Evaluation and optimization of underground thermal energy storage systems of Energy Efficient Buildings (*WKSP*) - A project within the new German R&D-framework *EnBop*

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Abstract

Until 2003 the research on buildings in operation in Germany focussed mainly on demonstration buildings. Starting with the EVA project managed by IGS the attention is shifting towards performance in operation. The paper gives a general review of these research projects and presents detailed results of project WKSP. The performance of buildings with systems for underground thermal energy storage is analysed in this project. As the analyses show several systems work worse than expected. Within the project most of the systems could be significantly improved in operation. The scientific work on building performance in operation will be broadened within the new R&D framework EnBop. IGS will coordinate the framework funded by the German Ministry of Economics and Technology.

Research on Building Performance in Operation

Since the mid 90th the German Ministry of Research and Economics funds research projects on energy efficient buildings with the R&D program *solarbau* respectively *EnBau* as it is called since 2007. It is part of the ministries research field “EnOB - Energieoptimiertes Bauen” which comprehends all R&D activities on energy efficient buildings. For the first 10 years EnBau focussed mainly on new technology and demonstration buildings. More than 20 buildings, mainly office buildings, have been built with funding for the use of new technology, innovative design an planning approaches as well as monitoring campaigns of two years or more in operation. The results on demonstration buildings have been published by Rozynski, Gerder et alt. (2005), Himmler, Fisch et alt. (2005), Plesser, Fisch (2008), Voss et alt. (2007) and others.

IGS carried out the research projects on three demonstration buildings: the EnergieForum Berlin, the Center of Informatics at the Technical University Braunschweig and the New house of the Region of Hannover (ongoing). Key findings included mayor problems to reach their energy efficiency and indoor climate targets without the support of the research teams. Among other aspects especially controls caused problems and indicated large potential for improvements in operation as shown by Plesser, Himmler et alt (2006).

Therefore IGS proposed to start research projects to analyse and evaluate the operation of existing buildings to gather data on the actual performance of buildings in operation. The first project within this new field was the project “EVA – Evaluation of Office Buildings in Operation”. 19 office buildings have been analyzed regarding overall energy efficiency, energy consumption of individual systems, indoor environmental qualities and building operation. The buildings had all been built between 1990 and 2002 representing state of the art technology of Germany. The key findings were:

Compared to buildings of the 1960 and 1970 the new buildings were more efficient by a factor of 2 although today heavily equipped with IT which was almost non existent in the older buildings.

1. The EVA sample used an average of 284 $kWh_{PE}/(m^2_{NGF}a)$ [1] which is about 70 % more than the average of the demonstration buildings of the EnOB program which can be considered as best practice.
2. The variables for the specific energy consumption had a wide range from 135 to 454 $kWh_{PE}/(m^2_{NGF}a)$. Within the sample the mechanically ventilated buildings used about 30 % more energy (339 $kWh_{PE}/(m^2_{NGF}a)$) than the natural ventilated buildings.
3. For 10 buildings the energy demand was calculated according to the mandatory German standard fo building energy efficiency EnEV 2007 and DIN V 18599 [2]. It showed that the total annual energy consumption in operation was about 70 % higher than the calculated value.
4. The user comfort in most buildings was predominantly good. There were almost no deficits identified regarding drought, radiation asymmetry or thermal layering.

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[1] PE: primary energy; NGF: net floor area

[2] The calculation of the energy demand includes only the energy consumption for heating, cooling, ventilation and lighting, not including appliances.

5. Significant problems have been identified regarding two aspects. During winter meterings ($T_{amb} < 10$ °C) 30 % of the rooms had a CO_2-Concentration in the air of more than 1.000 ppm which is defined as limit in the new DIN EN 13779 (formerly 1.500 ppm in DIN 1946). The average number of *Überhitzungsstunden* (hours with operative temperature above 26 °C) in 66 rooms during operation time (8:00 – 18:00, Monday – Friday = 2.600 h/a) was 182 h/a which is below the limit defined by DIN 4108. Some rooms though had more than 400 hours over 26 °C.
6. The user questionnaires that had been carried out in 7 buildings by fbta/University Karlsruhe showed that it was not indoor air temperature that was the most important factor for comfort satisfaction but the perceived capabilities to individually influence the temperature.

Although EVA was not specifically aiming at optimizing the buildings the analysis showed 55 potential individual measures to optimize building operation. 30 were low- or no-cost improvements with a payback time of less than 3 years mostly concerning operations and controls.

In some buildings the measures had been implemented during the project. In one building almost all measures have been implemented within a comprehensive commissioning project. This led to annual savings of about 30 % with a payback time of less than 3 years. The results are published in German by Plesser, Fisch et alt (2008).

As a consequence of the EVA- project several follow up projects have been started. Since the variety of buildings showed some methodological challenges in EVA the new projects focus on special types of technologies or systems e.g. Faced Integrated Ventilation Systems (“DeAL”) or Double Skin Facades (“TwinSkin”) and Underground Thermal Energy storage (“WKSP”).

Figure 1: Energy piles under construction: pile pattern of an office building near Spree riverside, Berlin

Figure 2: **pipes fixed at the reinforcement of two energy piles (on the left), pipes and reinforcement fitted-in the foundation (on the right)**

Principles of seasonal thermal energy storage in the Foundation

In consideration of using renewable energy sources, modern office buildings are more commonly operated with shallow geothermal energy. A evaluation of buildings with such heating- and cooling systems is administrated by the IGS within the research project „WKSP- thermal energy storage in foundations of energy efficient office buildings“, which is funded by the Federal Ministry of Economy and Technology.

Thermal utilization of surrounding soil for heating and cooling purposes of buildings is based on seasonal energy charge and discharge using a fluid heat transfer medium circulating in tube loops through the ground. An advantage in the process of using the ground for heating and cooling of buildings is the comparatively steady temperature level of the ground over the year. Regardless of high outdoor temperatures in summer, the ground can be used efficiently for free cooling processes without using cooling machines. The transfer fluid heated up in the building is cooled down in the ground and the ground stores the thermal energy for heating purpose in winter time.

A seasonal balance of cooling the ground in winter from its heat loads gained in summer and vice versa is however requirement for a long-term functionality of the system. Heat extraction in winter works via a heat pump, which raises the temperature level of the transfer medium to a point, where it can be used for heating the building. Essential for a reliable and lasting output of required heating- and cooling energy is an accurate equipment design, an appropriate realisation and a system control in full operation.

Storage systems of ground heat

One way to make use of the capacity of the ground to store heating and cooling energy are borehole heat exchangers placed below the building or within immediate vicinity of the building. Borehole heat exchangers consist of a single borehole or a network of various boreholes. Practically there are no depths limits for the borehole heat exchangers but depths between 50 m and 150 m have proven as economically reasonable. In Germany borehole heat exchangers are generally not placed below 100 m due to requirements of mining law. In those cases approval has to be given and a specially qualified business has to be commissioned with the drilling.

Thermal potentials of the ground for heating and cooling purposes should be considered at early planning stage before founding the building to take advantage of synergy effects and to reduce costs and effort. Most commonly piled foundations and ground slabs with integrated circulation tubes are used as so called energy piles and foundation absorbers for heat exchange. Dimensions of the heat exchanging surfaces follow statical aspects.

In case of energy piles, except from additional placing the tubes are fixed onto the reinforcement within the body of the piles. Beyond that the preparation of energy piles does not differ from the methods of regular foundation piles.

Similar to above mentioned method it works for foundation absorbers. Pipe loops are placed horizontally inside or below the bottom slab to activate storage capacities of the surrounding soil.

As a rule all three systems are fitted with a mixture of water and antifreeze like glycol as heat exchanging fluid.

Buildings in the monitoring campaign

Within WKSP six buildings fitted with Underground Thermal Energy Storage (UTES) systems like borehole heat exchangers, energy piles or foundation absorbers are being analyzed (see table 1).

Experiences show that it is possible and useful to fit UTES systems into today's office buildings energy concepts.

However an initial phase to optimize the interaction between the UTES system and the building itself, further equipment of thermal conditioning, and the occupants of the building is necessary.

Lack of experiences and knowledge on the part of constructing company and operators often lead to a longer initial phase.

Table 1: Data of UTES systems and heating-/cooling concepts of six monitored buildings (colored fields mark existing components)

UTES - systems	BHE			EP		FA
object	a	b	c	d	e	f
geometry						
quantity	17	36	28	196	101	
length of borehole / pile in [m]	99	150	80	8,5	20	
overall length in [m]	1.683	5.400	2.257	1.666	1.926	
absorber surface in [m²]						8.067
mode of operation						
heat pump	🟨	🟨	🟨	🟨	🟨	🟨
free cooling	🟨	🟨	🟨	🟨	🟨	🟨
refrigerating machine		🟨			🟨	
geothermal transfer/emission system						
concrete core activation	🟨		🟨	🟨	N	🟨
ceiling sails		🟨				
air conditioning plant	VBOX	🟨			D	
further heat and cold generators						
district heat	🟨		🟨	🟨	🟨	🟨
exhaust air heat pump	🟨					
air-cooled refrigerating machine			🟨			🟨
desiccant cooling system		BHGP				🟨
further transfer/emission systems						
radiators			🟨	🟨	🟨	🟨
ventilation						
natural			pa	SS	🟨	pa
mechanical	VBOX	🟨	🟨	WS	pa	🟨

borehole heat exchangers (BHE), energy piles (EP), foundations absorbers (FA),
decentralized façade integrated ventilation box (VBOX), block heating und generating plant (BHGP),
summer service (SS), winter service (WS), only day (D), only night (N), partial areas (pa)

Results of performance evaluation

A first appraisal of facility performance and efficiency is possible using the seasonal performance factor (SPF) as ratio of supplied thermal energy (heat and cold) to the used electric energy including the circulating pump of the ground heat storage.

At the beginning of the research project WKSP most systems had a SPF below 3 which indicated that they were not operating efficiently. Systems and operation have been optimized in the process of the monitoring, so that in 2007 all systems reached a SPF between 3 and 7 (see fig. 3).

Most of the analysed systems show potentials for further optimization in regard to free cooling. Up to now free cooling often was used very limited or not at all due to faulty modes of operation, overheated ground as well as system components not adapted to minor temperature differences between heat sink and cooling system. An accurate dimensioning and operation can lead to an SPF between 20 and 30. Therefore the analyzed systems could reach SPFs considerable above 3 in the sum of heating and cooling process.

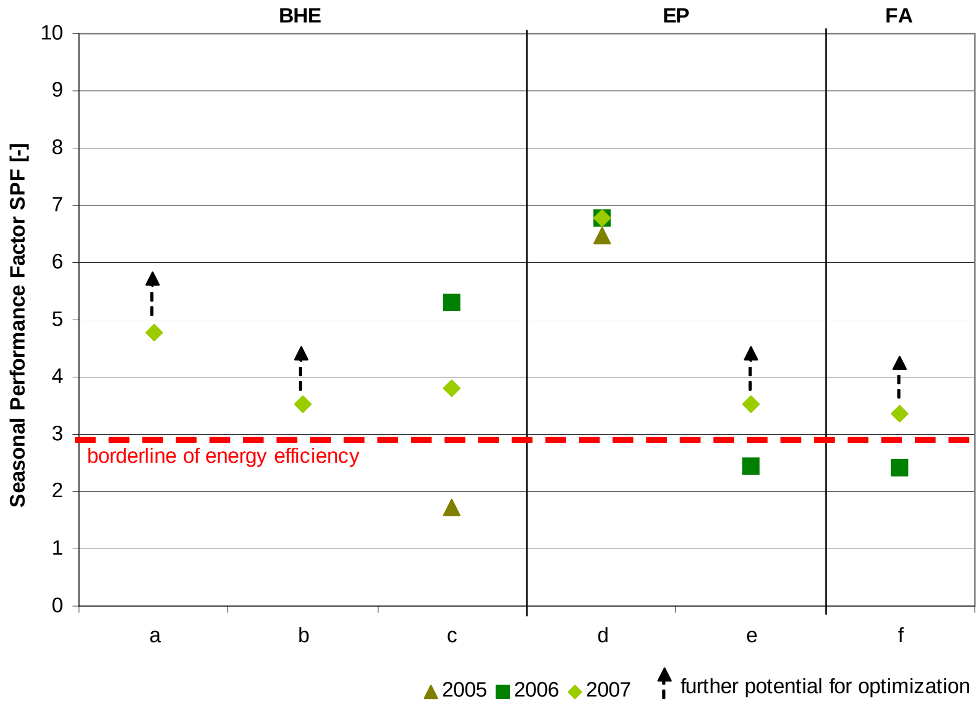

Figure 3: **Annul SPF of sixs UTES systems as ratio of supplied thermal energy (heating and cooling) and used electrical energy including pumps for ground systems for six buildings, 2005 to 2007**

Energy yields vary from object to object depending on the UTES system. Apart from few exceptions the quantity of extracted heat is equivalent to planned values. Heat addition however differs considerably due to faulty operation and high temperature levels of the ground

In order to obtain a steady temperature level over the year's most systems need a higher heat extraction than addition. Due to influences of weather and optimization of systems the annual registered energy gain of the monitoring fluctuates rather magnificent. Performances of heat extraction and addition were reached according to table 2. All data are averaged by operating hours and relate to length of boreholes and piles or surface of absorber.

Table 2: **Range of annual heat extraction and addition as well as average thermal power per meter or square meter of the UTES system (metering periods: 2005 – 2007)**

UTES system		**BHE**	**EP**	**FA**
thermal energy				
extraction	kWh/((m·a) or (m²·a))	20 - 105	5 - 70	5 - 20
addition	kWh/((m·a) or (m²·a))	40 - 75	5 - 45	0 - 25
thermal power				
extraction	W/(m or m²)	5 - 30	0 - 50	5
additon	W/(m or m²)	20 - 35	5 - 35	-

Energy cost savings and reduction of CO_2 achieved by thermal activation of the ground instead of using district heating and compression refrigeration machines (annual performance coefficient 2,5) for cold production greatly depend on size, efficiency and utilization of the equipment. Relating to energy prices and CO_2 emission factors as shown in table 3, in 2007 savings of energy costs ranged between 2.000 and 37.000 Euro/a and reductions of CO_2 reached values from 3.000 up to 80.000 kg/a depending on the building. Referring savings of energy costs and CO_2 reductions to operating hours and dimension of the heat exchanger, an approximate linear dependence on the annual coefficient of performance is recognizable. With a SPF of 7, energy cost savings of 0,24 Cent/(m_{pile}·h) and CO_2 reduction of 6,7 g/(m_{pile}·h) were reached (see fig. 4 and fig. 5).

Table 3: **Prices for energy and factors for CO2-emissions**

		electricity	district heating
Energy costs	in [Euro/kWh]	0,12	0,08
CO_2 emissions	in [kg/kWh]	683	241

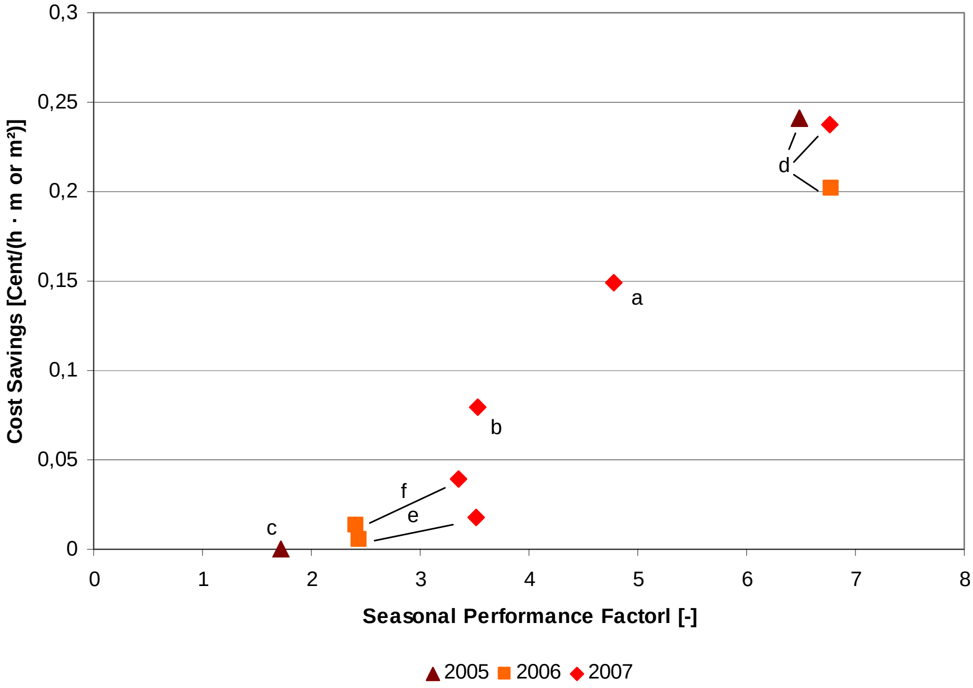

Figure 4 **Annual cost savings for energy per system length resp. area and hour of operation over SPF of the system. UTES systems compared to district heating combined with conventional mechanical cooling (energy prices according to Table 3)**

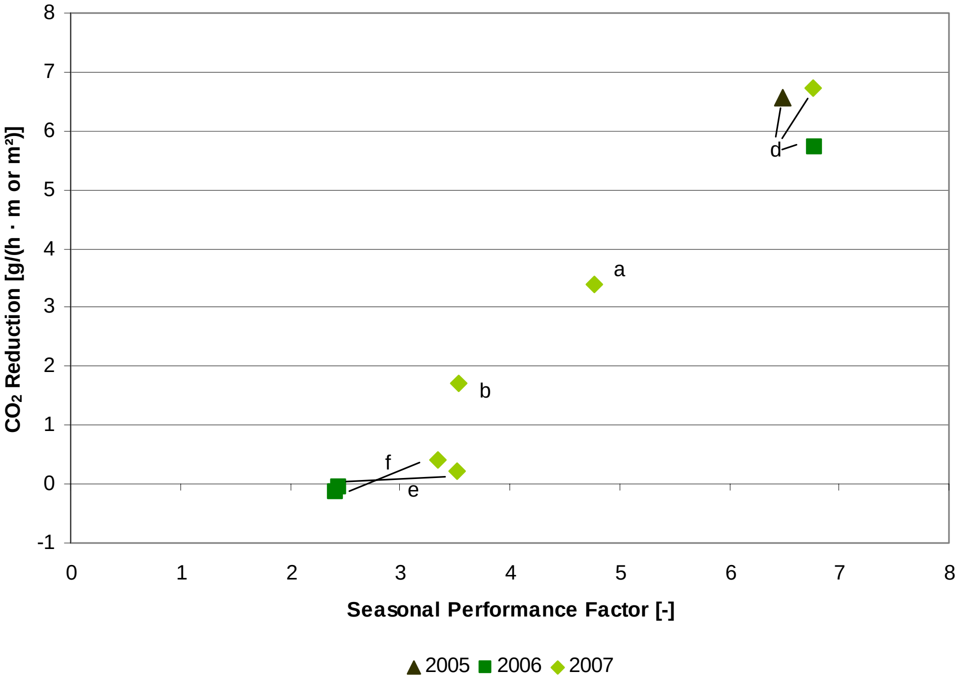

Figure 5 **Annual reduction of CO_2-emmission per system length resp. area and hour of operation over SPF of system. UTES system compared to district heating combined with conventional mechanical cooling (CO_2-emission factors according to Table 3)**

Experiences and Recommendations

All mentioned UTES systems can be very efficiently combined with low temperature heating and high temperature cooling systems like concrete core activation and heating/cooling ceilings. The heat supplied by heat pumps amounts to three and even five times as much as is spend of electrical energy. The efficiency of free cooling is even more significant. In this case electric energy is only needed to circulate the heat transfer medium in the ground.

Lack of experiences and knowledge on part of constructing companies and operators often cause lower energy efficiency than intended. Due to their slowness and the slight temperature differences between ground heat storage and heating/cooling system inside the building the systems react very sensitive to errors and failures. In worst cases the functioning of the entire system can be made impossible over a period of several years.

Due to the small temperature differences between the underground and the building system, close attention has to be paid to the right design. Only like that the required operation conditions can be reached. Under dimensioned panel heat exchangers or high volume drifts lead to such slight temperature differences that the heat or cold from the foundation might not even reach the building. A well-regulated seasonal energy-balance is mandatory for a lasting and sufficient functionality of the UTES system. Of importance is also the first initiation of the system during heating period. Throughout the heating period enough heat has to be extracted from the underground to provide the required low temperature level for free cooling mode at summer time.

Systems fitted with integrated refrigerating machines should only use them towards the end of cooling period when the cooling potential of free cooling via the ground is almost exhausted. Otherwise the ground might not be able to cool down the significantly higher temperature level of the backflow of the refrigerating machine before next cooling requests. The more efficient free cooling could thus not be used for the rest of the season.

Inert heating and cooling systems such as concrete core activation are often used to supply buildings with underground thermal energy. High requirements on the system occur in particular during transit times of spring and fall with stronger seasonal fluctuation of outdoor temperatures. During these seasons faulty control strategies often lead to night time heating of the building. Due to internal loads of the building it has to be cooled down again during the day. After-effect is an unnecessary consumption of electricity for circulation and heat pumps. This problem can be sufficiently avoided with the aid of a so called “death-band”. With the control system a temperature range (death-band) is defined that does not permit either heating or cooling when the averaged outdoor temperature lies within this range. Heating systems fitted with concrete core activation are often combined with fast reacting radiators to cover peak loads. Since the quick heating system reacts faster to temperature differences it might occur that the concrete core activation is rarely used and therefore does not extract as much thermal energy from the ground as necessary and expected from planning stage. Due to seasonal operation there might not be enough heat sink available next summer period. Corresponding control systems have to be applied to warrant the expected operation of concrete core activation and to avoid an override of the system caused by quicker systems.

To avoid the problems mentioned above all control strategies should be thoroughly checked and the building should be monitored until it reaches a regulated operation, which usually takes about two years. During this time of adjustment interactions of all components such as UTES-system, the building itself, further equipment of thermal conditioning, and at last the occupants are coordinated. It is furthermore recommendable to monitor inlet and outlet temperatures of the UTES-system as well as monthly heat extraction and addition beyond this initial phase. Inconsistency of the expected operation can thus be discovered in sufficient time and necessary measures taken without delay.

Conclusion

Compared with conventional heating and cooling systems significant savings of energy costs and reduction of CO_2 are possible with UTES-systems depending on accurate planning and adjusted operation. Rising energy prices will further increase the economic profitability of borehole heat exchangers, energy piles and foundation absorbers. Of mayor importance for energy efficiency of these systems, of thermal comfort inside the buildings and a long-term functioning of UTES systems is a high level quality management beyond the phase of design and realization. The monitoring of buildings and their systems as performed within the research project WKSP shows how important it is to analyze the functioning of the buildings and UTES systems during operation. In cooperation with the building management of the monitored objects, initial phases of regulation could be kept short and potentials for optimization were discovered step by step.

Outlook: Future Research on Building Commissioning in Germany

EnBop stands for „Energetische Betriebsoptimierung“ – in English „Optimizing Building Operations“. EnBop is a new research framework within the research activities on energy efficient building funded by the German Ministry for Economics and Technology. EnBop sets a frame for research projects such as case studies on operation in existing buildings and performance analysis of new systems and concepts. New methodologies and tools for enhanced building operations are being developed and tested. A special focus is set upon the cost-effectiveness and persistence of commissioning and optimization.

EnBop will be presented at ICEBO´08 in Berlin in cooperation with BINE Informationsdienst. For more information please check www.enob.info.

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