HEATING AND COOLING WITH HEAT PUMPS IN SWISS RESIDENTIAL BUILDINGS

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Abstract: The energy demand for heating decreases in highly-insulated dwellings. Comfort cooling becomes more important due to higher thermal loads and rising summer thermal comfort demands. Heat pumps can provide space heat and domestic hot water but may also provide cooling. The aim of the project is to support energy efficient solutions of heat pump heating systems with additional space cooling option for residential buildings. Nevertheless, first step should always be reducing heat loads by e.g. shading and night-time ventilation.
In a simulation study three heat pump systems have been compared. A brine-to-water borehole heat pump system yields the highest efficiency in all operation modes. Only few additional components are necessary to supply also a comfort cooling. An air-to-water heat pump shows the lowest efficiency but also lowest additional system expenditure. A relatively high efficiency achieved a state of the art multi-split air-to-air heat pump, albeit significantly below the brine-to-water in passive cooling mode. All systems achieve good thermal comfort. Furthermore, an approach is presented how to integrate passive cooling with borehole heat exchangers into the seasonal performance calculation of heat pump heating systems. Two field measurements of passive cooling with borehole heat exchanger confirm the simulation results and optimisation potential.

Key Words: space heating and cooling, low energy dwellings, heat pump

1 HEATING AND COOLING IN DWELLINGS

1.1 Background

People in industrialized countries spend most of their time inside buildings. In Switzerland, the main energy demand to keep a comfortable room climate, especially in dwellings, is needed for space heating in wintertime. Achieving a good thermal comfort with a low energy demand also with an increasing comfort demand in summertime requires energy efficient and economical system solutions. Minimizing the additional energy demand for summer cooling is therefore a challenge for highly energy efficient buildings. Good thermal insulation, effective shading and night-time ventilation if applicable always should reduce external thermal loads before using active cooling systems. Internal thermal loads in dwellings are significantly lower than for example in office buildings.

1.2 Objective

The objective of this paper is to show and evaluate if and how heat pump heating systems could also deliver space cooling since the heat pump process itself could be used for both applications space heating and space cooling. The integration into existing heat pump heating systems is usually more or less simple. Therefore three heat pump configurations were evaluated and juxtaposed in a theoretical study for the functions space heating (H), domestic hot water generation (W) and space cooling (C). Some of the main findings of the project SEK (Dott et al. 2010) are presented in this paper. The effect of the passive ground coupled cooling with borehole heat exchanger on the domestic hot water and space heating operation of the heat pump system has been evaluated. Two models have been derived using simple calculation methods as e.g. applied in standards suitable for the calculation of seasonal performance factors. Two additional field measurements of passive ground coupled space cooling systems affirm the theoretical results and the calculation models.

2 SYSTEM COMPARISON

Space cooling for dwellings is one way to provide extra thermal comfort in dwellings situated e.g. in Switzerland. Cooling in residential buildings is more and more requested by home owners. Therefore, heat pump systems for space heating and domestic hot water generation with an additional cooling function are the focus of this study. The main aim of the cooling function is not a strict limitation to and complying with a maximum room temperature, but an increase of the thermal comfort in summer by avoiding high room temperature peaks and achieving a gentle decrease of the average room temperature. The system comparison shows the behaviour of three systems supplying the functions space heating, domestic hot water and space cooling applied to a low energy building with mechanical ventilation system with heat recovery (Minergie 2009) and an energy reference area of 200 m^2_{EBF}. The building is simulated together with the heat pump system including control algorithms. All three systems were simulated with Matlab/Simulink. The borehole heat exchanger behaviour is included with a very simple model and then simulated and confirmed in a detailed simulation.

2.1 System description

Figure 1 shows the three systems, a variable refrigerant flow multi-split air-to-air heat pump (A/A-HP), an air-to-water heat pump (A/W-HP) and a brine-to-water heat pump (B/W-HP).

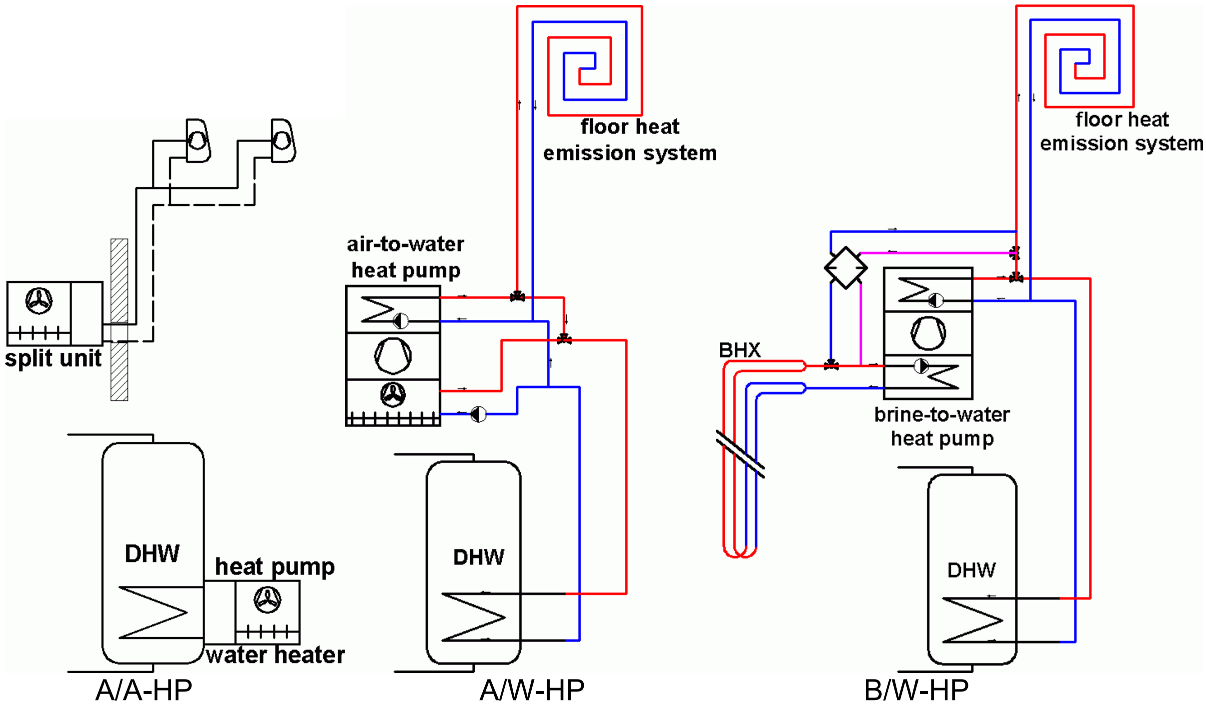

Figure 1: Hydraulic system concepts for space heating, domestic hot water & space cooling

The A/A-HP system uses a variable refrigerant flow (VRF) multi-split air-conditioning unit which is used for space cooling and in reverse mode for space heating. Domestic hot water is produced with an exhaust air heat pump using the air leaving the ventilation heat recovery as heat source. The A/W-HP system supplies all three functions H, W & C by an air-to-water heat pump with active heat pump operation. A low temperature floor heating system is used as heat emission system in heating and cooling mode. The same low temperature floor heating system is used in the B/W-HP system coupled to a brine-to-water heat pump with a borehole heat exchanger as heat source. For the cooling operation of this system the borehole heat exchanger is coupled directly to the floor heating system, to reject the heat from the building to the ground.

2.2 Control aspects

Based on the normal DesignReferenceYear climate data for the station "Basel-Binningen" from SIA 2028 (SIA 2008/1) Figure 2 shows the operating times and CoolingDegreeDays.

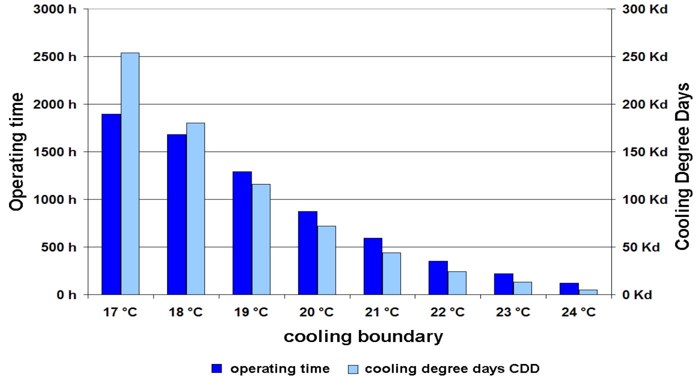

Figure 2: Typical space cooling operating times and cooling degree days

Space cooling is therein enabled only at outside temperatures higher than the given cooling boundary limit over a 24 hours gliding average as depicted in Figure 2. A rather high space cooling limit of 21 °C results in cutting off the highest room temperatures with an operating time of about 500 hours per year. With higher temperature limits the cooling function is de facto deactivated and only fast reacting heat emission systems can have an influence in reducing the room temperatures. A soft and steady lowering of the room temperature with a temperature limit of 17 °C to 19 °C results in about 1500 to 2000 operating hours per year.

2.3 Thermal comfort

Simulation results show a good thermal comfort corresponding to the operative room temperature evaluated according to EN 15251 (SIA 2007/1) in the winter as well as in the summer period. Figure 3 shows the operative room temperature distribution correlated to the outside-air-temperature for the summer period.

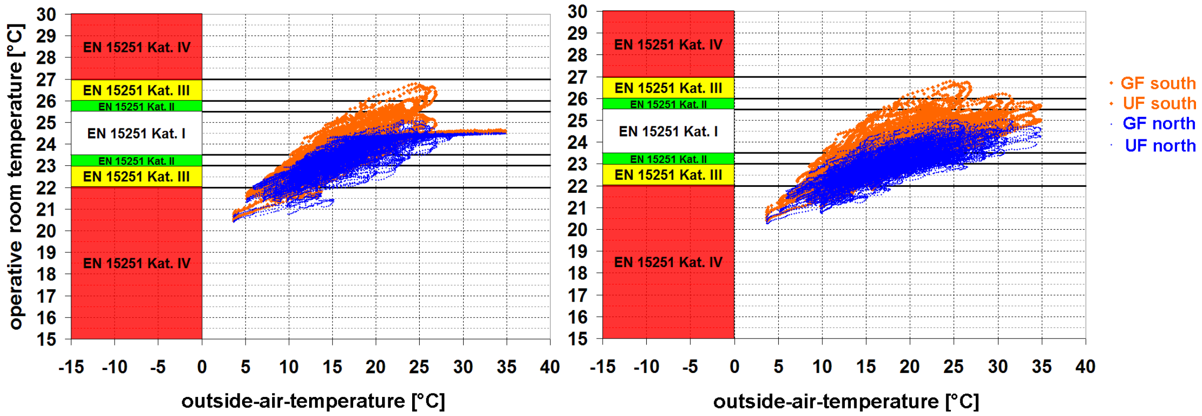

Figure 3: operative room temperature distribution correlated to the outside-air-temperature for the summer period (left: A/A-HP; right: B/W-HP)

The room temperatures show different characteristics caused by the heat emission systems for the A/A-HP with convector on the left side and for the B/W-HP with floor heating system on the right side of Figure 3. The convector system shows a defined room temperature curve with only small deviations caused by a fast reacting air heating- / cooling-power. The two systems with floor heating system, A/W-HP and B/W-HP, come with a wider distribution of the room temperature with identical outside air temperatures, caused by the thermal capacity of the floor heating system and with it a delayed reaction on the heating- / cooling-power.

2.4 Energy and Efficiency

Figure 4 depicts the system boundaries for the energetic evaluation. The generator seasonal performance factor (SPF-G) assesses the energetic quality of the heat generation and is calculated as sum of the generated heat divided by the required expenditure in the heat generator including the expenditure for the heat source. The system seasonal performance factor (SPF-SYS) shows the efficiency of the whole heat supply system, calculated as useful heat divided by the total expenditure in the whole system. The performance factors are based on energy sums over a defined period (e.g. winter, summer or whole year) and consider only the functions space heating, domestic hot water and space cooling. The ventilation system is identical for all systems and not considered in the presented energy and efficiency values. Figure 5 compares the generator seasonal performance numbers of the three systems depicted as single function performance and overall performance as well.

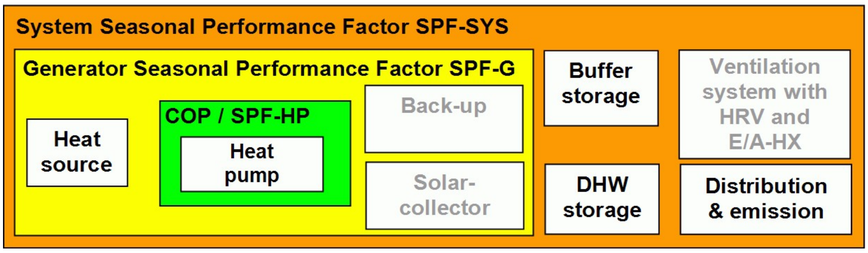

Figure 4: Definition of performance numbers and system boundaries

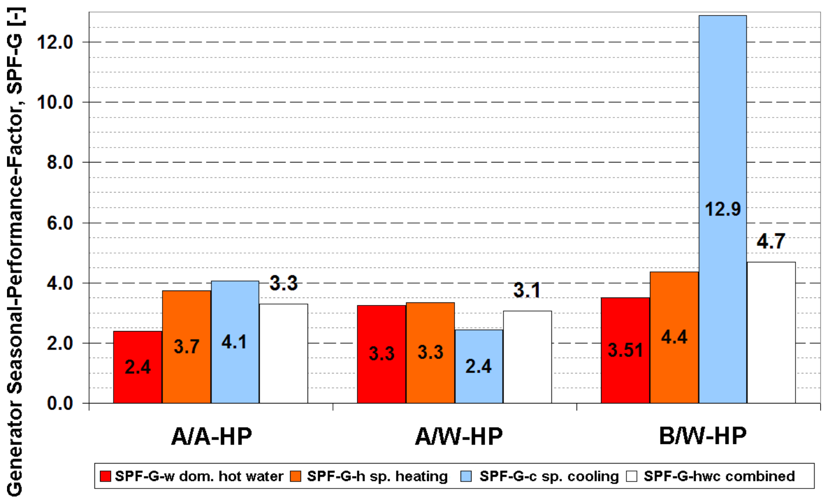

Figure 5: Juxtaposition of the generator seasonal performance numbers for the functions space heating, domestic hot water, space cooling and whole system of the three heat pump configurations A/A-HP, A/W-HP and B/W-HP

An A/W-HP shows the lowest overall efficiency with active cooling in reverse heat pump operation. With a heat emission of high thermal capacity it turns out to be more challenging to reach comfortable room temperatures near the comfort limits during cooling operation in summer, which could lead to an increased space cooling demand. Although the A/W-HP reaches an acceptable SPF-G in domestic hot water operation of 3.3, the efficiencies in the heating mode with 3.3 and the cooling mode with 2.4 are the lowest in this comparison. One advantage is the small equipment expenditure since all functions are supplied by one unit. A rather high efficiency for active heat pump operation is achieved by the VRF-A/A-HP with an

SPF-G of 3.7 for heating mode and 4.1 for the space cooling mode. The heat pump water heater with exhaust air heat source on the other hand shows a rather low SPF-G with 2.4. This system achieves the best thermal comfort correlated to the operative room temperature. The VRF-A/A-HP can by means of continuous capacity control follow changing heat loads due to varying shading or changing occupancy in a wide range, which results in the lowest space cooling need. Disadvantages are the big amount of refrigerant in the building, which is mainly not accepted in residential buildings, and the convector heat supply which requires special attention in engineering because of potential noise emissions and draught phenomena. By far the highest efficiency reaches the B/W-HP for the passive cooling operation with borehole heat exchanger with an SPF-G of 12.9 for space cooling and 4.7 as overall performance. Also the space heating and domestic hot water operation come with the highest performance numbers in this comparison. The additional equipment for supplying space cooling with a B/W-HP is small, basically a heat exchanger to bring the borehole hydraulic circuit and the floor heating circuit in contact and control equipment.

3 PASSIVE COOLING IN SEASONAL PERFORMANCE CALCULATION

The passive cooling with borehole heat exchanger turns out to be the system with the highest efficiency; it is also the most popular space cooling system in Swiss dwellings. Passive cooling uses the naturally lower ground temperature level to cool the building. Most Swiss buildings do not require space cooling and also not usually applied technology. Nevertheless there is a trend for space cooling in residential buildings in Switzerland, possibly caused by an increased space cooling usage e.g. in automotive A/C or offices.

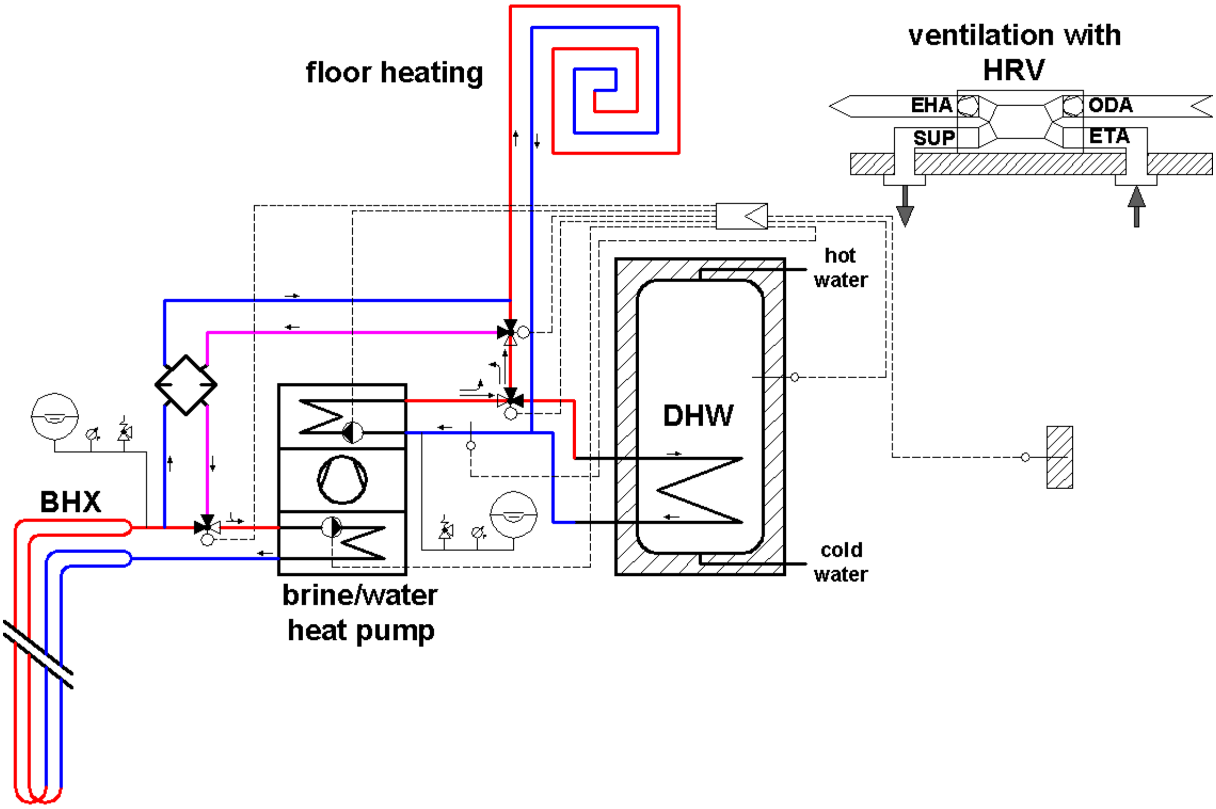

Figure 6: Hydraulic scheme for a brine/water-heat pump with passive cooling function

According to Swiss standards and legislation (EnDK 2008 and SIA 2007/2) space cooling systems require a public authority's permission. Requirements are defined for air tightness of the building envelope, sun protection of windows and the thermal capacity of the room surrounding surfaces. Furthermore, the need for space cooling has to be proven based on specific room temperature requirements or high internal heat loads or high room air

temperatures in summer, which usually is not applicable for dwellings. Only cooling systems with a small electric capacity for media transport and conditioning including cooling are allowed without permission. This small electrical capacity is defined at 7 W/m^2 cooled net floor area for new buildings and with 12 W/m^2 for existing and renewed buildings.
The development of calculation methods for the annual seasonal performance of heat pump systems for space heating and domestic hot water in residential buildings made significant steps forward recently. The calculation method developed in the SFOE-project “Calculation method for the seasonal performance of heat pump compact units and validation” (Afjei et al. 2007) has been implemented in the European standard EN 15316-4-2:2008 (SIA 2008/2). But there is up to now no standardized calculation method for passive cooling with borehole heat exchangers, likewise the influence of the passive cooling on heating and hot water operation. The following chapter suggests a method to determine the electric demand for passive cooling with borehole heat exchanger and the influence of the passive cooling on space heating and domestic hot water operation with ground coupled heat pumps.

3.1 Characteristic

Applying passive cooling with borehole heat exchanger means to bring two thermal separated areas, living space and ground, in a thermal contact. The two circulating fluids in the floor heating system and the ground loop are separated by a heat exchanger because of hydraulic reasons. It is called “passive cooling”, since energy is only required to circulate the heat transfer media. However the temperature of these heat transfer media is not directly influenced actively like with a capacity controlled heat pump in reverse mode. Hence, the electric expenditure arises only from the transport of the heat transfer media. The amount of rejected heat from the room to the ground is influenced by several more effects like shading or internal loads of the room, which increase the room temperature and thereby augment the heat to be rejected. Calculating an SPF for passive cooling would require a thermal room balance. Therefore, the calculation method presented here confines itself to the assumption of a full coverage of the cooling demand and furthermore the calculation of the electric expenditure and the influence of the passive cooling on heating and hot water operation.

3.2 Expenditure of the passive cooling

The electric expenditure for passive ground coupled cooling is basically calculated as integral of the electric consumption in all components used for the coupling of the cooled rooms to the ground. These components are here the two circulating pumps for the borehole heat exchanger, the heat emission system and control devices. Because of the approximately constant electric power of these components the integral could be simplified to the product of average electric power and operation time. According to the defined boundaries in Figure 4 the electric energy demand to be used for calculating the system performance SPF-SYS is calculated with equation (1) including heat generation, distribution and emission system. The corresponding electric energy demand to calculate the generator seasonal performance factor excludes the emission system and is calculated with equation (2).

$$E_{el,C,SPF-SYS} = (P_{el,ctr+aux} + P_{el,Pu,BHE} + P_{el,Pu,em})_C * t_C \tag{1}$$

$E_{el,C,SPF-SYS}$	electric energy consumption for the system seasonal performance factor	[kWh]
$P_{el,ctr+aux}$	electric power consumption in control and auxiliaries	[kW]
$P_{el,Pu,BHE}$	electric power consumption in circulation pump of the borehole heat exchanger	[kW]
$P_{el,Pu,em}$	electric power consumption in circulation pump of the heat emission system	[kW]

$$E_{el,C,SPF-G} = (P_{el,ctr+aux} + P_{el,Pu,BHE})_C * t_C \tag{2}$$

$E_{el,C,SPF-G}$	electric energy consumption for the system seasonal performance factor	[kWh]

3.3 Sensitivity analysis of component efficiencies

Highly efficient components have a crucial influence on the electric energy consumption for passive cooling. Therefore, a sensitivity analysis in Table 1 taken from (Dott et al. 2010) shows the influence of the component efficiencies on the seasonal performance of passive cooling applied to the Minergie reference building. The column with “low” efficiency represents actual new components with rather low efficiency; “average” represents actual widespread products with good efficiency and “high” represents today’s best available technology. The consumed energy is calculated for two scenarios, one with a rather high outside temperature limit for cooling aiming at cutting off excess room temperatures and a cooling operation time of 500 hours and the other one with a lower outside temperature limit for cooling aiming at a soft and steady cooling with a cooling operation time of 1500 hours.
Best available technology could easily half the electric power consumption of average 130 Watt to 60 Watt. But low efficient components or over sizing on the other hand could also raise the power consumption to 210 Watt. The most sensitive component in this comparison is the circulating pump of the borehole heat exchanger. Conventional AC motor pumps normally are still used for this application and bear a great potential of increasing efficiency, whereas for emission systems DC motor pumps are nearly standard or at least very widespread.

Table 1: Variation and sensitivity of electricity consumption in ground coupled passive cooling

	Efficiency	high	average	low
1	borehole heat exchanger circulating pump	45 Watt	100 Watt	150 Watt
2	control	5 Watt	15 Watt	30 Watt
3	heat emission system circulating pump	10 Watt	15 Watt	30 Watt
4	**sum of el. power consumption**	**60 Watt**	**130 Watt**	**210 Watt**
5	el. energy demand cut off excess temp. (operation time 500 h)	30 kWh/a	65 kWh/a	105 kWh/a
6	el. energy demand soft & steady cooling (operation time 1500 h)	90 kWh/a	195 kWh/a	315 kWh/a
7	rejected heat from room with soft & steady cooling	2500 kWh/a	2500 kWh/a	2500 kWh/a
8	**generator seasonal performance SPF-G**	**33.3**	**14.5**	**9.3**
9	**system seasonal performance SPF-SYS**	**27.8**	**12.8**	**7.9**

The rather high variance in the electric power consumption leads to a similarly range of seasonal performance factors. An assumed space cooling heat rejection of 2500 kWh/a yields generator seasonal performance factors between 9.3 and 33.3 and system seasonal performance factors between 7.9 and 27.8.
Hence, crucial for energy efficient ground coupled passive cooling are on the one hand an effective coupling of living space and ground, e.g. by a heat exchanger with low terminal temperature difference and high temperature cooling emission system, and on the other hand high efficient components (class “A”) for control and circulating the heat transfer medium as DC motor pumps and low consumption control devices are required. Halving the effort in passive cooling mode and doubling the seasonal performance is thereby possible.

3.4 Effect of borehole heat exchanger recharging

The heat rejection to the ground favours the efficiency of the heat pump withdrawing heat from the ground with higher borehole outlet temperatures. This effect is mainly related to hot water preparation in summer showing an increase in the range of 3.0 to 3.5 K. Figure 7 shows the seasonal devolution of the increase of the borehole heat exchanger outlet temperature referred to a variant without cooling mode. Only a small phase shift is visible compared to the rejected heat into the borehole heat exchanger from space cooling. The influence on the outlet temperature during wintertime is negligible.

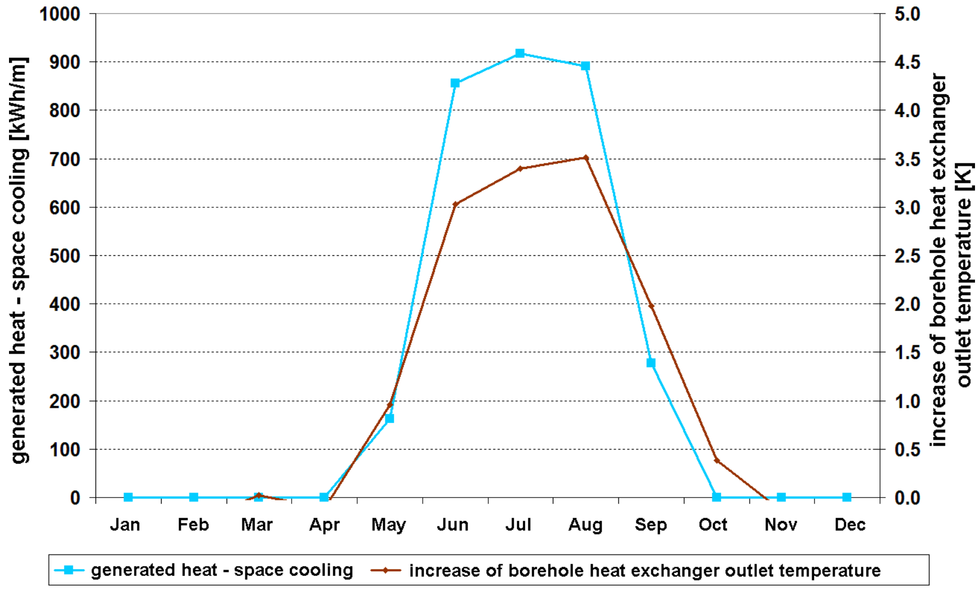

Figure 7: Seasonal correlation of heat dissipated from building to borehole in space cooling operation and the increase of the borehole heat exchanger outlet temperature compared to operation without space cooling for a Minergie building with reduced use of shading

3.5 Short time adiabatic heat storage model

The observations from the detailed simulations show an effect similar to short time heat storage in the borehole heat exchanger. The aim of the described model is an application in easy to use seasonal performance calculation methods like the bin-method in EN 15316-4-2. Therefore the model assumes that the heat from passive cooling could be stored in the borehole heat exchanger during one day and is lost afterwards. This is a strong simplification, which is dedicated to a very simple calculation. The dynamic heat injection based on a daily cyclic heat load pattern then defines the diameter of the active storage volume around the borehole where the outlet temperature increase is identical to the result of the detailed simulation. The temperature increase could on this basis be calculated with equation (3).
The active storage volume based on a daily cyclic heat load pattern has been derived from several simulation variants. The equivalent heat capacity for the active ground heat storage equals 89 Wh/mK. This corresponds to a diameter of the active ground heat storage d_G of 0.4 m. The total heat capacity of the borehole heat exchanger then for this case then is 8.9 kWh/K.
Comparing this simple model to the detailed simulation results shows a very good agreement of the results for the month June to August with high cooling demand, where the deviations are between 0 K and 0.4 K for several simulation variants. The times in the begin and at the end of the cooling period show bigger deviations of up to 1 K, but have less influence on the seasonal performance calculation results because of the small cooling energy. The overall increase of the outlet temperature of the borehole heat exchanger in domestic hot water

operation for the whole year furthermore show a very good agreement with deviations in the range of 0.1 K to 0.2 K.

$$\Delta\Theta_{BHE,W,C,d} = \frac{Q_{C,d}}{C_{BHE}} = \frac{Q_{C,d}}{(c_{p,Bh} * \rho_{Bh} * \frac{d_{Bh}^2}{4} + c_{p,G} * \rho_G * \frac{d_{G,d}^2 - d_{Bh}^2}{4}) * \pi * l_{BHE}} \quad (3)$$

$\Delta\Theta_{BHE,W,C,d}$	daily increase of the borehole heat exchanger outlet temperature in domestic hot water operation with heat injection into the borehole from ground coupled passive cooling	[K]
$Q_{C,d}$	daily rejected heat from space cooling	[kWh]
C_{BHE}	activated borehole heat capacity for a daily cyclic heat load pattern	[kWh/K]
$c_{p,Bh}$	specific heat capacity of borehole backfilling material	[J/kgK]
ρ_{Bh}	density of borehole backfilling material	[kg/m^3]
d_{Bh}	diameter of the borehole	[m]
$c_{p,G}$	specific heat capacity of the ground	[J/kgK]
ρ_G	density of the ground	[kg/m^3]
d_G	diameter of the active ground heat storage for a daily cyclic heat load pattern	[m]
l_{BHE}	length of borehole heat exchanger	[m]

3.6 Ground coupled passive cooling in bin-method seasonal performance calculation

Implementing the above calculation methods for passive cooling into the bin-method according to the EN 15316-4-2 leads to very good agreement of the generator seasonal performance factors compared to detailed simulation results as shown in Table 2.

Table 2: Comparison of seasonal performance factors from simulation and calculation method

generator seasonal performance factors without passive cooling			
	simulation	bin-method	
SPF-G_H	4.4	4.6	5%
SPF-G_W	3.3	3.2	-3%
SPF-G_{HW}	4.0	4.1	2%
generator seasonal performance factors with passive cooling			
	simulation	bin-method	
SPF-G_H	4.4	4.6	5%
SPF-G_W	3.5	3.5	-1%
SPF-G_C	12.9	12.6	-2%
SPF-G_{HWC}	4.7	4.8	2%

The negligence of the heat storage effect on the space heating operation in the calculation method leads to equal good agreement like without heat injection into the borehole and confirms the simplification to neglect the effect of heat injection into the borehole on the winter heat withdrawal. The increase of the domestic hot water seasonal performance factor by the heat injection from passive cooling could be reproduced by a very simple calculation model based on a short time adiabatic ground heat storage model. The performance factor of the passive cooling could be reproduced with good agreement also by a simplified calculation based on average electric power consumption if the assumption of full cooling need coverage is valid.

4 EXPERIENCES IN FIELD MEASUREMENTS

In two field measurements of ground coupled heat pump systems with passive cooling function data have been acquired to evaluate the indoor climate, generated heat and consumed electricity. One heat pump system operates in a multi-family house in Basel-City (Genkinger et al. 2010) the other one in a single family house in Muolen (Lederle et al. 2010). Measurement periods were from 2007 until 2009 for the CosyPlace building and from 2009 until 2010 for the Muolen building. The building characteristics are summarized in Table 3. The applied energy standards are the Swiss Minergie (38 kWh/m^2/a final energy for H,W,C) and Minergie-P (30 kWh/m^2/a final energy for H,W,C; 15 kWh/m^2/a heat demand for H) standard (Minergie 2009). In the following some aspects are shown that confirm the principal effects of the detailed simulations.

Table 3: Building characteristics of two field measurement objects in Basel and Muolen

	CosyPlace	Muolen
Object		
location	Basel canton BS, 316 m a.s.l.	Muolen canton SG, 492 m a.s.l.
exposition	north oriented hillside, detached	flat terrain, detached
completion	2007	2008
qualification	Minergie-P®	Minergie®
energy reference area	1064 m^2	279 m^2
apartments / inhabitants	5 / 9 adults, 3 children	1 / 2 adults, 1 child
HP capacity (B0/W35)	15.5 kW	8.4 kW
borehole length	2 x 130 m	1 x 150 m

4.1 Energy and efficiency

Both systems showed good efficiencies in space heating and in cooling mode. Energetic performance figures are summarized in Table 4. Weekly average performance factors of up to 15.2 were reached for the passive cooling with enhanced control.

Table 4: Energetic and efficiency performance numbers for both buildings

	CosyPlace	**Muolen**
measurement period	winter 2008/09: 01.10. – 31.03. summer 2009: 01.04. – 30.09.	winter 2009/10 :01.10. – 30.04. summer 2009: 01.05. – 30.09.
generated space heat (whole year)	32'850 kWh	9'186 kWh
generated DHW heat (winter / summer)	7'258 / 5'552 kWh	1'522 / 765 kWh
rejected heat in space cooling	3'637 kWh	1'058 kWh
SPF-G space heating	4.3	3.8
SPF-G DHW (winter/summer)	2.5 / 2.9	2.8 / 3.6
SPF-G passive space cooling	8.1	7.3
SPF-SYS passive space cooling	7.3	7.1
total consumed electricity for H,W,C	12'968 kWh	3'657 kWh
SPF-G overall	3.8	3.8

4.2 Electricity consumption of ground coupled passive cooling

The passive cooling operation requires only electricity for circulating pumps, control and auxiliaries. The CosyPlace building uses for the floor heating system a highly efficient brushless direct current permanent magnet motor that adapts the electric power consumption to the varying mass flow caused by thermostatic valves. The average electric power consumption is between 30 W and 40 W, the electric energy consumption about 2% of the total electric energy consumption of the heat pump system. In space cooling operation this pump consumes 48 kWh, which is about 10% of total electric energy consumption for space cooling. Main consumer is the borehole heat exchanger circulating pump with 427 kWh.

4.3 Thermal behaviour of borehole heat exchanger

Figure 8 exemplarily shows the correlation between the generated respectively rejected heat and the borehole heat exchanger inlet and outlet temperatures taken from the CosyPlace measurements in summer 2009. During winter the outlet temperatures are in a range of 0 °C to 7 °C. With a reduced heat withdrawal in spring the temperatures increase to about 10 °C in May/June. During periods with passive cooling and heat injection into the borehole, the borehole temperatures rise by 3…5 K up to maximum of 16 °C and fall back by the same amount after the cooling period to about 10 °C in September. A seasonal storage effect could not be observed. Before the control optimization the room air temperature stays at a maximum level around 25 °C, with the more intensive cooling after the control optimization the room air temperature even drops to a rather low level of 22…23 °C.

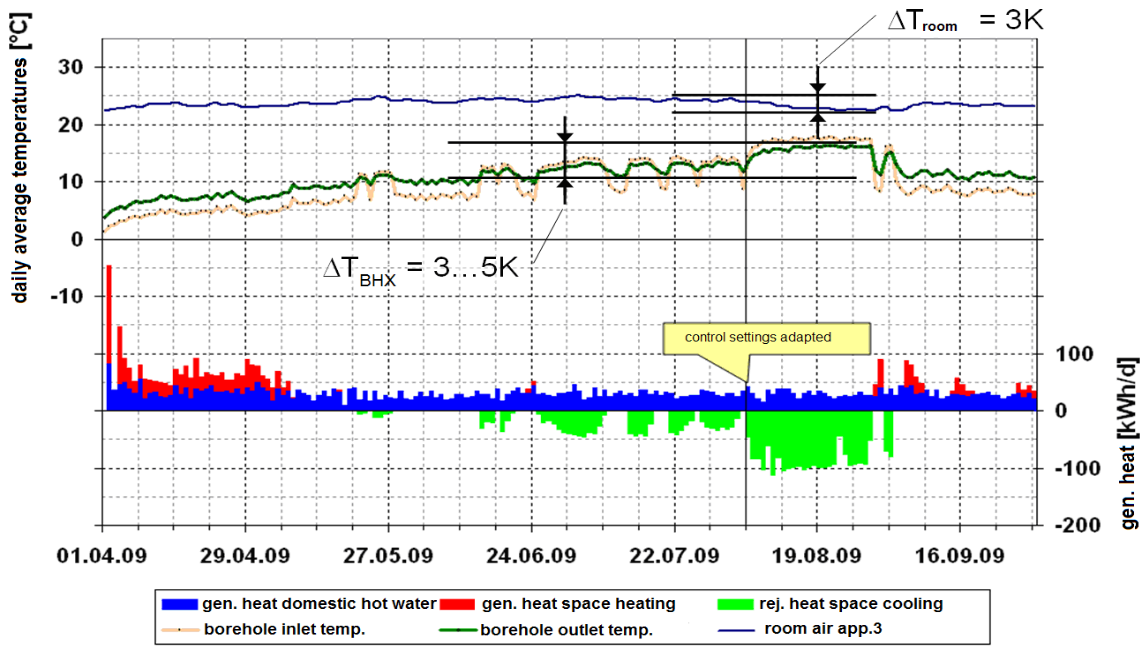

Figure 8: CosyPlace: generated heat correlated to borehole heat exchanger flow temperatures

5 CONCLUSIONS

Space cooling in Swiss residential buildings is not a standard application up to now and in many cases also not necessary, but still more and more used. Hence energy efficient and robust solutions as shown in this paper are necessary to be available and implemented if required. Furthermore, space cooling, in particular passive cooling, is worth to be considered in calculation methods and legislative requirements. Especially in future ultra-low to plus energy buildings all consumptions and the potential energy savings of the integration of functionalities need to be considered.

6 ACKNOWLEDGEMENTS

The results presented in this paper are part of the Swiss contribution to the IEA HPP Annex 32 “Economical Heating and Cooling Systems for low energy houses“ which is presented in another session by Wemhoener et al. (2011). The authors are grateful for the project advising and financial support by the Swiss Federal Office of Energy with the research programme manager Prof. Dr. Thomas Kopp, the Viessmann (Schweiz) AG Geschäftsbereich SATAG Thermotechnik, and the Amt für Umwelt und Energie of the canton Basel-Stadt and furthermore the involved companies and inhabitants of the buildings measured.

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