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ABSTRACT

The combination of geothermal heat pumps (GEO HPs) and thermally activated building systems (TABS), that allow both low temperature heating and high temperature cooling, could yield primary energy savings of around 20-71% in comparison with conventional heating/cooling systems. However, the potential energy savings are rarely reached in practice due to bad integration of the different subsystems and inefficient control. The present paper presents the analysis of two monitoring campaigns by stressing the influence of relevant parameters such as the performance of components (heat pump, ground heat exchangers, TABS, etc.), building characteristics and the implemented control strategies. The buildings have been monitored and analyzed in the frame of the WKSP-project realized by Institute of Building Services and Energy Design (IGS) at Technical University of Braunschweig. The results show good performance of ground coupled heat pump with seasonal COP up to around 5. Moreover, the use of ground heat exchangers to perform free chilling allows seasonal EER up to 20. Furthermore, the control strategies implemented in the different buildings are quite different. It is also shown that this system can lead to a running cost reduction up to 50% compared to conventional systems and that CO_2 emissions can be reduced by 40%.

1. INTRODUCTION

Regarding the total energy use world-wide, 38% is used in buildings. Moreover, in the USA, 66% of which was used for HVAC and lighting in 2005 (IEA, 2008; US Department of Energy, 2007). During the past decades, the interest of sustainable office buildings has grown dramatically, due to the depletion of energy resources and the environmental impact of energy use. An important number of new solutions have been proposed as alternative heating and cooling systems. Among these, TABS have emerged as energy efficient and economical solutions.

The principle of TABS is to use massive parts of the building structure as thermal buffer. Usually it consists in pipes embedded into a concrete floor and in which a fluid, typically water, flows through in order to heat or to cool down a room. The large heat exchange surfaces involved in TABS are of great interest because low energy cooling or heating sources can be used (Lehmann B. *et al.*, 2007; Gwerder M. *et al.*, 2008). Moreover, the use of the building's thermal mass allows reducing the peak in energy demand (Rijksen DO. *et al*, 2010; Saelens D. *et al*, 2011).

Within the scope of the European R&D-project "GEOTABS", this article presents a detailed comparison of the performance of two monitored buildings. Investigated buildings are first described in terms of configuration of the cooling and heating plants. Energy performance is analyzed on monthly and seasonal bases and the influence of different control strategies is discussed. First conclusions are finally drawn regarding comfort performance and potential running cost reduction as well as CO_2 emissions.

2. ENERGY CONCEPT

The two monitored office buildings presented in this paper are both located in Germany and have a net floor area of 20,693 m² for building A and round 4,000 m² for building B. The energy concepts of these two buildings are presented in Figure 1 and Figure 2 for building A and building B respectively.

In the case of building A (Figure 1), the geothermal system is composed of 196 energy piles of 9 meters length each. In winter, the geothermal water to water heat pump (106 kW) extracts heat from the ground in order to supply the TABS. The rest of the heat consumption is provided by district heating through radiators, floor heating and ventilation systems. In summer, the entire cooling load is provided by geothermal energy through the TABS (free chilling mode (150kW)).

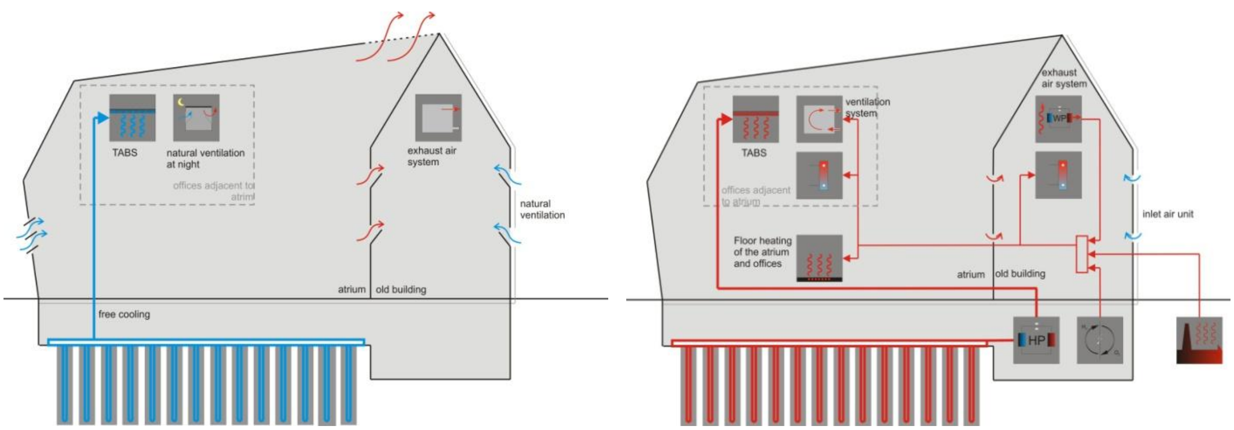

Figure 1: Energy concept of building A for heating (right) and cooling (left) [Source IGS]

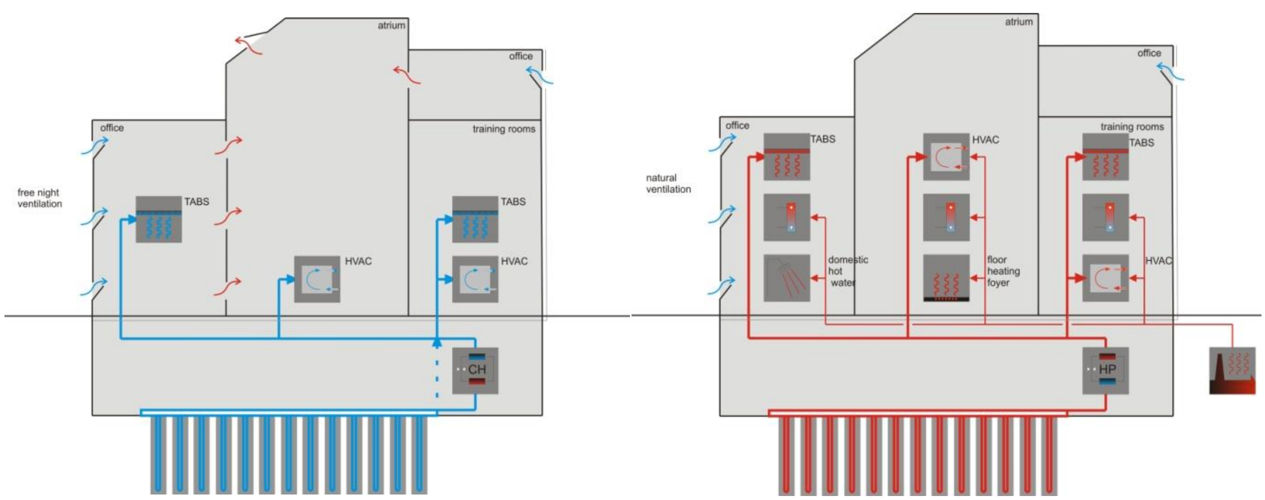

Figure 2: Energy concept of building B for heating (right) and cooling (left) [Source IGS]

For the second building (Figure 2), there are 100 energy piles, with length from 17 to 22 meters. In the wintertime 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 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 the summertime, two cooling modes are planned. 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 then used as a chiller (89 kW). As in wintertime, the soil 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.

3. ENERGY BALANCE AND PERFORMANCE

3.1 Measurement data

The available measurement data cover a period ranging from January 1st, 2010 to December 31st, 2010 and from January 1st, 2009 to December 31st, 2009 for building A and B respectively with a quarter-hourly sampling rate. Moreover, measurements comprise thermal data such as temperatures and water flow rates, but also electrical energy use.

3.2 Seasonal analysis

Based on the thermal data, the thermal powers of the system's components are computed as follows:

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

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, determined by counters placed inside the circuit, [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 exhaust water temperature from the circuit, [°C]

Knowing the electricity consumption of the compressor of the heat pump, its performance in heating and cooling mode are respectively:

$$SCOP = \frac{Q_{h,gen,out}}{W_{h,gen,in}} \qquad [-] \qquad (2)$$

$$SEER = \frac{Q_{c,gen,out}}{W_{c,gen,in}} \qquad [-] \qquad (3)$$

Where:

$SCOP$	is the Seasonal Coefficient Of Performance [-]
$Q_{h,gen,out}$	is the heating energy provided at the condenser of the heat pump [kWh]
$W_{h,gen,in}$	is the electrical energy use of the compressor of the heat pump in heating mode [kWh]
$SEER$	is the Seasonal Energy Efficiency Ratio [-]
$Q_{c,gen,out}$	is the cooling energy provided at the evaporator of the heat pump [kWh]
$W_{c,gen,in}$	is the electrical energy use of the compressor of the heat pump in cooling mode [kWh]

In the case of free chilling operating mode, the performance of the system is given by:

$$SEER = \frac{Q_{c,fc,out}}{W_{c,fc}} \qquad [-] \qquad (4)$$

Where:

$Q_{c,fc,out}$	is the cooling energy provided to the building in free chilling mode [kWh]
$W_{c,fc}$	is the electrical energy use of the circulating pumps on ground and TABS side [kWh]

The heating energy provided at the condenser of the heat pump of building A and B is respectively:

$$Q_{h,gen,out} = Q_{h,TABS} \qquad [\text{kWh}] \tag{5}$$
$$Q_{h,gen,out} = Q_{h,TABS} + Q_{h,vent,ground} \qquad [\text{kWh}] \tag{6}$$

The cooling energy is respectively for building A and B:

$$Q_{c,fc,out} = Q_{c,TABS} \qquad [\text{kWh}] \tag{7}$$
$$Q_{c,fc,out} + Q_{c,gen,out} = Q_{c,TABS} + Q_{c,vent,ground} \qquad [\text{kWh}] \tag{8}$$

Results are presented in Table 1. It is shown that for both buildings, the annual cooling load 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 provide only 14.2% of the total heat load in case of building A and 13.6% in case of the second building. 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 twice as higher as the one of building B because the entire cooling load is provided only by free chilling.

Table 1: Annual energy consumption and performance

		Building A (2010)	Building B (2009)
Annual heating load	[MWh/year]	1200	355
Annual cooling load	[MWh/year]	46.47	19.69
Heating load by ventilation (district heating)	[MWh/year]	109.28	5.3
Heating load by ventilation (geothermal)	[MWh/year]		42.3
Heating load by TABS	[MWh/year]	171.3	48.2
Heating load by radiators	[MWh/year]	885.78	219.3
Heating load by floor heating	[MWh/year]	33.66	23.9
Heating load by DHW	[MWh/year]		15.9
Cooling load by ventilation	[MWh/year]		4.2
Cooling load by TABS	[MWh/year]	46.47	15.2
SCOP	[-]	5.15	3.7
SEER	[-]	20.9	10.8

These results are also presented on a monthly base (Figure 3 and Figure 4). It can be seen that most of the time, heating and cooling are not provided at the same time. Except 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).

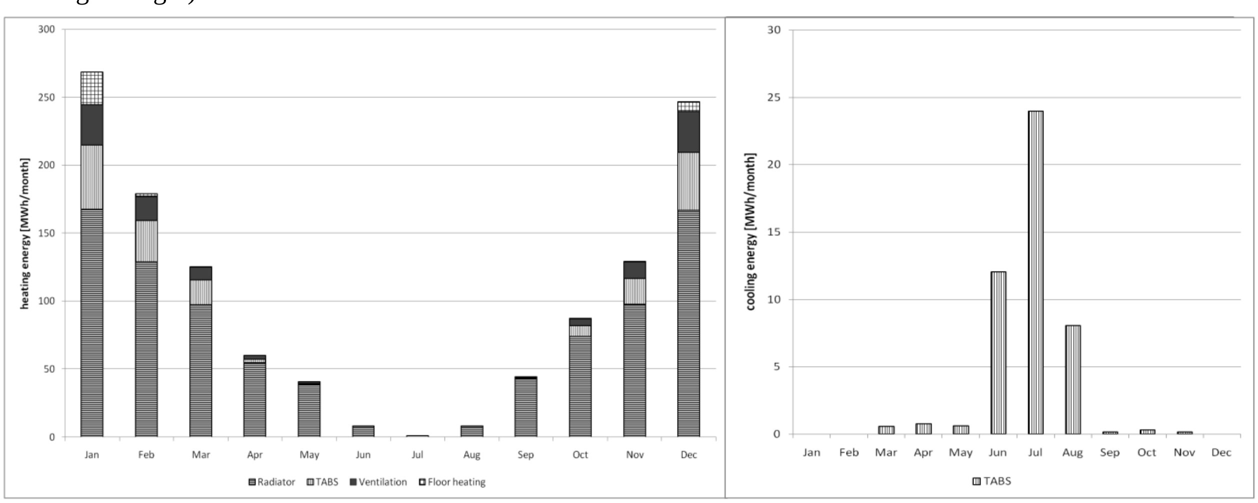

Figure 3: Heating (left) and cooling (right) load of building A

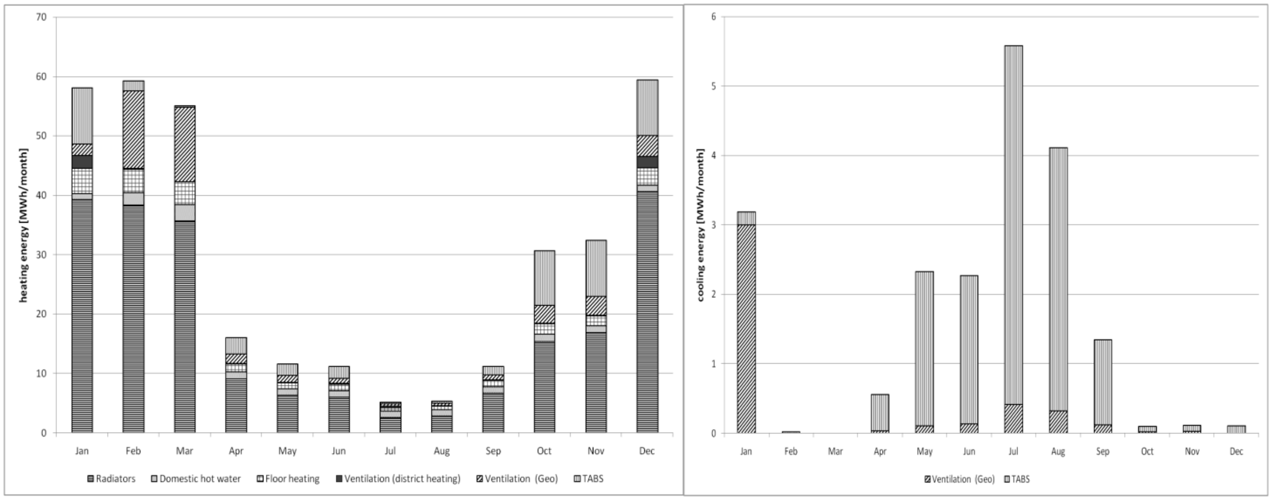

Figure 4: Heating (left) and cooling (right) load of building B

4. ECONOMIC AND ENVIRONMENTAL INTEREST ASSESSMENT

4.1 Cost reduction

Table 2 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 building 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 2: Estimation of the cost reduction

	Energy [MWh/year]		Average cost [€/kWh]	Traditional cost [€/year]		Geothermal cost [€/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 energy cost				16,653.6	8,428	4,464	3,244
Energy cost savings						12,189	5,184

4.2 CO_2 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, Institut Wohnen 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 building A and B respectively.

Table 3: Estimation of the CO_2 reduction

	Energy [MWh/year]		CO_2 emission [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_2 emission				51,246	25,111	23,547	17,116
CO_2 reduction						27,699	7,995

5. CONTROL STRATEGIES

5.1 Building A

There was only information concerning the applied control strategies of the TABS in this building. TABS (geothermal source) operate 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 5 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 2K, in average. Furthermore when the average outdoor temperature is between 14°C and 20°C there should be a deathband, 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.

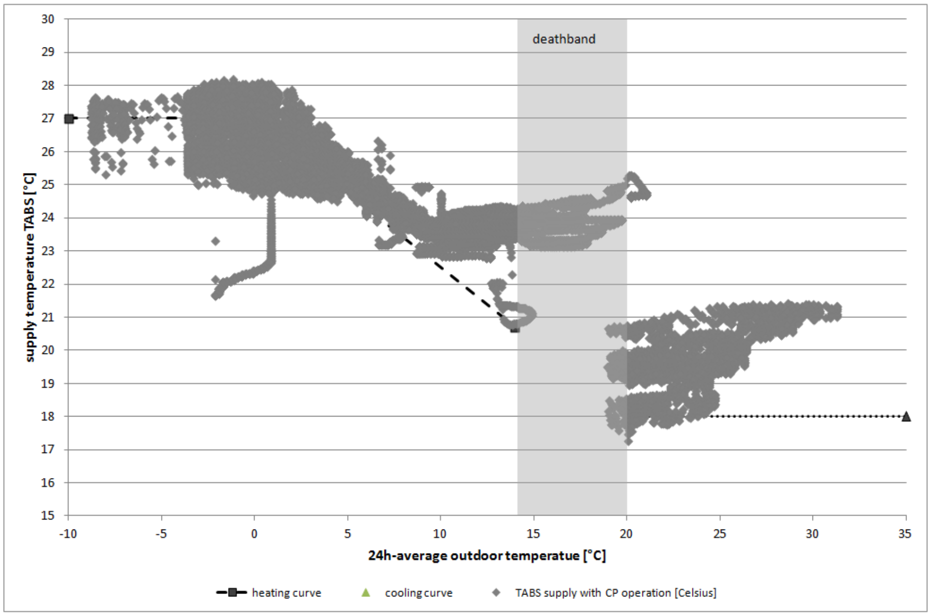

Figure 5: Control strategy of TABS (building A)

5.2 Building B

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

- Radiators (district heating source) operate at day time 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 6 and Figure 7 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 7 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 6 and Figure 7 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, for which, the supply temperature of TABS decreases with the outdoor temperature.

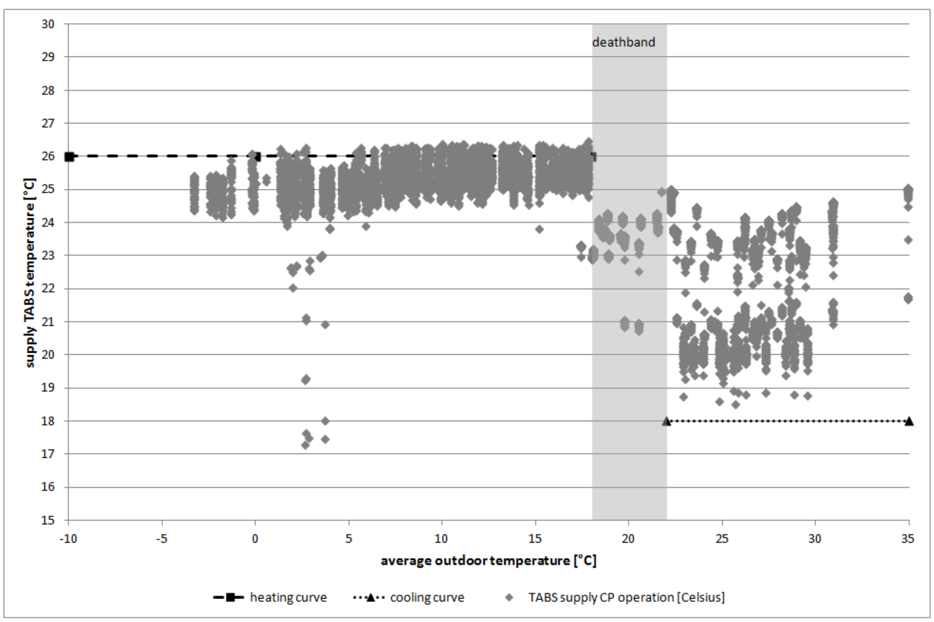

Figure 6: Control strategy of TABS (building B)

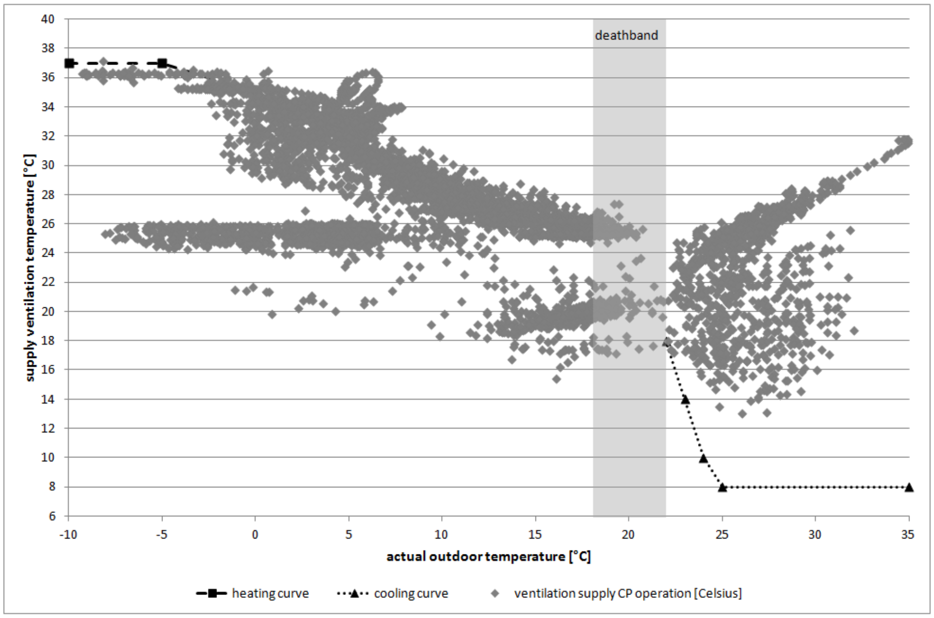

Figure 7: Control strategy of ventilation (building B)

6. COMFORT ANALYSIS

A long term thermal comfort analysis has been performed in building B, 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 which is a function depending on how many degrees the range has been exceeded.

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 8 shows the indoor temperature in function of the outdoor temperature that occurred in a representative zone of the building B in 2009 and Table 4 and 5 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 9). 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.

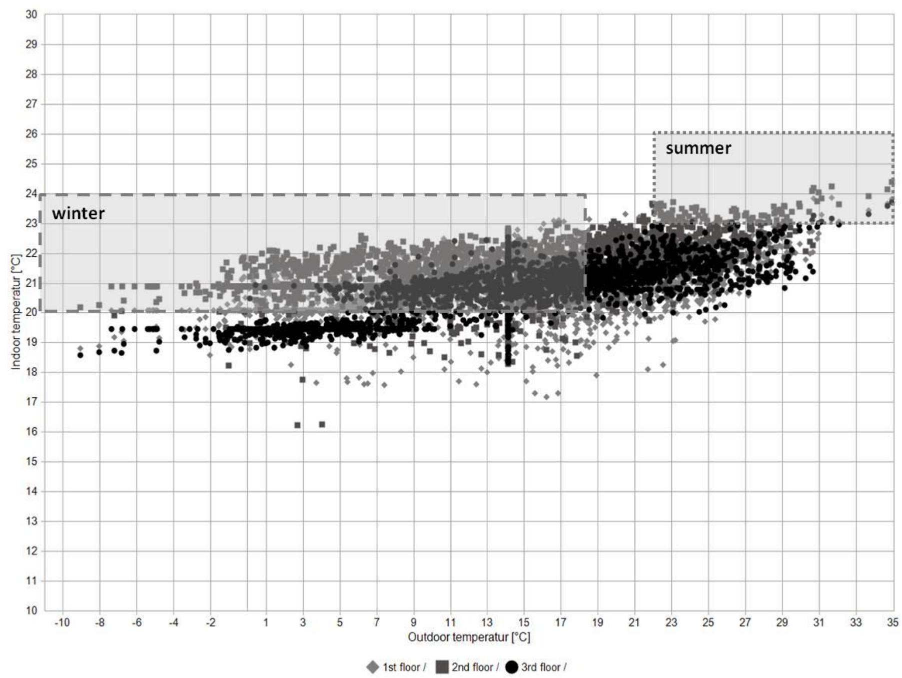

Figure 8: Indoor temperature of southeast zone each hour in 2009 (building B)

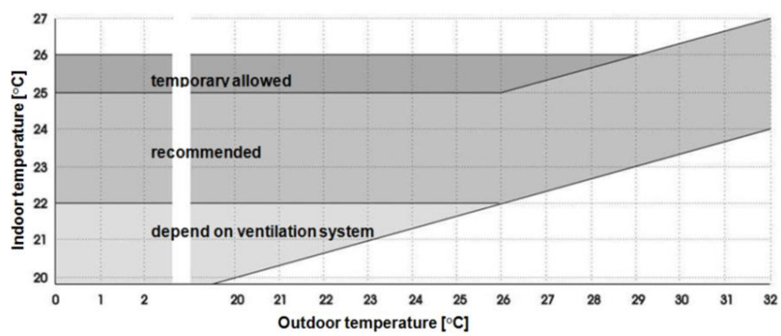

Figure 9: Limits for operative temperature according to DIN 1946-T2

Table 4: Temperature outside the range building B (2009)

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

Table 5: 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 1st floor	0	0	0	0	54	54
Southeast 1st floor	0	172	172	0	541	541
Southwest 1st floor	0	26	26	0	200	200
Southeast 2nd floor	0	74	74	0	232	232
Southwest 2nd floor	0	29	29	0	174	174
Southeast 3rd floor	0	223	223	0	479	479
Southwest 3rd floor	0	0	0	0	157	157

7. CONCLUSIONS

The two monitored buildings are quite different in term of net floor area and the quality of the data varies for each system. It has been shown in this paper that the part of the TABS in the heating load was limited; around 13.5% for each case but, regarding the cooling load, the TABS provides almost the entire building consumption (more than 75%) or even the total load. The use of geothermal energy for heating (heat pump) or cooling (free chilling and/or heat pump in reverse) allows a running cost reduction up to 71% compared to traditional systems and also a decrease of CO_2 emission by 54%. Concerning the control strategies, the TABS of both buildings are controlled in different ways: one is operating 24h/24h with a supply water temperature depending linearly on the outdoor temperature and the other is running only at night time with fixed supply water temperature according to winter or summer time. Finally, the comfort analysis performed for the building B showed a significant percentage of subcooling in summer that could yield to possible energy savings by reducing the cold production.

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