15min	X	X	NA

In addition to this, it has to be noticed that the quality and the availability of the data varies from one building to another but also from one production/emission system to another in the same building. This will be shown and discussed in the further analysis.

4.2 Performance indicators

Based on mass flow rates and temperatures, thermal powers transferred through the different components of the system are computed as follows:

$$\dot{Q}_{heating\,/\,cooling} = \dot{M}_w \cdot cp_w \cdot (T_{w,su} - T_{w,ex}) \tag{1}$$

Where:

$\dot{Q}_{heating\,/\,cooling}$	is the thermal power of the component (TABS, radiator, ventilation, floor heating, DHW), [W]
$\dot{M}_w$	is the water mass flow rate, [kg/s]
cp_w	is the water specific heat capacity, [J/kg.K]
$T_{w,su}$	is the supply water temperature injected into the circuit, [°C]
$T_{w,ex}$	is the return water temperature from the circuit, [°C]

When possible, the water (or glycol water) mass or volume flow rate is measured. If it is not the case, nominal values are considered.

The following seasonal coefficients of performance of the geothermal heat pump system are proposed in this project (similarly, but not exactly to what has been proposed in SEPEMO Project (Zottle et al., 2012)):

$$SCOP_1 = \frac{Q_{cd,hp}}{W_{cp,hp}} \tag{2}$$

$$SCOP_2 = \frac{Q_{cd,hp}}{W_{cp,hp} + W_{pp,ground}} \tag{3}$$

$$SCOP_3 = \frac{Q_{cd,hp}}{W_{cp,hp} + W_{pp,ground} + W_{pp,cd}} \tag{4}$$

$$SCOP_3 = \frac{Q_{cd,hp}}{W_{cp,hp} + W_{pp,ground} + W_{pp,cd} + W_{pp,TABS}} \tag{5}$$

Where:

$SCOP_1$	is the Seasonal Coefficient Of Performance (heat pump alone) [-]
$SCOP_2$	is the Seasonal Coefficient Of Performance (heat pump + circulating pumps on heat source side (ground)) [-]
$SCOP_3$	is the Seasonal Coefficient Of Performance (heat pump + circulating pumps on heat source side (ground) + circulating pumps on the condenser side) [-]
$SCOP_4$	is the Seasonal Coefficient Of Performance (heat pump + circulating pumps on heat source side (ground) + circulating pumps on the condenser side + circulating pumps of the TABS) [-]
$Q_{cd,hp}$	is the heating energy provided at the condenser of the heat pump [kWh]
$W_{cp,hp}$	is the electrical energy use of the compressor of the heat pump in heating mode [kWh]
$W_{pp,ground}$	is the electrical energy use of the circulating pumps of the ground heat exchangers [kWh]
$W_{pp,cd}$	is the electrical energy use of the circulating pumps of the condenser [kWh]

$W_{pp,TABS}$	is the electrical energy use of the circulating pumps of the TABS [kWh]

Introducing those performance indicators will allow a fairer comparison between the performance of the heating/cooling plants of all 5 buildings.

Similar seasonal performance indicators could be defined in cooling mode.

$$SEER_1 = \frac{Q_{ev,ch}}{W_{cp,ch}} \tag{6}$$

$$SEER_2 = \frac{Q_{ev,ch}}{W_{cp,ch} + W_{pp,ground}} \tag{7}$$

$$SEER_3 = \frac{Q_{ev,ch}}{W_{cp,ch} + W_{pp,ground} + W_{pp,ev}} \tag{8}$$

$$SEER_4 = \frac{Q_{ev,ch}}{W_{cp,ch} + W_{pp,ground} + W_{pp,ev} + W_{pp,TABS}} \tag{9}$$

Where:

$SEER_1$	is the net Seasonal Energy Efficiency Ratio (chiller alone) [-]
$SEER_2$	is the net Seasonal Energy Efficiency Ratio (chiller + circulating pumps on heat sink side (for instance ground-couple heat exchangers)) [-]
$SEER_3$	is the net Seasonal Energy Efficiency Ratio (chiller + circulating pumps on heat sink side (for instance ground-couple heat exchangers) + circulating pumps on the condenser) [-]
$SEER_4$	is the net Seasonal Energy Efficiency Ratio (chiller + circulating pumps on heat sink side (for instance ground-couple heat exchangers) = circulating pumps on the condenser + circulating pumps on the TABS side) [-]
$Q_{ev,ch}$	is the cooling energy provided at the evaporator of the heat pump [kWh]
$W_{cp,ch}$	is the electrical energy use of the compressor of the heat pump in cooling mode [kWh]
$W_{pp,ground}$	is the electrical energy use of the circulating pumps of the ground heat exchangers [kWh]

$W_{pp,ev}$ is the electrical energy use of the circulating pumps of the evaporator [kWh]

$W_{pp,TABS}$ is the electrical energy use of the circulating pumps of the TABS [kWh]

In the case of free chilling operating mode, the electrical consumption of the compressor $W_{cp,ch}$ is set to zero in the four previous equations.

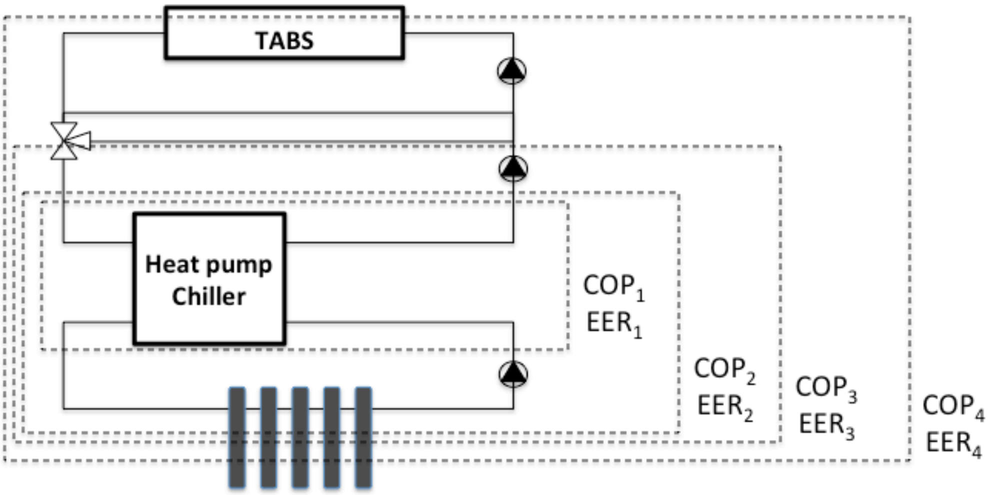


Figure 4-1: System boundaries considered for the definition of the different performance indicators

The heating energies ([kWh]) provided at the condenser of the heat pump for buildings A, B, C, D and E are respectively:

$$Q_{cd,hp,A} = Q_{h,TABS} \tag{10}$$

$$Q_{cd,hp,B} = Q_{h,TABS} + Q_{h,vent} \tag{11}$$

$$Q_{cd,hp,C} = Q_{h,TABS} + Q_{h,vent} + Q_{h,floor} \tag{12}$$

$$Q_{cd,hp,D} = Q_{h,TABS} \tag{13}$$

$$Q_{cd,hp,E} = Q_{h,TABS} + Q_{h,vent} + Q_{h,floor} \tag{14}$$

Where $Q_{h,TABS}$ is the heating load provided by TABS, $Q_{h,vent}$ is the heating load provided by ventilation and $Q_{h,floor}$ is the heating load provided by floor heating.

The cooling energies provided by the evaporator of the chiller and in free chilling operation (and eventually by a heat pump working in reverse) are respectively for buildings A, B, C, D and E:

$$Q_{fc,A} = Q_{c,TABS} \tag{15}$$

$$Q_{fc,B} + Q_{ev,ch} = Q_{c,TABS} + Q_{c,vent} \tag{16}$$

$$Q_{fc,C} + Q_{ev,ch,C} = Q_{c,TABS} + Q_{c,vent} + Q_{c,floor} \tag{17}$$

$$Q_{fc,D} = Q_{c,TABS} \tag{18}$$

$$Q_{fc,E} + Q_{ev,ch,E} + Q_{ev,hp,E} = Q_{c,TABS} + Q_{h,vent} + Q_{h,floor} \tag{19}$$

Where $Q_{c,TABS}$ is the cooling load provided by TABS, $Q_{c,vent}$ is the cooling load provided by ventilation and $Q_{c,floor}$ is the cooling load provided by floor cooling.

4.3 Seasonal analysis

Table 4-2 and Table 4-3 show a comparison of the seasonal performance of the different HVAC plants in cooling and heating modes. In order to allow for the most correct comparison, the seasonal coefficients of performance (in heating and cooling modes) introduced previously have been used. More explanations and details about the analyses conducted on each building are given hereunder.

4.3.1 Buildings A and B

It is shown that for both German buildings (A and B), the annual cooling load of the whole building is very small compared to the heating load (from 3.5 to 5.5%). Moreover, the entire cooling load is provided by the geothermal system in both cases. Regarding the heat load, the TABS provides only 14.2% of the total annual heating load in case of building A and 13.6% in case of building B. Concerning the performance of the system, it is shown that the heat pump of the first building has a better SCOP than building B. This could be due to the fact that the heat pump of building B has lower nominal performance and thus higher electrical consumption than the one of building A. Results also show that the SEER of building A is much larger than the one of the building B because the whole cooling load is provided only by free chilling.

4.3.2 Building C

Regarding building C, the available data allowed the analysis of the geothermal system only. Indeed, there were no data about the boiler and the emission systems related to this (ventilation and floor heating). Moreover, the main difficulty in the interpretation of these data lies in the fact that since its inauguration until the time of this study, the building has not been fully rented and occupied. At the time of this study, about 75% of the second floor and the roof apartment were still vacant.

Investigated period

The considered period for the energy analysis extents from December 1st 2010 to November 30th 2011. Actually, monitoring data are not complete for the month of December 2011.

Data acquisition rate

The sampling rate for the electrical energy measurement is 24 hours. The electrical consumption of the heat pump is the overall consumption of the components comprised inside the green square shown in Figure 4-2. It comprises the consumption of the compressors, the consumption of ground heat exchangers' pumps P2 and P3 (see Figure 4-22 and Figure 4-28) and the consumption of the pump P4 between the heat pump and the storage tank. The sampling rate for temperature measurements is 8 minutes.

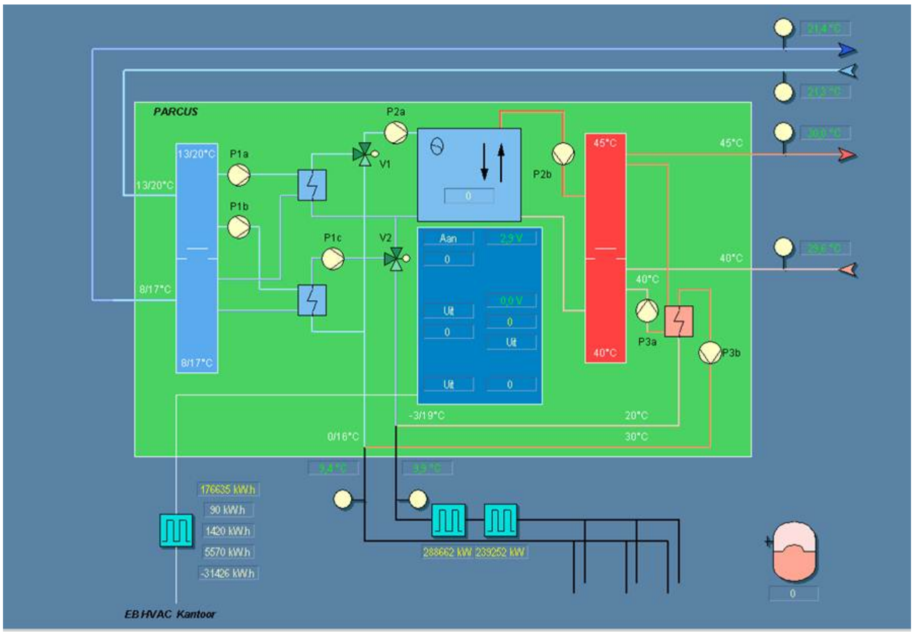


Figure 4-2: Auxiliaries taken into account in the measurement of the electricity consumption of the heat pump

Evaluation of the cooling and heating energies transferred into the manifolds

The heating and cooling powers provided to the TABS are evaluated by considering the measurements of the water temperatures at the heating and cooling manifolds and the nominal flow rate of the pump P04 (28.5 m^3/h) (see Figure 4-3). When the temperature difference is lower than 0.4 (0.7) in cooling (heating) mode, the power is assumed to be equal to 0. This allows filtering the points with potential uncertainty errors.

The heating and cooling powers provided to the AHU are evaluated in a similar way as for the TABS. The same temperature difference as for the TABS is considered (same heating and cooling manifolds) and the water flow rate is the nominal flow rate of pump P08 (28.5 m^3/h). Because there is no measurements of the flow rate delivered by variable speed pump P07, and for the sake of simplicity, the power transferred to the floor heating system is assumed to equal to 20% of the power transferred to the TABS.

The overall powers transferred into the manifolds are the sum of the powers transferred to the TABS, AHU and heating floor (heating manifold) and to the TABS and AHU (cooling manifold).

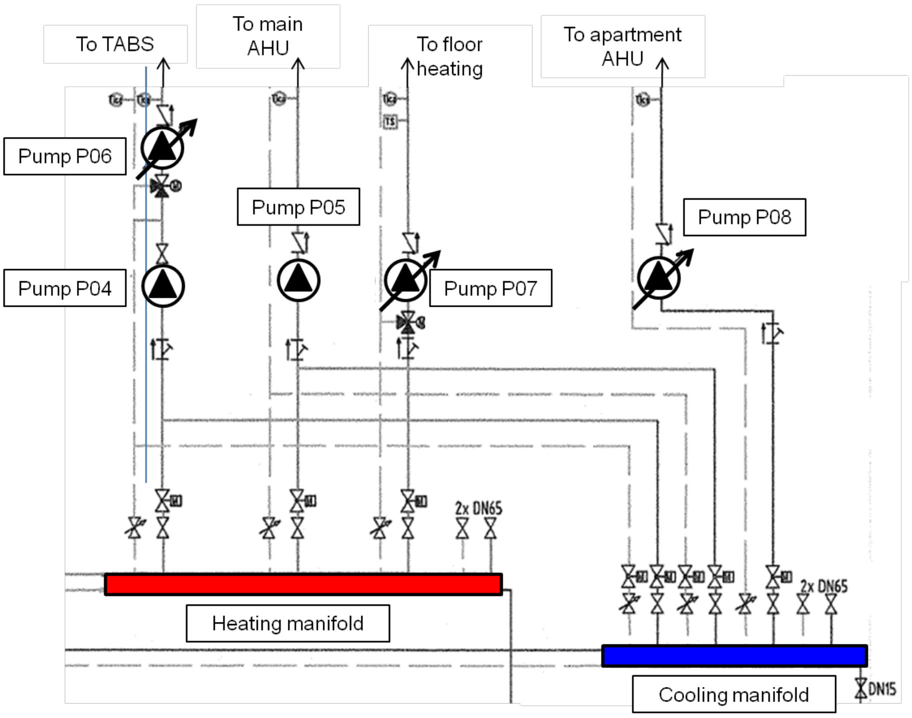


Figure 4-3: Hydraulic scheme of the distribution system (building C)

Energy balance across the heat pump + cooling/heating storages

Since the sampling rate of the electrical consumption of the heat pump system is 24 hours, heat balance across the system made up of the heat pump + heat/cool storage can be at best expressed on a daily basis. Figure 4-4 shows the residual on the energy balance as function of the energy injected into the hot manifold for the days of December 2011, January 2011 and February 2011. It could be observed that the residual is acceptable for large transferred energies but sharply increases for low energies (whose weight on the seasonal energy balance is hopefully less important). This residual could be explained by different reasons: 1) part of the electrical energy (compressors and pumps) is released to the ambient and not recovered as thermal energy; 2) heat losses from the heat pumps and the pipes to the ambient; 3) uncertainty on the evaluation of the energy injected into the heating manifold (uncertainty on the real flow rate delivered by the pump, uncertainty on the temperature measurements (low difference of temperatures)); 4) assumption on the power delivered to the floor heating at the ground floor.

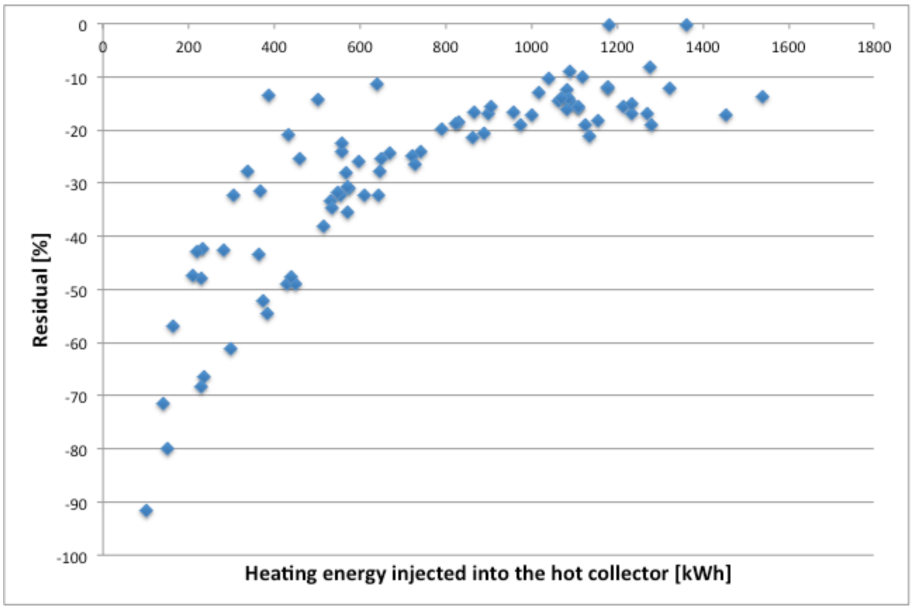


Figure 4-4: Residual on the energy balance across the heat pump + storage tank (building C)

As mentioned previously, the heat pump electricity consumption is measured on a daily basis. No distinction can be directly done between the consumption in cooling mode and that in heating mode. Hence, both consumptions have been evaluated in the following way. In the absence of cooling demand the daily electrical consumption corresponds to heating operation. In the absence of heating demand, the daily electrical consumption corresponds to cooling operation. If heating and cooling occur in the same day, the electrical consumption of the heat pump working in heating mode is evaluated by dividing the heating demand (heating manifold) by an average COP_3 of 3.22. The latter value corresponds to the average COP_3 of the heat pump over the months of December 2010, January 2011 and February 2011.

The energy balances on monthly basis can be visualized in Table 4-1. The seasonal COP_3 in heating mode is equal to 3.01. This COP_3 is defined as the ratio between the heating energy transferred into the hot manifold (from December 2010 to November 2011, i.e. 80901 kWh) and the electrical energy consumed by the heat pump working in heating mode (during the same period, i.e.: 26899 kWh).

An upper limit can be defined to this COP_3 by correcting the energy transferred into the hot manifold. In the absence of ambient losses, this energy should be the sum of the energy extracted from the ground (76518 kWh) and the electrical consumption of the heat pump (26899 kWh), i.e. 103417 kWh. In that case, the seasonal $SCOP_3$ should be equal to 3.84.

A similar correction could be done in cooling mode. In this case, an upper limit to the cooling energy transferred into the cold manifold would be the energy extracted from the ground minus the electrical consumption of the heat pump in cooling mode (mainly free-chilling), i.e. 65926 kWh. In this case, the $SEER_3$ would be equal to 13.26, against 13.16 in the absence of correction.

Table 4-1: Monthly heat balance on the geothermal heat pump system (building C)

	Man H	Grou H	Res H	Man C	Grou C	Res C	Elec H+C	COP_3 H	Elec H	EER_3 C	Elec C
Dec 10	29284	25556	-5312	0	208	-208	9040	3,24	9040	/	0
Jan 11	20325	18492	-4557	0	232	-232	6390	3,18	6390	/	0

Feb 11	13926	13583	-4267	0	211	-211	4610	3,02	4610	/	0
Mar 11	6015	6854	-3626	1028	150	1472	2830	2,16	2787	1,73	593
Apr 11	693	903	-587	5712	5008	1067	650	1,84	378	15,76	362
May 11	77	165	-112	10954	10586	954	610	3,22	24	18,69	586
Jun 11	108	0	75	10342	13858	-2789	760	3,22	34	14,24	726
Jul 11	8	31	-66	8519	13044	-3677	850	0,19	42	10,05	848
Aug 11	0	0	0	10131	13745	-2764	850	/	0	11,92	850
Sep 11	0	0	0	7527	10317	-2220	570	/	0	13,21	570
Oct 11	1904	2244	-1094	5026	2867	2424	1000	2,52	754	18,91	266
Nov 11	8561	8690	-2970	1215	671	713	3010	3,01	2841	7,18	169
Total	80901	76518	-22516	60455	70897	-5472	31170	3.01	26899	12.16	4971
Total correc	103417			65926				3.84		13.26	

4.3.3 Building D

For the building D, only the geothermal system has been analyzed at the time of this report. The main difficulty in the interpretation of these data is that they do not seem to be reliable after March 2011, as it will be shown in the monthly analysis.

Evaluation of the heating energy provided by the geothermal heat pump system

The most reliable thermal measurements are those on the evaporator side. The power extracted from the ground is computed every 5 minutes by considering the difference of temperature and the mass flow rate measured by the calorimeter. An assumption is done on the concentration of glycol (30%) in the aqueous solution of glycol water. This computed value is close to the value indicated by the calorimeter.

The evolution of this thermal power weighted by the status of the heat pump (the pumps on the ground side are switched off, when the heat pump is switched off) is integrated over each month.

The electrical consumption of the heat pump is measured every 30 minutes. As mentioned before, the measurements after March 2011 are not reliable. Figure 4-5 shows the monthly energy balance on the geothermal heat pump system of the building D. The energy at the evaporator (green) is measured based on the flow rate and temperature difference given by the calorimeter. The energy at the condenser side is evaluated based on the temperature difference at the condenser side (that is rather small) and the nominal flow rate of the condenser pump. It can be observed that the heat balance is only partially checked (except from April to September). The residual on the heat balance may be due inaccuracy on measurements, to an error on the condenser mass flow rate (probably different from the nominal flow rate) and to ambient losses (especially from the compressors).

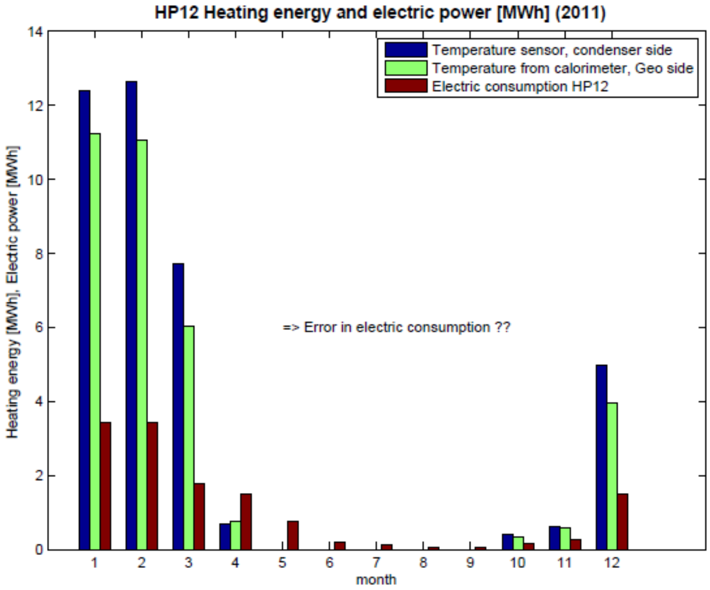


Figure 4-5: Monthly Energy balance on the geothermal heat pump system (building D)

Hence, in order to be more accurate, it is proposed to evaluate the heating energy released at the condenser by summing the energy transferred at the evaporator and the electrical energy.

Evaluation of the heating energy provided by the boiler

The heating energy provided by the boilers is evaluated based on the nominal flow rate of the pumps and the supply and return temperatures. The flow rate of the pumps is adjusted in order to predict the monthly gas consumptions.

Evaluation of the cooling energy provided by the geocooling system

During geocooling operation, the cooling energy is evaluated by expressing the energy balance on the heat exchanger between the ground glycol-water loop and the TABS water loop. The balance on the ground side is preferred, because of problems of temperature measurements on the TABS side. The flow rate and temperature difference measured by the calorimeter are considered.

Evaluation of the cooling energy provided by the chiller

The cooling energy provided by the chiller is evaluated by expressing the heat balance on the evaporator. The nominal water flow rate is considered (what introduces a large uncertainty) and the temperature difference is measured. The chiller electrical consumption is measured monthly.

The cooling energy is split among the air handling unit (AHU) and the fan coil units. The cooling energy provided by the AHU is evaluated based on a heat balance on the air side. The rest of the energy is provided by the fan coil unit.

4.3.4 Building E

The thermal energies transferred by the different components of the building E are measured by means of heat-meters (Figure 4-6 and Figure 4-7).

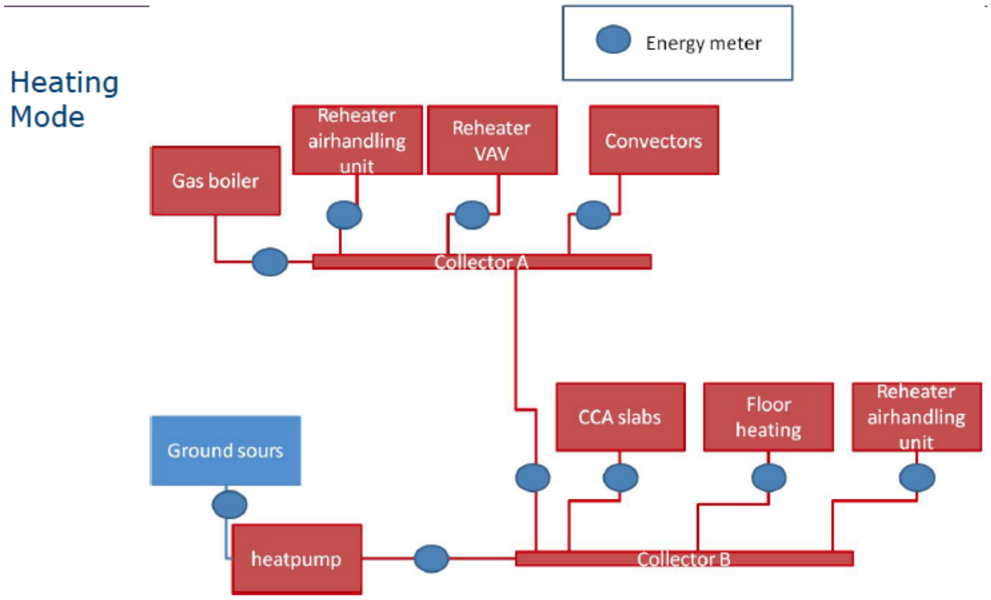


Figure 4-6: Locations of the heat meters on the heating plant (building E)

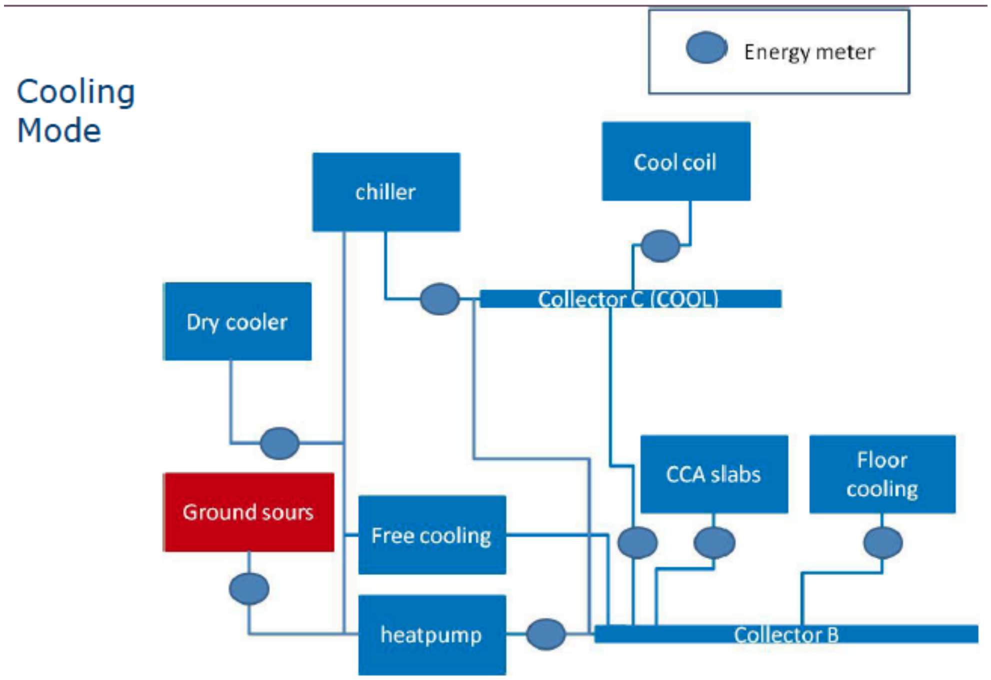
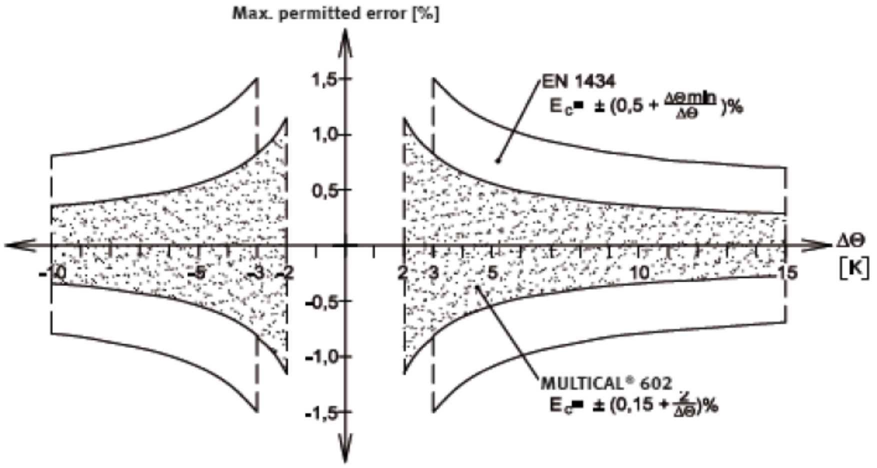


Figure 4-7: Locations of the heat meters on the cooling plant (building E)

The investigated period extends from May 10th 2010 to May 10th 2011. The main problem associated with such measurement device is the low temperature differences, which are characteristic of low-temperature heating systems. As shown in Figure 4-8, the accuracy of the heat-meters is typically decreasing sharply for temperature differences lower than 2-3 K.



The above diagram shows the tolerance band of MULTICAL® 602 compared to the tolerance requirements of EN 1434.

Figure 4-8: Accuracy of the heat-meter vs temperature difference across it

Figure 4-9 shows the fraction of time when the temperature difference across the heat-meter on the condenser side of the heat pump is lower than 2K. It can be observed that such a situation occurs a large part of the time. Consequently, there is an uncertainty on the annual energy balance on the heat pump. This inaccuracy could explain the difference between the value measured by heat meter on the boiler/heat pump and the sum of all the energies measured by the heat-meters on the different emitters (see last column of Table 4-2).

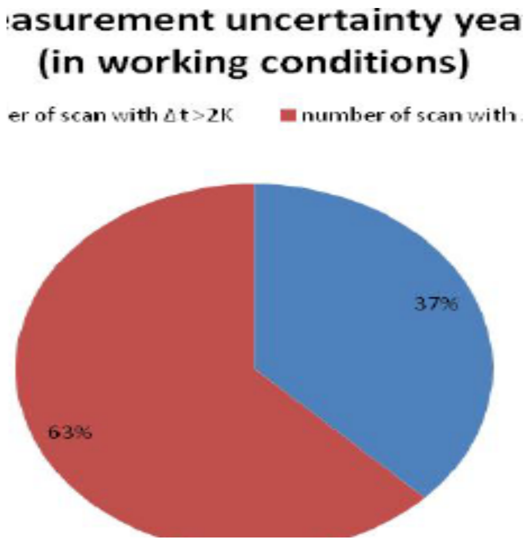


Figure 4-9: Fractions of time with DELTAT across the heat pump heat-meter lower and larger than 2K (building E)

4.3.5 Summary

Heating mode

Table 4-2: Annual energy consumption and performance in heating mode

			A (2010)	B (2009)	C (2011)	D (2011)	E (2010-11)
Annual heating load		[MWh]	1200	355	80.90	461.15	502.26
Ventilation	Boiler	[MWh]	/	/	ND	99.55	72.28
	District heating	[MWh]	109.28	5.3	/	/	/
	Geothermal HP	[MWh]	/	42.3	10.14	/	51.38
Fan coils	Boiler	[MWh]	/	/	/	198.17	131.87
TABS	Geothermal HP	[MWh]	171.3	48.2	58.97	47.13[i]	32.33
Heating load by radiators	Boiler	[MWh]	/	/	/	39.11[ii]	/
	District heating	[MWh]	885.78	219.3	/	/	/
Floor heating	Boiler	[MWh]	/	/	ND	65.19[iii]	2.70
	District heating	[MWh]	33.66	23.9	/	/	/
	Geothermal HP	[MWh]	/	/	11.79	/	107.08
DHW		[MWh]	/	15.9	/	12.00[iv]	ND
Electrical consumption	Heat pump	[MWh]	33.24	21	25.12	13.26	100.91[i]
	Ground hex pumps	[MWh]	3.1	ND		10.84[v]	ND
	Condenser side pumps	[MWh]	2.73	ND		5.59	ND
	TABS pumps	[MWh]				8.70	ND

Boiler	[MWh]	0	0	3.4	402,02	206,85 (232.53)[ii]
District heating	[MWh]	1028.72	248.5	0	0	0
Geothermal HP	[MWh]	171,3	90,5	80.90	47,13	190.79 (268.73)[iii]

$SCOP_1$	[-]	5.15	3.70	ND	3.56	2.67
$SCOP_2$	[-]	4.71	ND	ND	1.96	ND
$SCOP_3$	[-]	-	ND	3.01	1.59	ND
$SCOP_4$	[-]	4.38	ND	ND	1.23	ND

Remarks:

ND: No data

Building D

[i] The energy at the condenser is estimated by summing the thermal energy at the evaporator and the electrical consumption of the compressors
[ii] According to the installed power desegregation
[iii] According to the installed power desegregation
[iv] Theoretical estimation for DHW
[v] The electrical consumptions of the different pumps have been measured by means of watt-meters

Building E

[i] The heat pump electrical consumption is evaluated by expressing the heat balance across the heat pump: it is computed as the difference between the energy measured at the condenser side and the energy measured at the evaporator side (ground-coupled heat exchangers).
[ii] The value in brackets is measured by the heat-meter on the boiler. The value not in brackets corresponds to the sum of the energies measured at the different heat meters (ventilation, convectors, radiant floor).
[iii] The value in brackets is measured by the heat-meter on the heat pump. The value not in brackets corresponds to the sum of the energies measured at the different heat meters (ventilation, TABS, radiant floor).

A comparison, for the different buildings, of the disaggregation of the heating energy into the different primary systems is given in Figure 4-10. It could be observed that 2 buildings (A and B) are connected to a district heating system. In most of the buildings, except for building C, the part of the heating energy provided by boilers is pretty large.

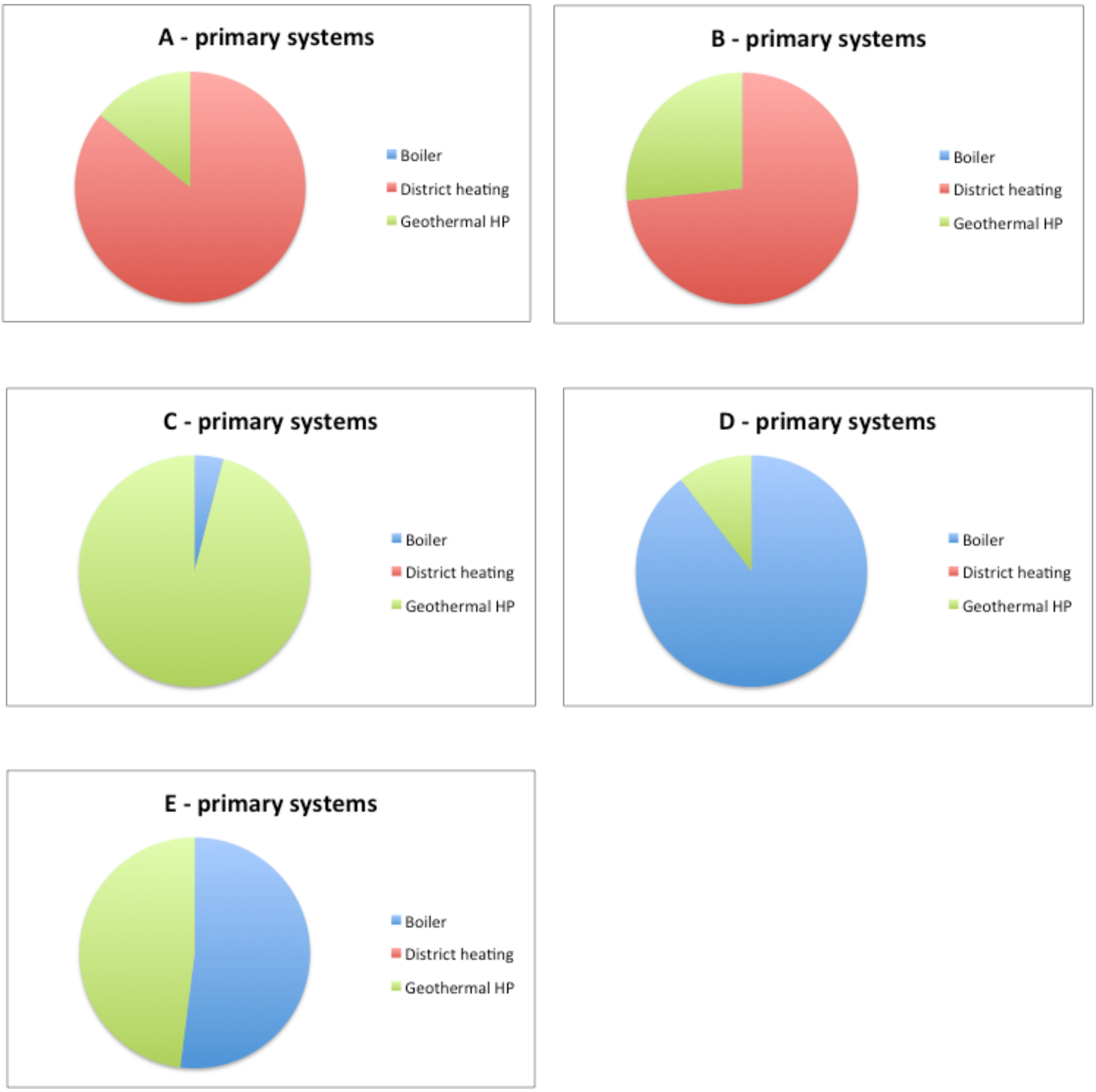


Figure 4-10: Disaggregation of yearly heating energy into the different primary systems

A similar disaggregation is done into the different secondary systems and shown in Figure 4-11. It could be observed that the part of the heating load covered by the TABS is very limited.

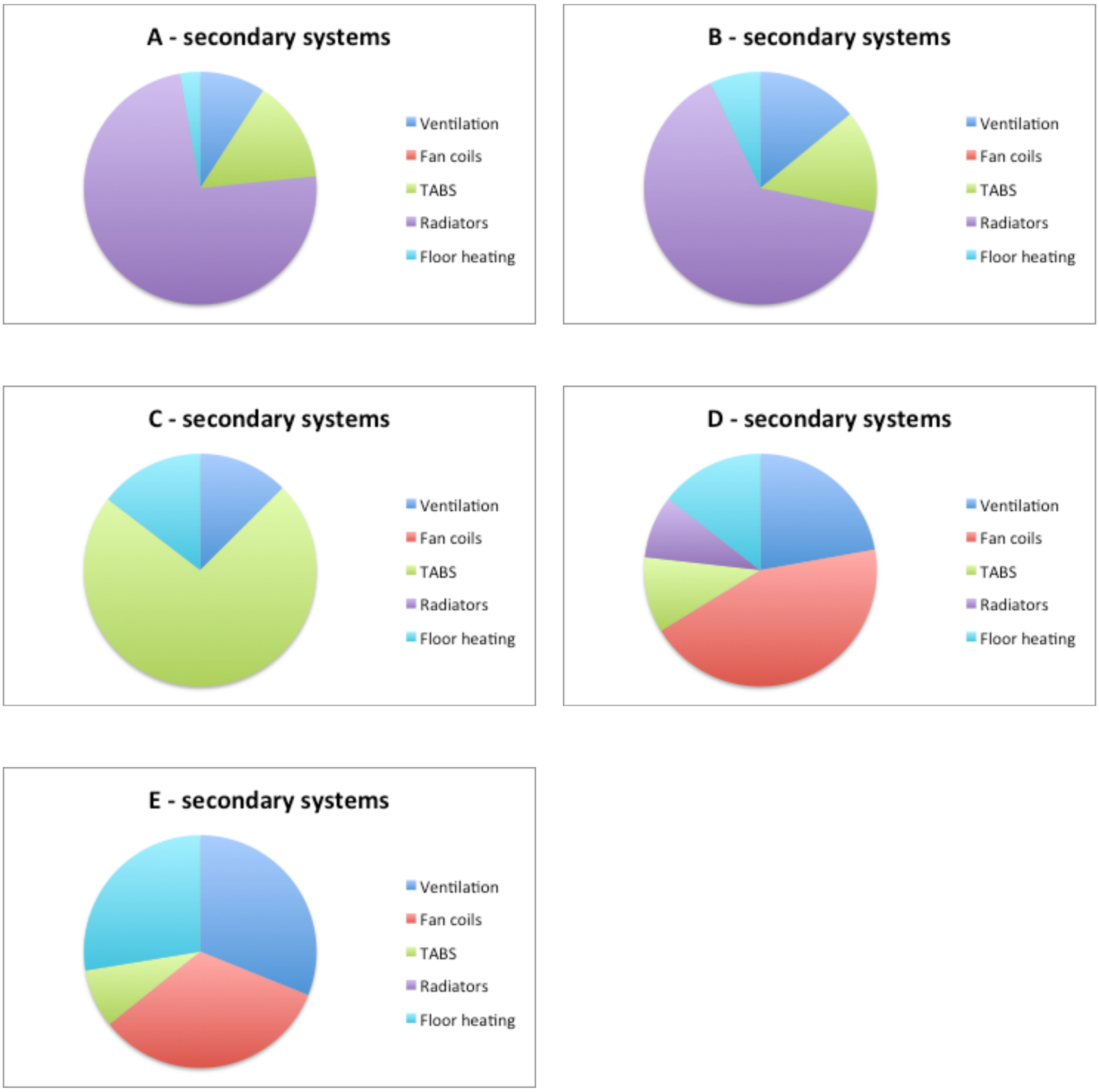


Figure 4-11: Disaggregation of yearly heating energy into the different secondary systems

Cooling mode

Table 4-3: Annual energy consumption and performance in cooling mode

			A (2010)	B (2009)	C (2011)	D (2011)	E (2010-11)
Annual cooling load		[MWh]	46.47	19.69	60.45	92.70	68.29
Ventilation	Chiller	[MWh]	/	4.2	4.76	6.67	6.66
	Geocooling	[MWh]					
Fan coils	Chiller	[MWh]	/	/	/	21.19	/
TABS	Geocooling	[MWh]	46.47	15.2	70.46	64.84	61.69
Electrical consumption	Chiller	MWh]	/	/	4.97	No data	
	Ground hex pumps	[MWh]	0.935	No Data		17.41	No data
	Brine/water hex	[MWh]				9.57	No data
	TABS side pumps	[MWh]	1.283	No Data		5.04	No data

SEER$_1$	[-]	-	10.8	ND	-	ND
SEER$_2$	[-]	49.70	ND	ND	3.72	ND
SEER$_3$	[-]	20.95	ND	12.16	2.89	ND
SEER$_4$	[-]	-	ND	ND	2.08	ND

Figure 4-12 indicates that in most of the buildings, the entire or most of the entire cooling energy is provided by the geocooling system.

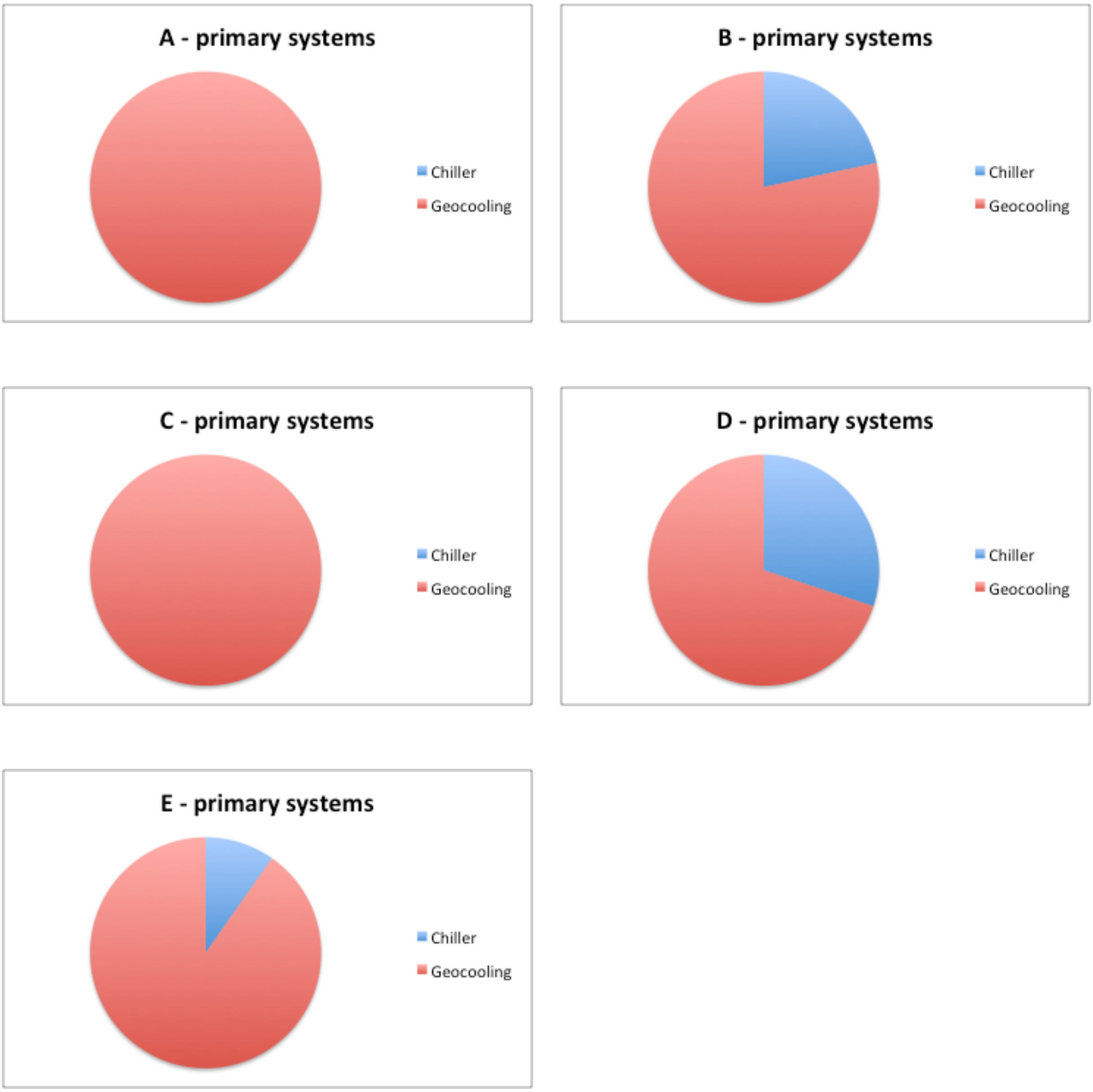


Figure 4-12: Disaggregation of yearly cooling energy into the different primary systems

In contrary to what is observed in heating operation, the TABS provides a large part of the cooling energy (Figure 4-13).

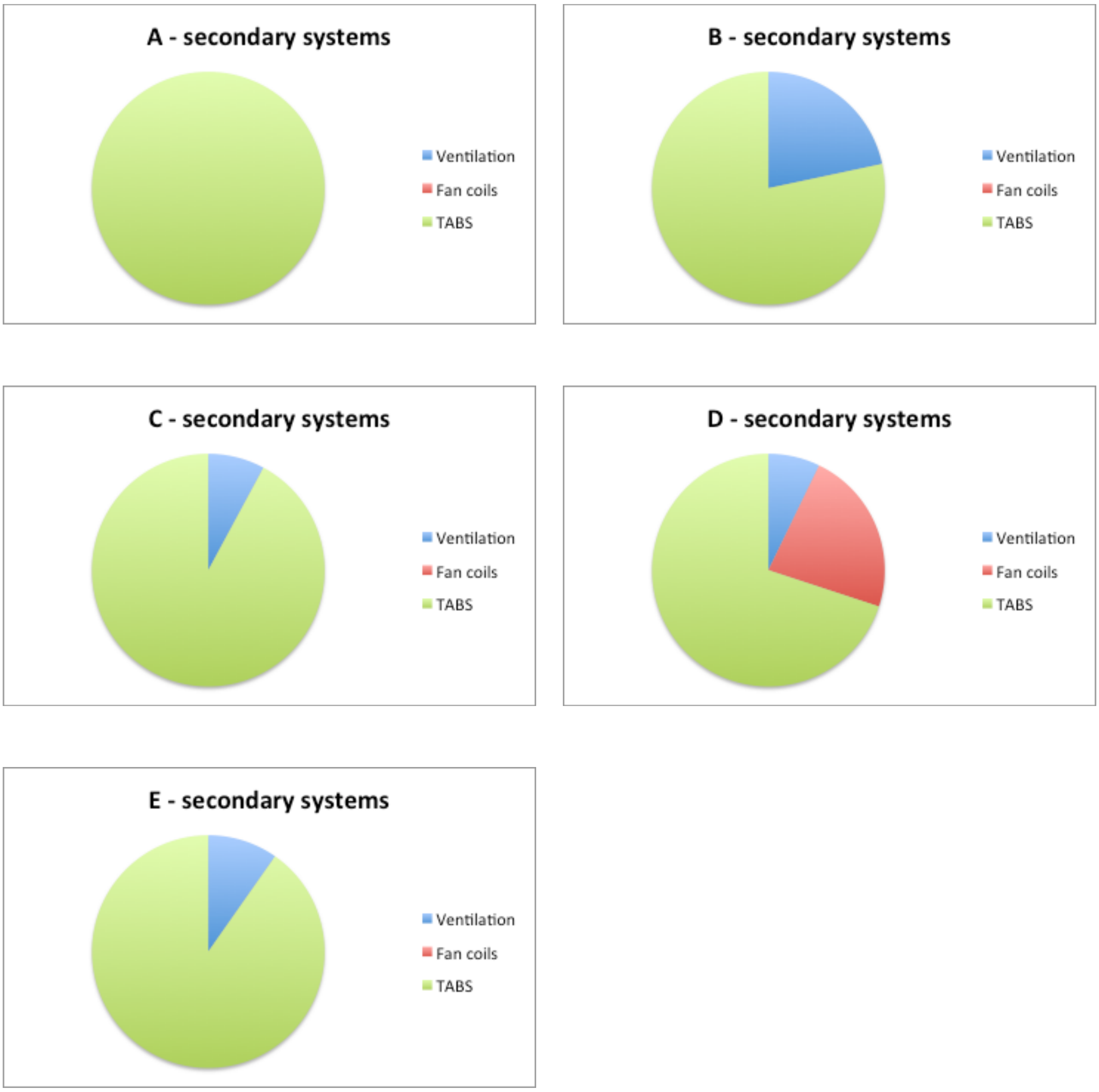


Figure 4-13: Disaggregation of yearly cooling energy into the different secondary systems

4.4 Monthly analysis

4.4.1 Buildings A and B

Energy performance of buildings A and B are also analyzed on a monthly basis (Figure 3-1 and Figure 3-2). It can be seen that most of the time, heating and cooling are not provided at the same time. There is an exception in January for building B, where the TABS and the ventilation provided 3.2 MWh of cooling energy (the reason of this unexpected load could not be explained by the building manager). Figure 4-14 and Figure 4-15 also indicate that the cooling energies are much lower than the heating energies.

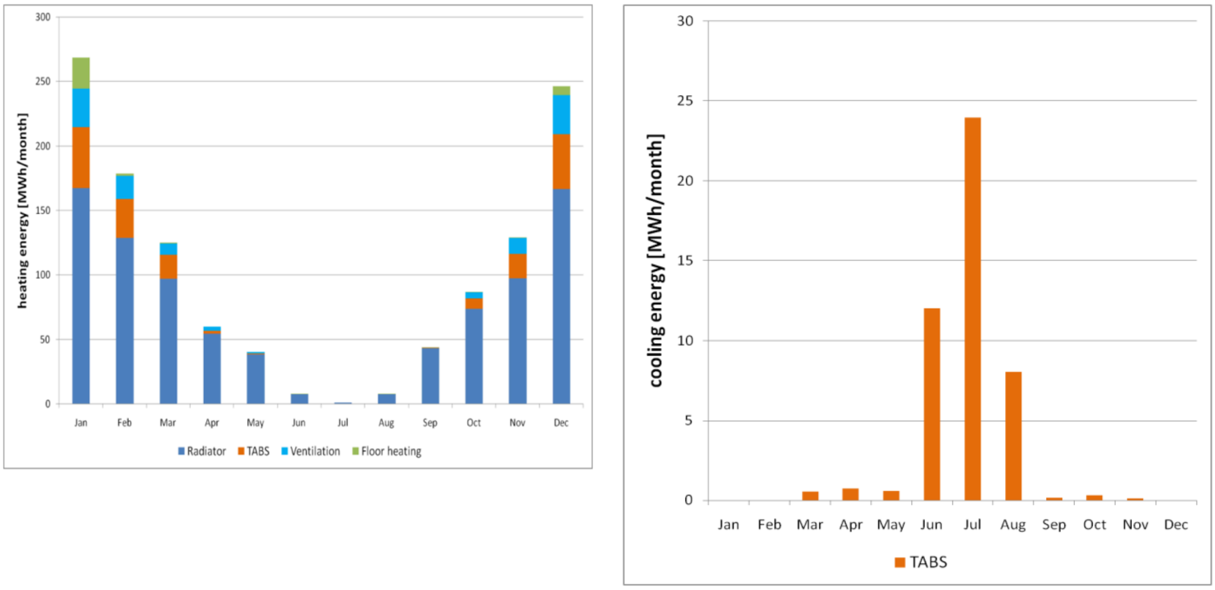


Figure 4-14: Heating (left) and cooling (right) load of building A

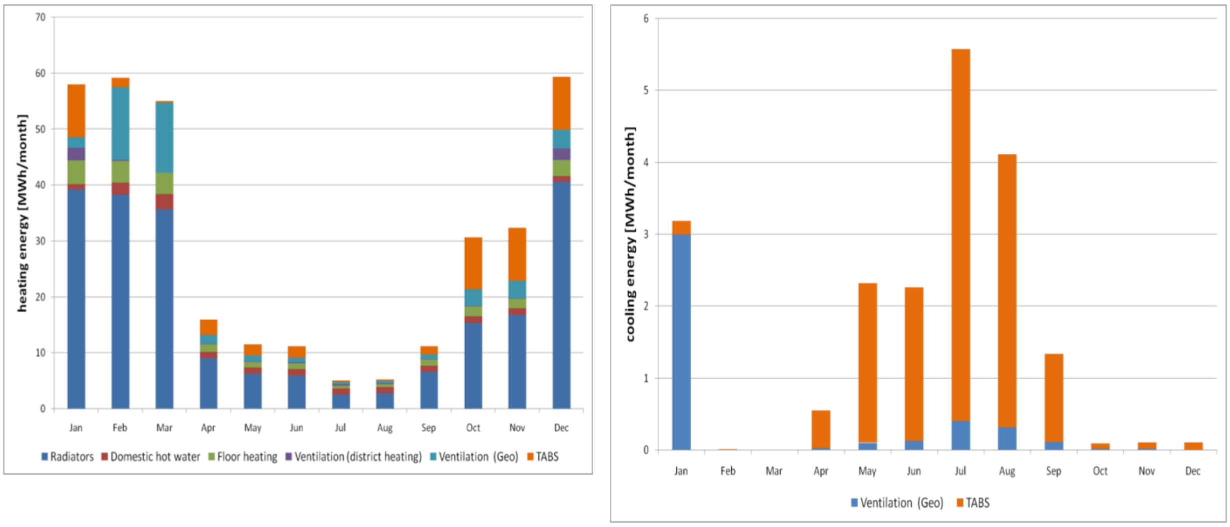


Figure 4-15: Heating (left) and cooling (right) load of building B

4.4.2 Building C

Figure 3-3 shows the results of building C on a monthly basis for the geothermal system. It can be seen that cooling and heating energies are not provided at the same time except in March and November. Compared to the previous cases, the cooling period is quite larger: from March to November. Moreover, as mentioned before, cover factor of TABS is 4 times higher than the other emission systems connected to the geothermal system.

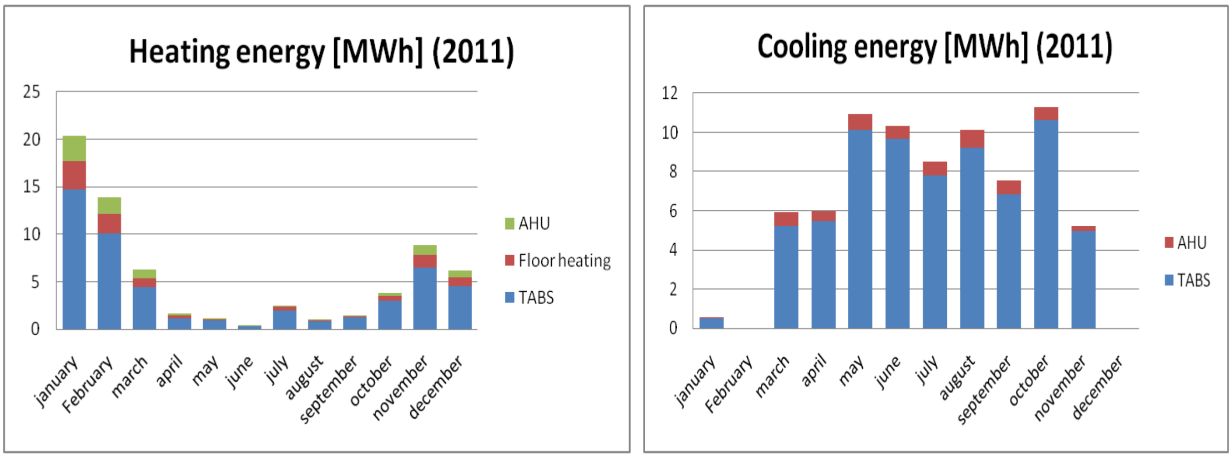


Figure 4-16: Heating (left) and cooling (right) load of geothermal system of building C

4.4.3 Building D

Concerning the building D, results are presented in Figure 3-4. Again for this building, it can be seen that heating and cooling energy are not provided at the same time. Indeed, due to the seasonal “change over” system by the system manager, it is not possible to provide heating and cooling energy in the same time. Moreover, Table 3-3 presents the energy balance of the 2 heat pumps.

As it is shown in Table 3-3, the energy balance is completely wrong from April 2011: as mentioned in section 3.3, data after March 2011 is not reliable. This Table also shows that the second heat pump shows a better COP than the first one. This observation has also been done during the daily analysis.

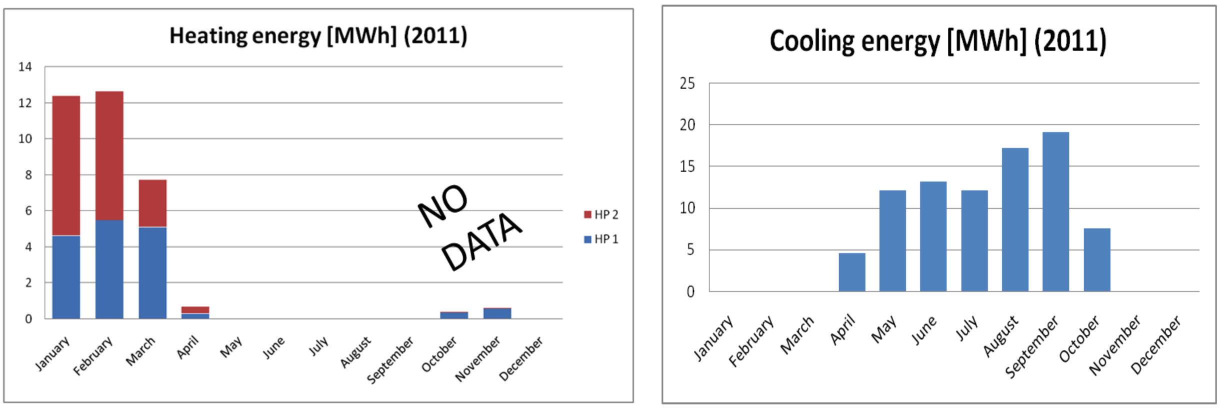


Figure 4-17: Heating (left) and cooling (right) load of geothermal system of building D

Table 4-4: Energy balance of the 2 heat pumps (building D)

	HP 1		HP 2	
	COP	Balance	COP	Balance
January	3.3	-8.8%	3.7	-15%
February	3.4	-8.1%	3.8	-13%
March	4.1	-2%	4.5	-23%

April	0.3	-326%	0.7	-227%
…				
SCOP	2.1		3.3	

The monthly cooling and heating energies provided by the TABS systems are shown in Figure 4-18. Contrary to buildings A and B, the cooling energy is larger than the heating energy. This is partially explained by the fact that the TABS is not fully used in heating mode, because of the good thermal insulation if the building and the large internal gains (the sizing of the heating plant did not account for internal gains).

It should also be mentioned that the geothermal heat pump system could also be used to preheat the water before entering the boiler, what would limit the use of the boilers.

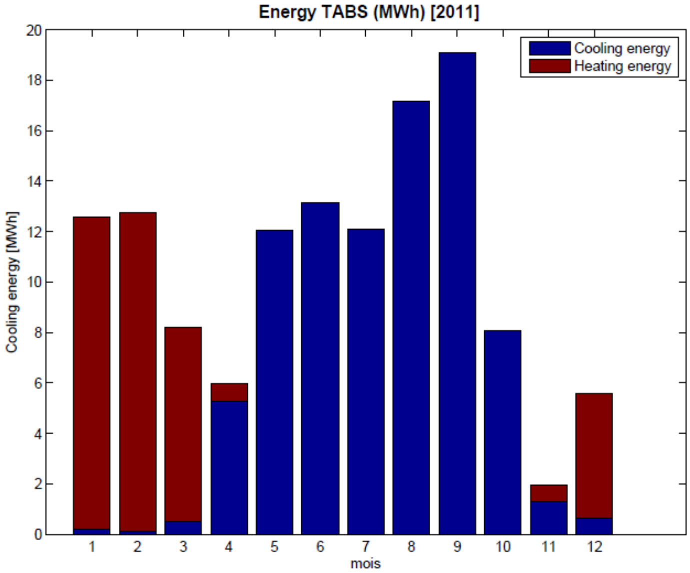


Figure 4-18: Monthly cooling and heating energies provided by the TABS (building D)

4.5 Daily analysis

4.5.1 Building A

Representative cold day

Figure 4-19 presents the evolution of the outdoor temperature on the 26th of January 2010. As it can be seen, it is a very cold winter day with temperature ranging between -8°C and -12°C.

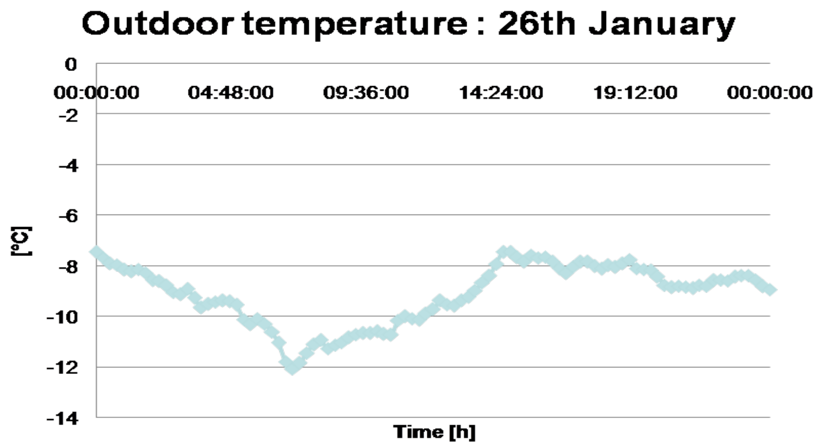


Figure 4-19: Time evolution of the outdoor temperature during a typical winter day (building A)

The evolution of the thermal and electrical powers of the heat pump is shown in Figure 4-20. The red curve is the outlet thermal power, the blue curve is the inlet thermal power and the green curve is the electrical power consumption. The green curve shows the 3 electrical power levels of the heat pump (as it is composed of 2 compressors):

- 2 compressors ON: electrical power ≈ 20kW
- 1 compressor ON, 1 compressor OFF: electrical power ≈ 10kW
- 2 compressors OFF: electrical power = 0kW

Moreover, as it is a cold winter day, it can be seen that the heat pump operates at full load (2 compressors ON) most of the time in order to deliver a high heating power (around 85kW).

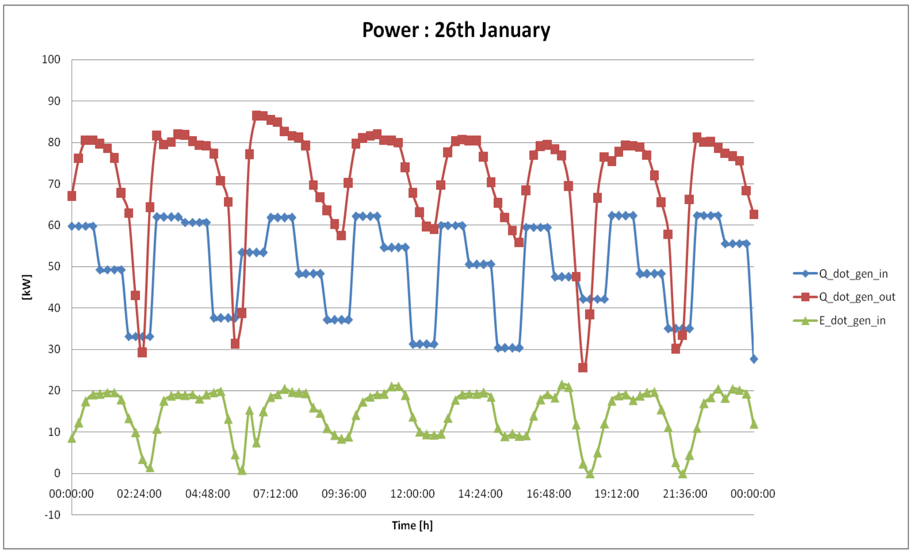


Figure 4-20: Time evolution of the thermal and electrical powers of the heat pump during a typical winter day (building A)

For this typical winter day, the COP is around 4.82 which is lower than the SCOP previously computed because of the very cold weather conditions that involve producing heat at a higher temperature (see control strategy).

Representative hot day

Figure 4-21 shows the evolution of the outdoor temperature on the 26th of June 2010. The weather conditions are those of a typical summer day with temperature between 18°C and 25°C.

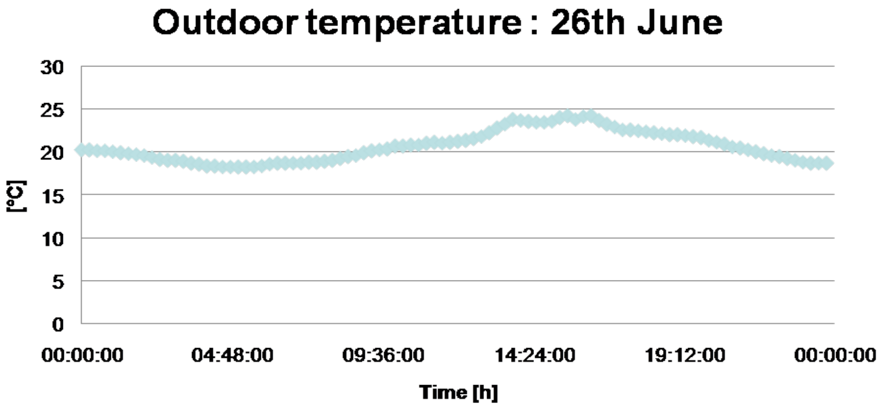


Figure 4-21: Time evolution of the outdoor temperature during a typical summer day (building A)

As mentioned previously, the cooling needs are produced by free chilling and thus, the circulating pumps (on ground and TABS sides) are the only energy consumers. This involves high energy performance with EER around 47.2.

4.5.2 Building C

Representative cooling week

The analysis of the operation of the cooling plant for a representative cooling week is carried out in this section. The hydraulic scheme of the plant working in geo-cooling operation is represented in Figure 4-22.

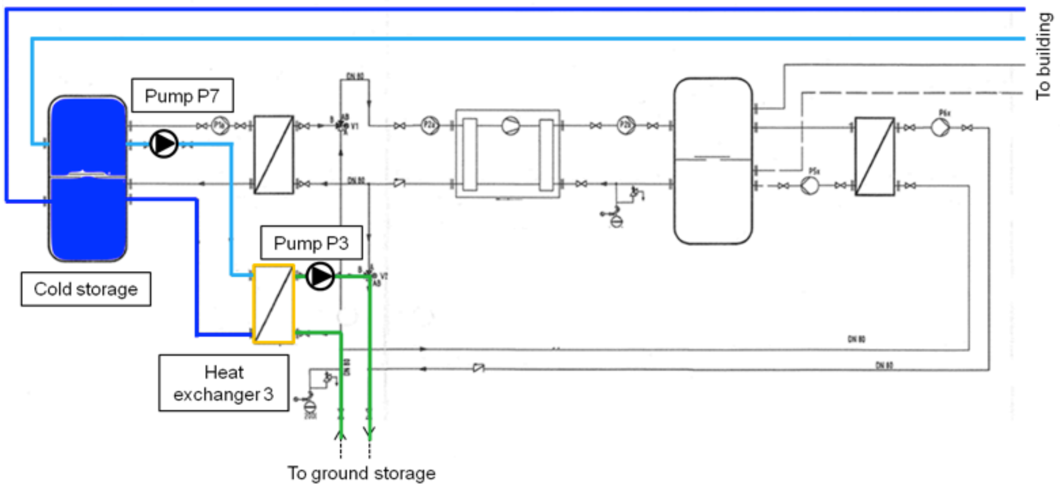


Figure 4-22: Hydraulic scheme of the cooling plant in geo-cooling mode (building C)

Figure 4-23 shows the time evolution of the outside air temperature for a representative cooling week. It should be mentioned that this temperature is measured on the roof of the office building, what results in an overestimation of the outside air temperature.

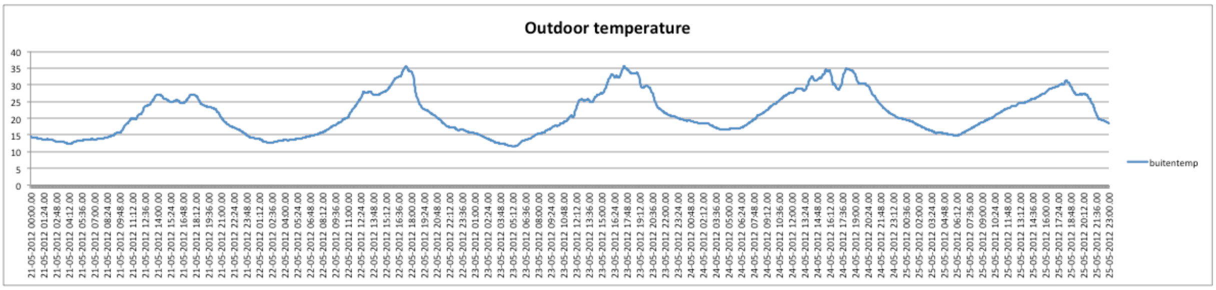


Figure 4-23: Time evolution of the outdoor temperature (building C)

Figure 4-24 shows the time evolution of the temperature in different rooms. It could be observed that at the end of the week, it takes a longer time to remove all the heat out off the building (the 3-way valve is fully open over a longer period). The start of the working day can be observed (with a slow delay which is logic in this kind of building) in the room temperature graph.

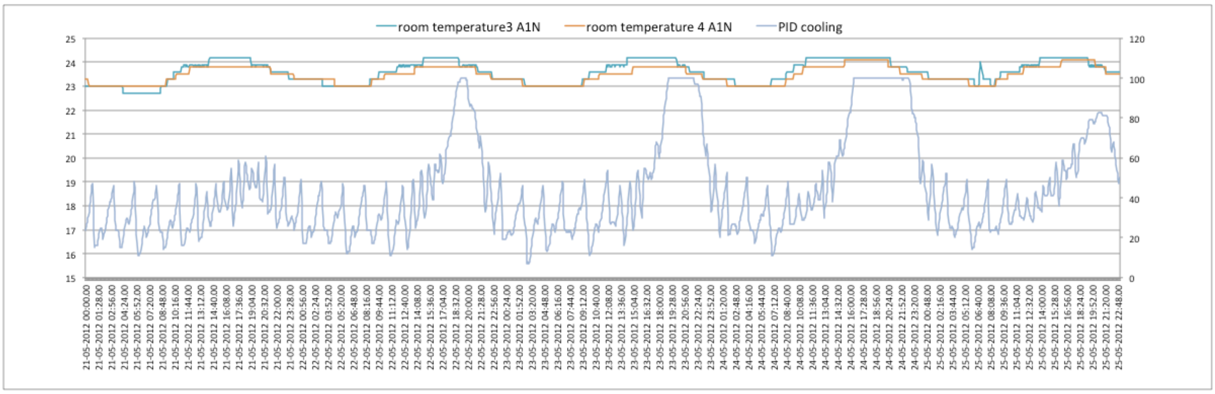


Figure 4-24: Time evolution of the room temperature (building C)

The evolution of the water supply and return temperatures in one of the TABS elements (A1N: TABS element on the north side of the 1st floor and supplied by water circuit from the technical shaft A) is shown in Figure 4-25. The evolution of the position of the 2-way valve is also represented in this figure. It can be seen that after 10 minutes of opening, the valve is maintained open when the temperature difference is too high (it remains open until the temperature difference is lower than 2 K). This phenomenon occurs more often in the circuit in the ceiling than in the floor, because of the better heat transfer in cooling mode in the ceiling.

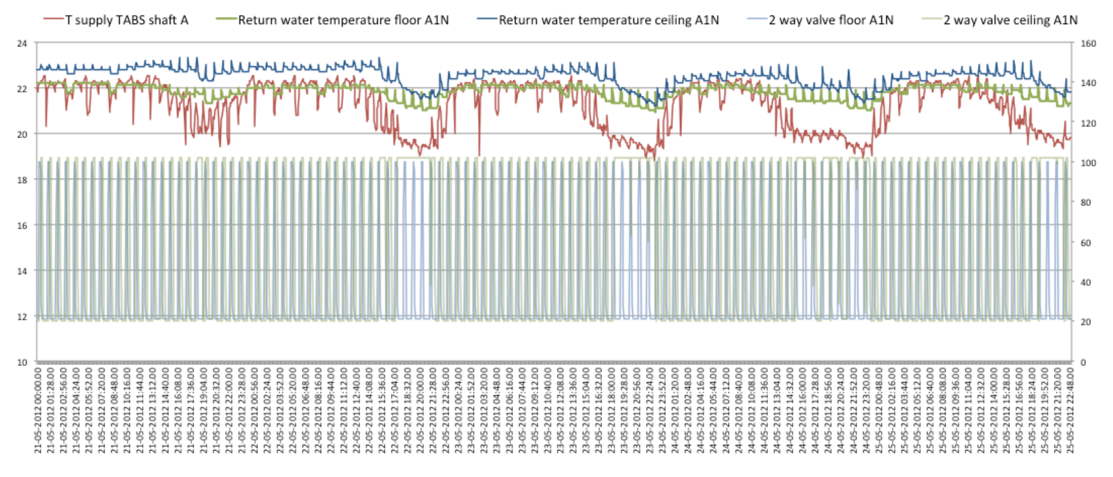


Figure 4-25: Supply and return water temperatures of a TABS portion (building C)

Figure 4-26 shows the operation in geo-cooling mode: the temperature of the ground is much lower than the set point supply water temperature (defined via cooling curve). It can also be seen that the set point supply temperature is calculated based on the 6-hour average outdoor temperature. Hence, the minimum supply set point temperature is always these 6 hours later than the peak in outdoor temperature.

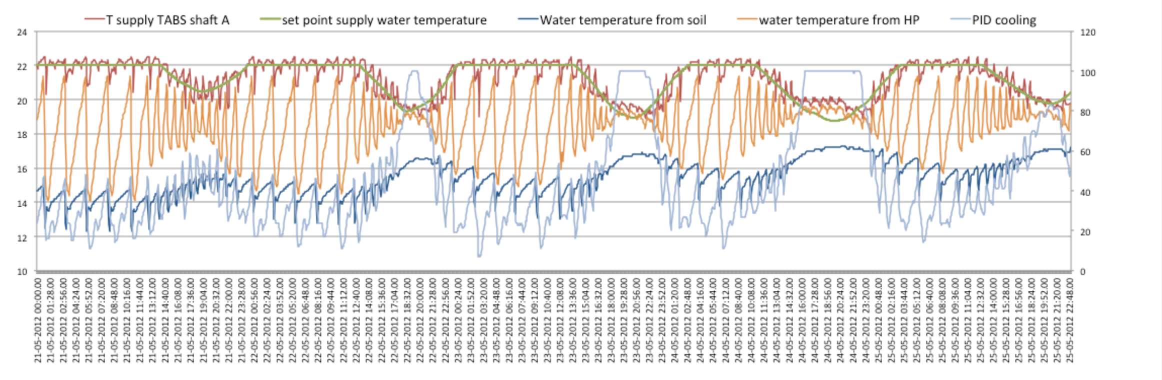


Figure 4-26: Temperatures at different locations between the ground and the TABS (building C)

Figure 4-27 indicates that the set point is reached during most of the time, except for the 24th in the evening. Probably, the cooling load of the whole building was too high at that moment and most of the 2-way valves were open. Consequently, half of the return flow from the TABS is mixed with the cold supply temperature of the free-cooling unit of the heat pump, because of hydraulic reasons. Actually, the flow of the primary pump (before the bypass and the 3-way valve) has only half of the nominal flow as the circulating pumps of the TABS (28 vs 48 m^3/h).

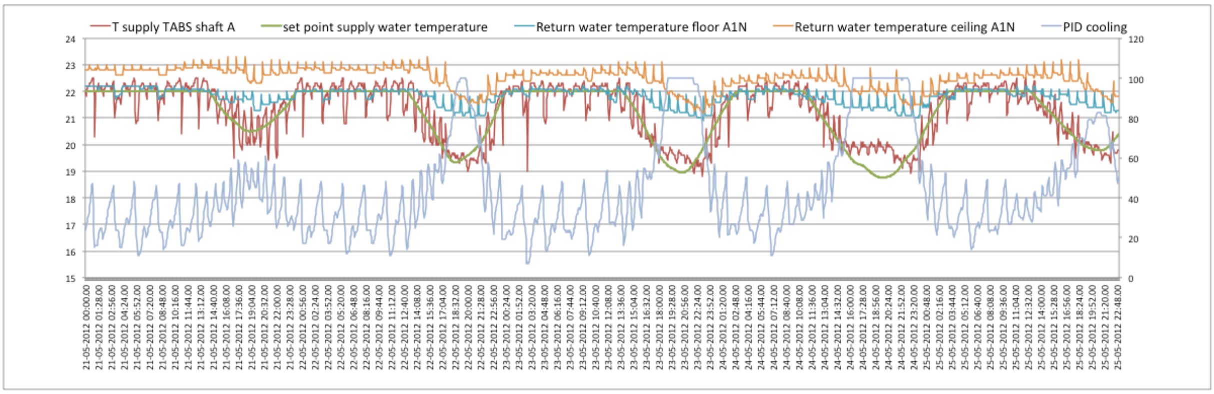


Figure 4-27: Supply, return and set point water temperatures of a TABS portion (building C)

Representative heating week

The hydraulic scheme of the heating plant is given in Figure 4-28.

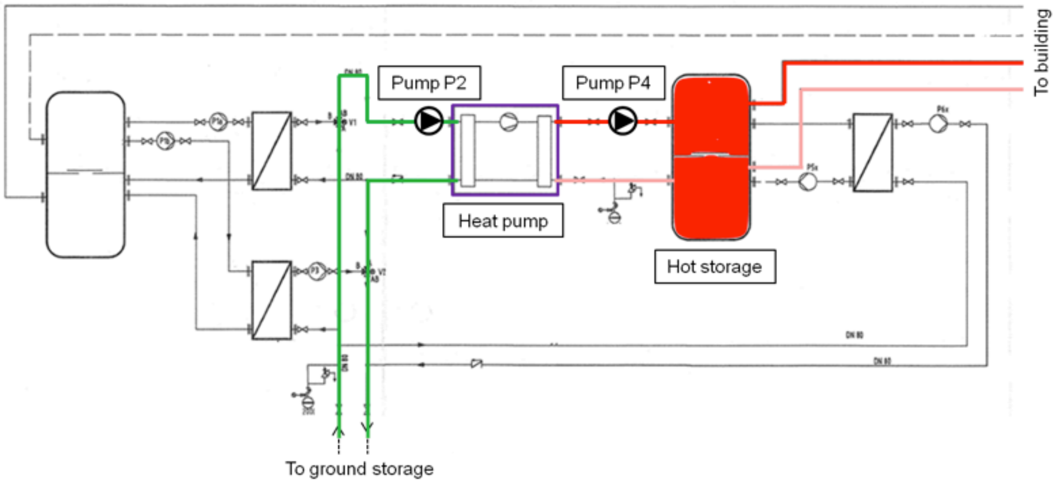


Figure 4-28: Hydraulic scheme of the heating plant (building C)

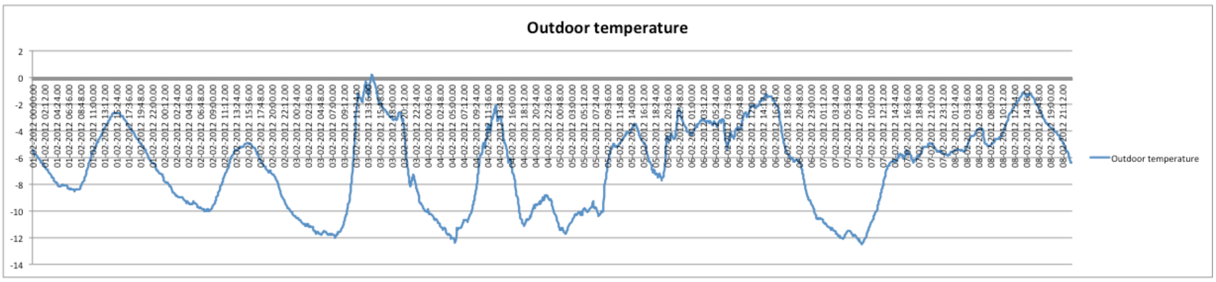


Figure 4-29: Time evolution of the outdoor temperature (building C)

The evolution of the room temperatures is given in Figure 4-30. It can be seen that the whole installation has been switched off during the weekend in order to identify the building model parameters. In normal practice, such a behavior should not occur and the TABS installation keeps working in the same regime as during the week. From the 3 days, we can conclude that the room temperatures are very stable. This is due to the large inertia of the building and its high insulation from the outdoor environment.

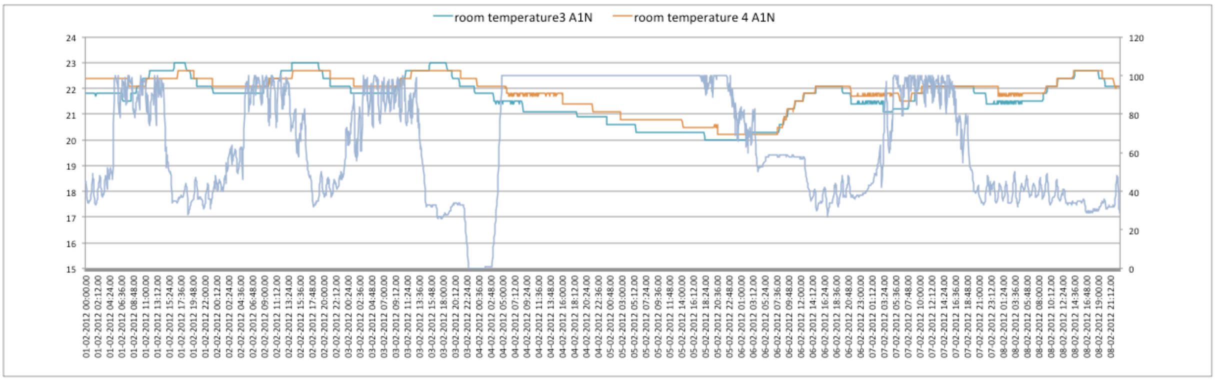


Figure 4-30: Time evolution of the room temperature (building C)

If the period right after the cooling down experiment is not taken into account, acceptable room temperatures could be reached by opening the 2-way valves for periods of only 10 minutes. It never happens that the 2-way valve has to open for a longer period, because the temperature difference after this 10 minutes period is always lower than the set point on this temperature difference (2K).

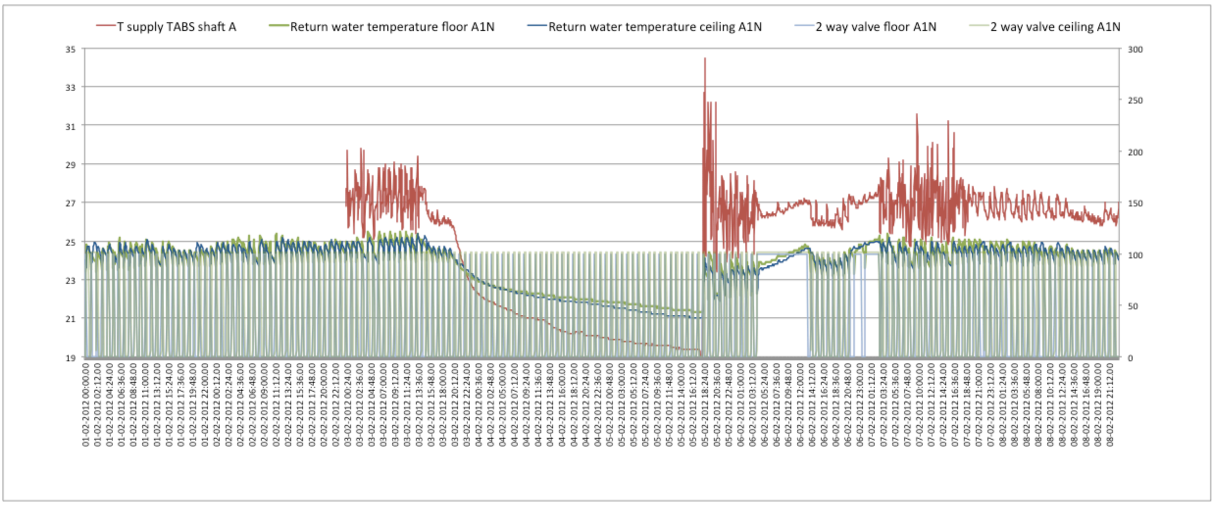


Figure 4-31: Supply and return water temperatures of a TABS portion (building C)

Figure 4-32 indicates that the set the set point at the heat pump outlet is 3K higher than the set point on the TABS supply in order to cover heat losses in the distribution system.

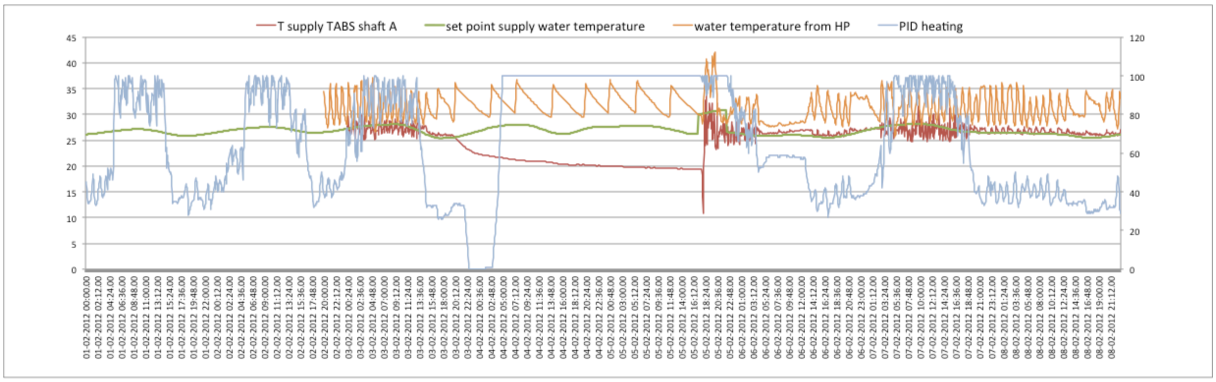


Figure 4-32: Temperatures at the TABS supply and heat pump exhaust (building C)

4.5.3 Building D

Representative cold day

Figure 4-33 shows the evolution of the outdoor temperature for a typical cold day (March 7th, 2011), characterized by an average outdoor temperature of 2.65°C.

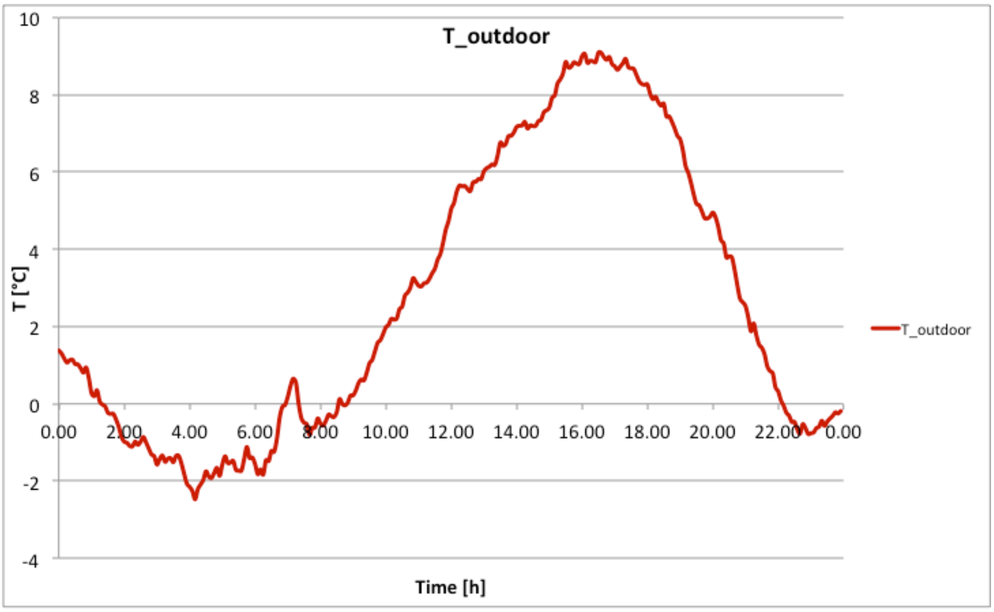


Figure 4-33: Time evolution of the outdoor temperature for a typical winter day (building D)

The time evolution of the temperatures inside different zones of the building and of the water at the TABS inlet is given in Figure 4-34. It could be observed that, during the day, the TABS supply temperature is comprised between the minimum and maximum zone temperatures. Increasing the TABS supply temperature would certainly lead to overheating in the warmest zones of the building. This is the reason why the set point on the TABS supply temperature is so low (around 22.5°C).

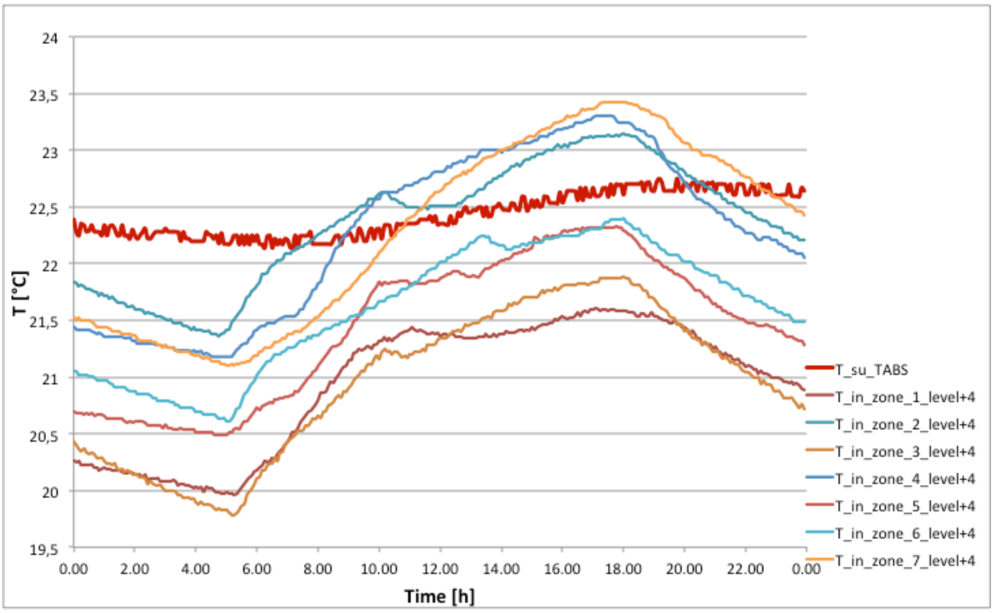


Figure 4-34: Time evolution of different zones and water supply TABS temperature for a typical winter day (building D)

The use of the TABS during the night prevents the temperature not to drop too fast. For this particular day, the use of the TABS during daytime prevents the temperature of the warmest zones not to increase too much (prevent overheating). The extracted heat from the hot zones is re-injected in the coldest zones. The TABS system works as water loop heat pump: heat is transferred from the hot zones to the cold zones through the water loop. The deficit in heating capacity is provided by the geothermal heat pump system. If the system were operating as it was designed, the red curve (supply temperature of the TABS) would have been above the other curves. This difference in operation is probably due to an underestimation of internal gains.

The set point on the water temperature at the exhaust of the condenser is around 31°C. In order to reach the set point on the water temperature at the supply of the TABS (around 22.5°C), the flow rate from the condenser is mixed with a fraction of the flow rate coming back from the TABS.

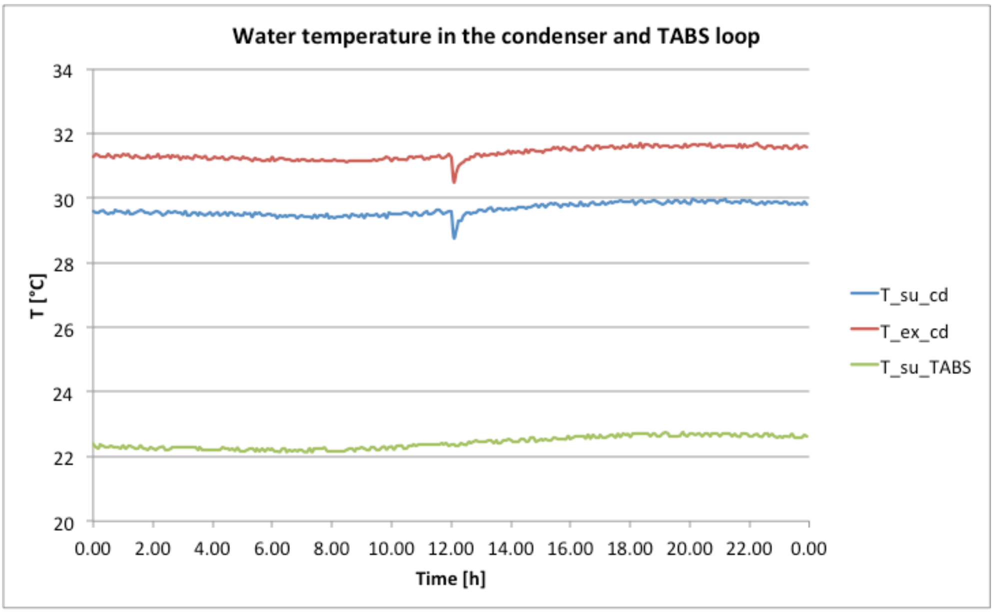


Figure 4-35: Time evolution of the condenser supply and exhaust water temperatures and TABS supply temperature (building D)

The average COPs during that day are given in Table 4-5. The definitions of those COPs are identical to those introduced for the seasonal analysis (see Table 4-2). Similarly to what has been found during the seasonal analysis, the electrical consumptions of the different pumps largely decrease the COP of the heat pump system.

Table 4-5: Daily COP during a representative cold day (building D)

COP_1	[-]	3.2
COP_2	[-]	2.3
COP_3	[-]	2.0
COP_4	[-]	1.7

From this daily analysis, the following recommendations could be drawn:

1) Control independently the water temperatures or flow rates in the different zones of the TABS. The currently used unique control is probably due to the open plan office.
2) Use variables speed pumps, in order not to operate the pumps at their maximal flow rates in part load conditions

Representative hot day

Figure 4-36 shows the evolution of the outside temperature on the 2nd of August 2011. The average temperature over the day was 21.96°C. The evolution of the outside temperature is compared to the evolution of the temperature inside several zones of the building.

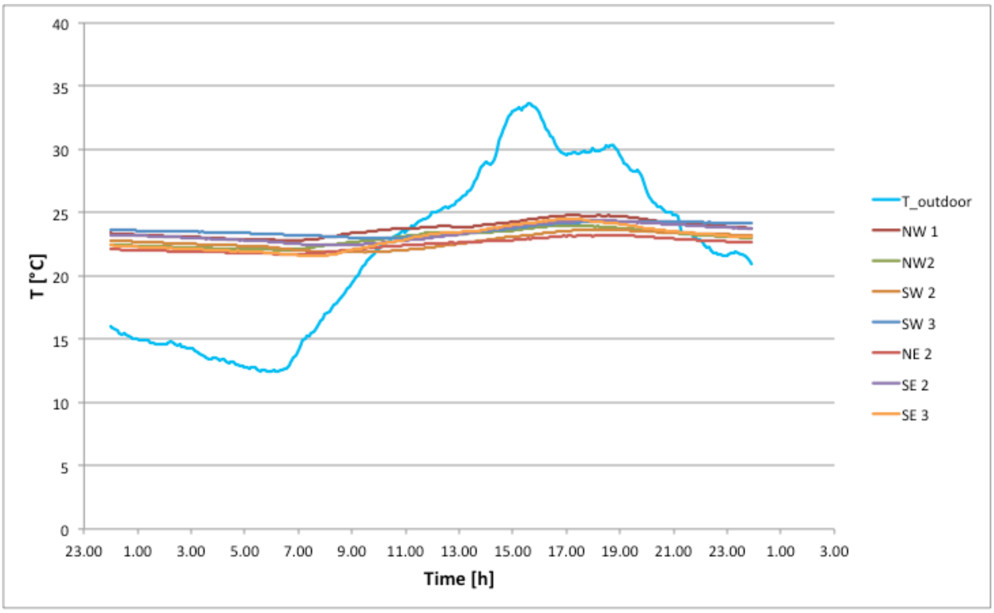


Figure 4-36: Time evolution of the outdoor temperature for a typical summer day (building D)

Figure 4-37 gives the evolution of the temperatures in different zones of the buildings as well as the TABS supply temperature. The different zones are cooled down by the TABS that works 24 hours with the same supply temperature.

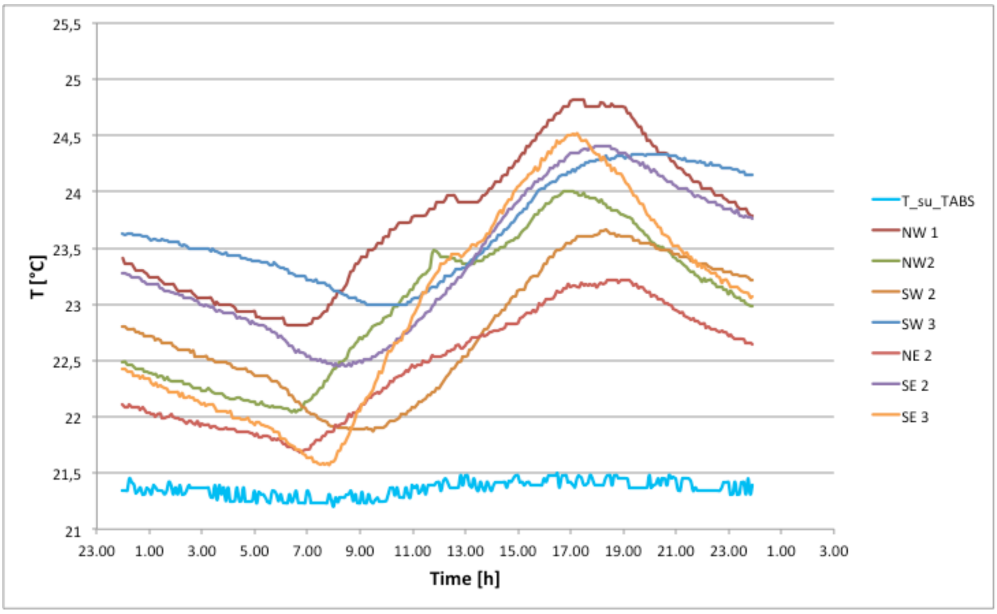


Figure 4-37: Time evolution of different zones and water supply TABS temperature for a typical summer day (building D)

At 7 am, the fancoil units and the ventilation systems are switched on and the outside temperature starts to increase, what explains the increase in the zones temperatures. Until 1 pm, the supply TABS temperature continuously increases. At 1pm, the 3-way valve is progressively opened, allowing more energy to be extracted from the borehole heat exchanger. Consequently, the TABS supply temperature is maintained around 21.5°C.

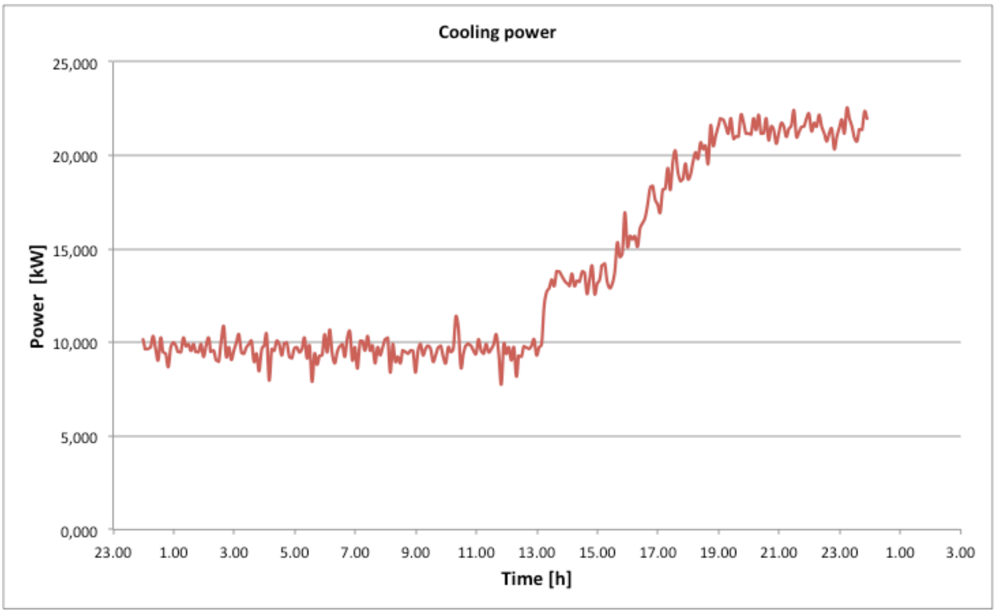


Figure 4-38: Time evolution of different zones and water supply TABS temperature for a typical summer day (building D)

During that day, the following SEER are evaluated:

Table 4-6: Daily SEER during a representative hot day (building D)

EER_1	[-]	-
EER_2	[-]	3.4
EER_3	[-]	2.7
EER_4	[-]	1.9

5 Comfort analysis

A long term thermal comfort analysis has been performed in all buildings except building A. It was based on the two following criteria of the norm EN15251:

- Performance outside the range: the number or percentage of occupied hours when the PMV (Predicted Mean Vote) or the operative temperature is outside a specific range.
- Degree hours: the time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor that is a function depending on how many degrees the range has been exceeded.

5.1 Building A

Unfortunately, there was no data available concerning the thermal comfort in building A.

5.2 Building B

The occupied hours of the building are 08:00 AM till 6:00 PM, Monday till Friday. The acceptable temperature ranges given by the second category of norm EN15251 (CEN, 2007) are 20-24°C in winter and 23-26°C in summer. In our case, winter conditions are assumed during heating period, e.g. if outdoor temperature is lower than 18°C, while summer conditions are assumed during cooling period, e.g. if outdoor temperature is higher than 22°C. Figure 6-1 shows the indoor temperature in function of the outdoor temperature that occurred in a representative zone of the building B in 2009 and Table 6-1 and 6-2 summarize the results of the comfort analysis for the entire building. As it can be seen, overheating never occurs, neither in winter, nor in summer. However, temperatures under the acceptable range appear in both seasons. In winter, too low temperatures occur in average 10% of the time but in summer, this phenomenon occur more than 60% of the time. This difference can be explained by the fact that the requirement for the comfort in the building was set based on standard DIN 1946-T2 (DIN, 1994), which allows lower temperatures in summer (see Figure 6-2). Nevertheless, having too low temperatures in summer compared to EN15251 means that increasing the energy savings is still possible by reducing the cooling energy produced.

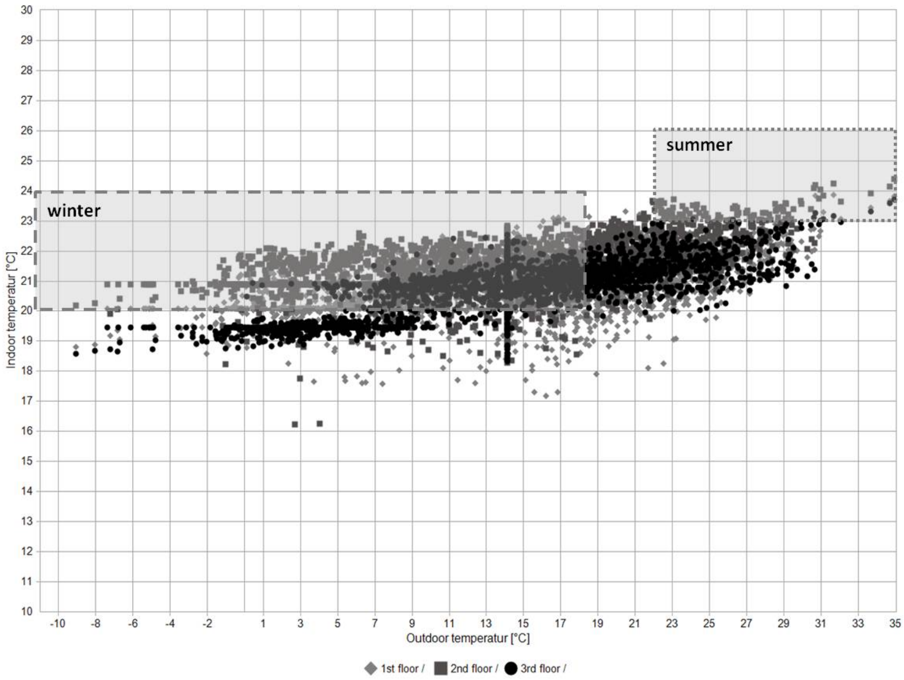


Figure 5-1: Indoor temperature of southeast zone each hour in 2009 (building B)

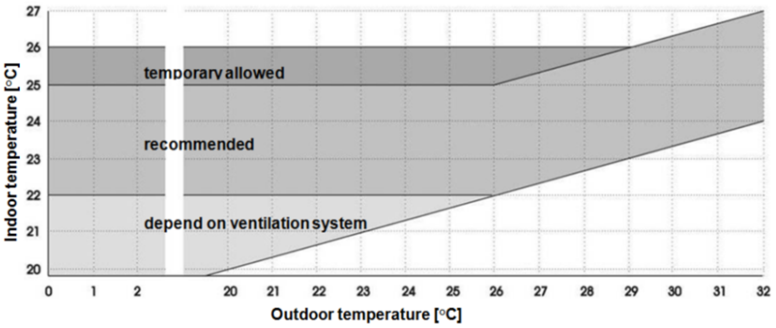


Figure 5-2: Limits for operative temperature according to DIN 1946-T2

Table 5-1: Temperature outside the range (building B, 2009)

	Winter				Summer			
	Excess	Under	Total		Excess	Under	Total	
	[h]	[h]	[h]	[%]	[h]	[h]	[h]	[%]
North 1stfloor	0	0	0	0	0	167	167	46
Southeast 1stfloor	0	260	260	15	0	357	357	98
Southwest 1stfloor	0	53	53	3	0	276	276	76
Southeast 2ndfloor	0	122	122	7	0	270	270	74
Southwest 2ndfloor	0	53	53	3	0	256	256	70
Southeast 3rdfloor	0	381	381	22	0	354	354	97
Southwest 3rdfloor	0	1	1	0	1	125	126	35
Total working hours (by zone)	1749				364			

Table 5-2: Degree hours outside the range (building B, 2009)

	Winter			Summer		
	Excess	Under	Total	Excess	Under	Total
	[degree h]	[degree h]	[degree h]	[degree h]	[degree h]	[degree h]
North 1stfloor	0	0	0	0	54	54
Southeast 1stfloor	0	172	172	0	541	541
Southwest 1stfloor	0	26	26	0	200	200
Southeast 2ndfloor	0	74	74	0	232	232
Southwest 2ndfloor	0	29	29	0	174	174
Southeast 3rdfloor	0	223	223	0	479	479
Southwest 3rdfloor	0	0	0	0	157	157

5.3 Building C

Thermal comfort in building C has been investigated based on the comfort envelope defined by Ashrae Standard 55-2004. The comfort is assed during the period extending from August 5 to 8, 2011. The comfort envelope is represented in the axes RH vs operating temperature in Figure 5-3 for an occupant characterized by clothing of 0.5 clo (summer clothing) and a metabolism of 1.1 met. The measurement points are superimposed to this figure. It can be deduced that occupant will feel too cold during that period.

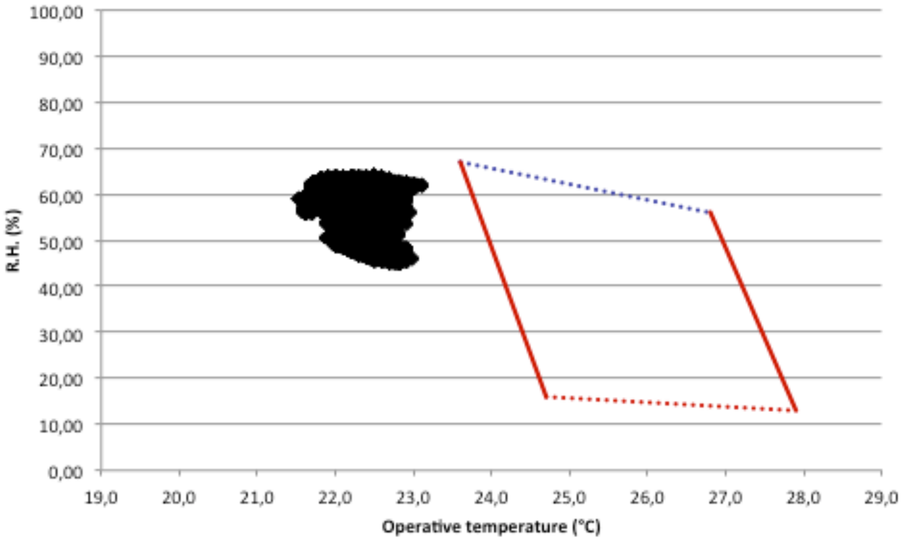


Figure 5-3: Comfort envelope defined in the RH and operative temperature axes (0.5 clo and Met 1.1) and actual operating points (building C)

As shown in Figure 5-4, adaptation of the clothing (from 0.5 to 1.0 clo) could allow shifting the comfort envelope in such a way to integrate the operating points. Another way to ensure thermal comfort in the building would consist in increasing the set point temperature in the zones, yielding energy savings.

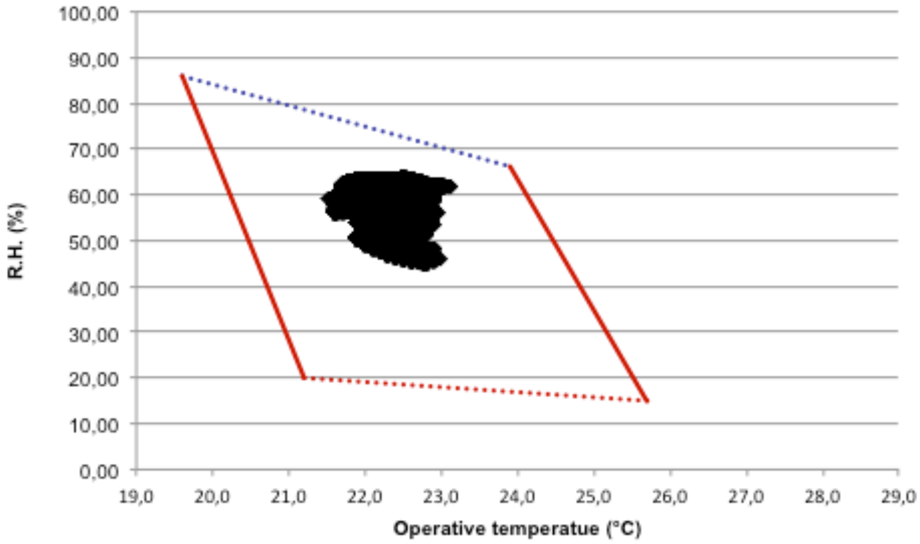


Figure 5-4: Comfort envelope defined in the RH and operative temperature axes (1.0 clo and Met 1.1) and actual operating points (building C)

5.4 Building D

For the year 2011, indoor air temperature data were available from first to fifth floor in the building D. The BMS is actually recording 11 or 12 temperatures in each floor (sampling rate 15 minutes). These sensors are used by quarter of floor to control the fan coils using average value of the 2 or 3 sensors recording inside this quarter of zone. These data were used to perform a thermal comfort analysis also based on the CEN Standard EN15251 (previously defined) and only during the operating schedule of the building (5am – 9pm Monday to Friday).

The 2 ranges of acceptable temperature are here applied in term of heating or cooling mode of the TABS (TABS working respectively with the 2 heat pumps or the heat exchanger). The results obtained are presented in the following table.

Table 5-3: Degree hours outside the range (building D, 2011)

	Heating Mode (TABS)			Cooling Mode (TABS)		
	Excess [h]	Under [h]	Total [h]	Excess [h]	Under [h]	Total [h]
Northeast 1st floor	4	43	47	0	25	25
Southeast 1st floor	3	241	244	0	591	591
Northwest 1st floor	0	128	128	0	184	184
Southwest 1st floor	1	182	183	0	784	784
Northeast 2nd floor	0	380	380	0	470	470
Southeast 2nd floor	3	44	47	0	56	56
Northwest 2nd floor	0	163	163	0	233	233
Southwest 2nd floor	0	509	509	0	581	581
Northeast 3rd floor	0	86	86	0	28	28

Southeast 3rdfloor	1	222	223	0	378	378
Northwest 3rdfloor	0	184	184	0	345	345
Southwest 3rdfloor	0	132	132	0	159	159
Northeast 4thfloor	0	271	271	0	513	513
Southeast 4thfloor	3	91	94	0	114	114
Northwest 4thfloor	0	102	102	0	73	73
Southwest 4thfloor	2	76	78	0	106	106
Northeast 5thfloor	0	310	310	0	275	275
Southeast 5thfloor	0	125	125	0	269	269
Northwest 5thfloor	0	130	130	0	27	27
Southwest 5thfloor	1	150	151	0	426	426

From these results, one can observe overheating rarely occurs neither in heating nor in cooling mode. However, it appears for both modes that temperatures inside the zones are lower than the expected range. These observations are similar to the ones observed in building B thermal comfort analysis. In this building, the indoor temperature set point, especially during cooling mode (around 21°C) are not consistent with the CEN standard (23°C – 26°C) used for the thermal comfort analysis. This set point could still be modified to increase energy savings in term of chilled or cooled water needs.

5.5 Building E

Only the temperatures are being measured in the open-space offices of the building. The building is occupied between 08:00 and 18:00, from Monday till Friday. The set point temperature in winter and summer can be manually set between 22.5°C and 23 °C.

Figure 6-4 shows that, at ground floor, temperatures diverge a bit in winter and in summer but it is reasonable. Figure 6-5 shows that, at the first floor, the temperature is totally inside the range in winter but diverges a lot in summer. This Figure is also representative of what happens at the second floor.

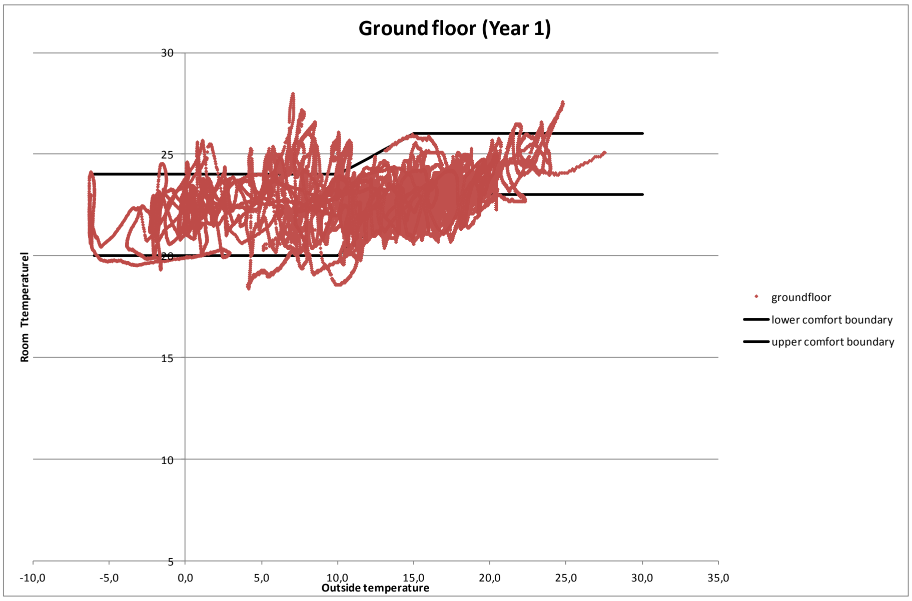


Figure 5-5: Room temperature at ground floor each 8 min (building E, 2010)

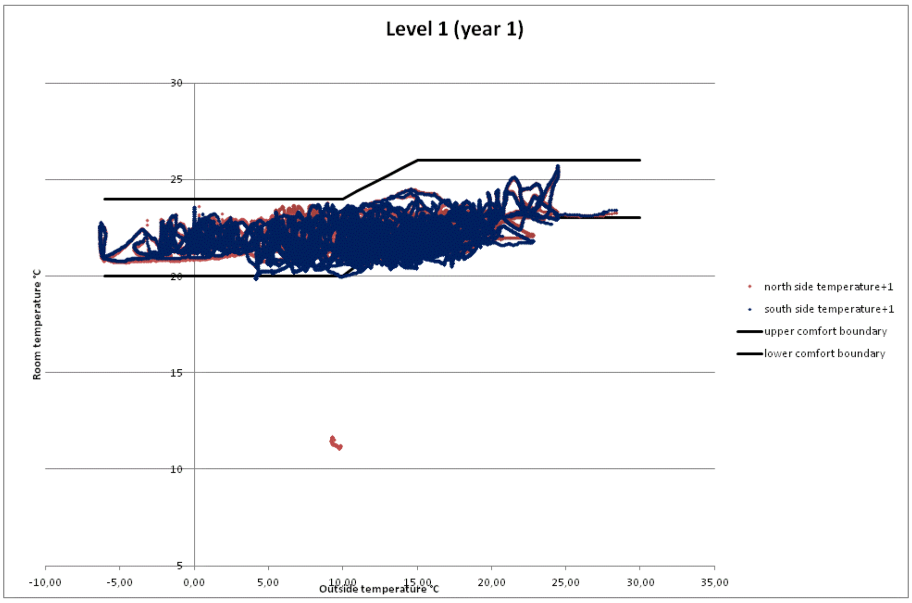


Figure 5-6: Room temperature at 1st floor each 8min (building E, 2010)

6 Economic and environmental interest assessment

6.1 Cost reduction

Table 5-1 presents an estimation of the running cost reduction allowed by the use of geothermal energy. In order to assess this reduction, costs have been compared to an average cost of 0.08€/kWh for district heating and to an electricity cost of 0.12€/kWh for the chiller, compressor of the heat pump and circulating pump on ground side, according to the German Federal Statistical Office. Moreover, a COP of 2.5 and an efficiency of 95% are chosen respectively for the chiller and for the district heating.

The results show that the use of geothermal energy allows, for buildings A and B respectively, a reduction of round 12,000€/year and 5,000€/year in comparison with a traditional heating and cooling system.

Table 5-1: Estimation of the cost reduction

	Energy [MWh/year]		Averagecost [€/kWh]	Traditionalcost [€/year]		Geothermalcost [€/year]	
	A	**B**		**A**	**B**	**A**	**B**
Traditional							
District heating	171.3 / 0.95 = 180.3	90.5/0.95 =95.3	0.08	14,424	7,624	-	-
Chiller	46.47 / 2.5 =18.58	19.69/2.5 =6.7	0.12	2,229.6	804	-	-
Geothermal							
	37.2	27.04	0.12	-	-	4,464	3,244
Total energycost				16,653.6	8,428	4,464	3,244
Energycostsavings						12,189	5,184

6.2 CO2 reduction

The assessment of the reduction of CO_2 emissions is also based on the comparison with traditional district heating and chiller. The CO_2 emission factors are 219 gCO_2/kWh and 633 gCO_2/kWh, respectively for district heating and electricity (Gemis 4.5, InstitutWohnen und Umwelt GmbH, Germany).

Results show that the use of geothermal energy allows for a reduction of round 27 tons of CO_2 per year and 8 tons of CO_2 per year for buildings A and B respectively.

Table 5-2: Estimation of the CO_2reduction

	Energy [MWh/year]		CO_2emission [gCO_2/kWh]	Traditional CO_2 emission [$kgCO_2$/year]		Geothermal CO_2 emission [$kgCO_2$/year]	
	A	**B**		**A**	**B**	**A**	**B**
Traditional							
District heating	171.3 / 0.95 = 180.3	90.5/0.95 =95.3	219	39,485	20,870	-	-
Chiller	46.47 / 2.5 =18.58	19.69/2.5 =6.7	633	11,761	4,241	-	-
Geothermal							
	37.2	27.04	633	-	-	4,464	3,244
Total CO_2emission				51,246	25,111	23,547	17,116
CO_2reduction						27,699	7,995

7 Conclusions

The energy and thermal comfort performance of 5 different buildings (A and B located in Germany and C, D and E located in Belgium) were analyzed based on monitoring data. These buildings showed large differences in terms of net floor area, design of the HVAC plant (and its control) and quality of the monitoring information. The energy performance was analyzed on the seasonal (yearly), monthly and daily bases.

Seasonal performance analysis

The comparison of the seasonal energy performance of the 5 buildings indicated that, except for building D, the part of the heating load provided by the geothermal heat pump is still limited. In the German buildings, the major part of the heating demand is provided by a district-heating network. In the Belgian buildings, it is provided by boilers. The limited use of the geothermal heat pump for heating may be due to a too conservative design of the HVAC plant. For instance, in building D, only the TABS is connected to the geothermal heat pump, while the fan-coil units and AHUs are fed by the boiler. However, performance of building C demonstrates that the geothermal heat pump could cover almost the entire heating load of a commercial building.

It was observed that the part of the heating load covered by the TABS is limited. Except for building C, the TABS provides from 8 to 14% of the heating load.

Results in cooling mode are different. The geothermal heat pump (working in active cooling or in geocooling modes) could provide much of the cooling load. The TABS covers almost the entire cooling load (more than 75%) or even the total load (building A).

Except for building A, whose heat pump performance is much larger, building B, C and D show similar seasonal coefficients of performance in heating mode (SCOP). However, accounting for circulating pumps, this coefficient of performance can be dramatically decreased. This is the case of the building D whose SCOP drops from 3.56 to 1.23 when electricity consumption of ground heat exchanger circulating pumps, condenser pumps, and TABS pumps are taken into account. In cooling, SEER up to 21.0 can be achieved.

Monthly energy analysis

Monthly analysis allows distinguishing the impact of climate on the cooling/heating loads. For the buildings A and B, the part of the heating load covered by the TABS is limited, while the latter covers almost the entire cooling load.

The most frequent problems encountered during the analysis of the measurements are:

- The lack of relevant sensors. Here are a few examples. In buildings D, only the TABS supply temperature is provided but not the return temperature. In building D, there is no measurement of the gas consumption on hourly or daily bases. The cost of installing a gas flow meter would be prohibitive. In building E, there are no measurements of the electricity consumption.

- The low temperature differences (lower than 2K), which results in a very large uncertainty on the energy loads measured by calorimeters. These low temperature differences are characteristic of low-temperature heating and high-temperature cooling systems. It is recommended to conduct a commissioning of the heat-meters (check the position of the temperature sensors and their insulation). When possible, heat balances across components should be expressed in order to check the plausibility of the measurements. The compressor or the heat pump themselves could also be used as calorimeters using performance tables indicated in manufacturer's datasheets. In that case, the knowledge of the heat pump evaporating and condensing pressures could be really useful. Low temperature differences may also be due to large oversizing of the pumps (this is the case in building D). In that case, there is still margin for performance improvement.

Daily analysis

Daily analysis allows better understanding the control of the HVAC plant. The analysis of both the energy performance and the thermal comfort can also be conducted in parallel, what allows pointing out technical limitations. For instance, in building D, the TABS supply temperature is limited by the overheating in the warmest zones of the buildings. Having a separate control for the different portions of the TABS would enable increasing the part of the heating load provided by the TABS in the coldest zones.

Thermal comfort

Analysis of the thermal comfort indicates that there is seldom overheating in the investigated buildings. However, three of the investigated buildings (buildings B, C and D) shows significant fractions of time where overcooling is observed. Hence, energy savings could be achieved by decreasing the cooling energy provided by the HVAC plant (by increasing the air temperature set point during cooling operation).

8 References

Bockelmann, F., Kipry, H., Fisch, M. N., 2010: Forschungsbericht: WKSP – Wärme- und Kältespeicherung im Gründungsbereich energieeffizienter Bürogebäude, BMWi Fkz 032736A,

Bockelmann, F., Kipry, H., Fisch, M. N., 2011: Erdwärme für Bürogebäude nutzen, BINE-Fachbuch im BINE Informationsdienst, Frauenhofer IRB Verlag, Stuttgart, ISBN 978-3-8167-8325-1

Zottl, A., R. Nordman, M. Coevoet, P. Rivière, M. Miara, A. Benon, P. Riederer. 2012: A defined methodology for calculation of the seasonal performance factor and a definition which devices of the system have to be included in this calculation. – Heat pumps with hydronic heating systems; IEE/08/776/SI2.529222; May 31st 2012; pp. 1-18; 2012.