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An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings

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ABSTRACT

Over a three years period, an aquifer thermal energy storage system was monitored in combination with a heat pump for heating and cooling of the ventilation air in a Belgian hospital. The installation was one of the first and largest ground source heat pump systems in Belgium. Groundwater flows and temperatures were monitored as well as the energy flows of the heat pumps and the energy demand of the building. The resulting energy balance of the building showed that the primary energy consumption of the heat pump system is 71% lower in comparison with a reference installation based on common gas-fired boilers and water cooling machines. This corresponds to a CO_2-reduction of 1280 ton over the whole measuring period. The overall seasonal performance factor (SPF) for heating was 5.9 while the ATES system delivered cooling at an efficiency factor of 26.1. Furthermore, the economic analysis showed an annual cost reduction of k€ 54 as compared to the reference installation, resulting in a simple payback time of 8.4 years, excluding subsidies.

1. Introduction

Hospitals and health care buildings typically have a high energy demand for heating. Moreover, increasing comfort claims in the rooms and high internal loads resulted in a significant growth of the cooling demand during the past decade. Consequently, heating and cooling of hospitals with conventional HVAC installations are energy intensive and thus expensive. To reduce the energy use and the emission of greenhouse gases by these installations, the health care sector needs energy efficient solutions operating at the lowest cost [1]. A solution is to shift away from the use of conventional heating and cooling techniques towards the use of renewable energy sources. Underground thermal energy storage (UTES) provides a technically and economically feasible alternative for current conventional technologies for heating and cooling [2–4]. Ground source heat pumps (GSHPs) are recognized as outstanding heating, cooling and water heating systems which provide high levels of comfort, have very low maintenance requirements and are environmentally attractive [5,6]. Furthermore, the integration of thermal energy storage for space heating and cooling of buildings is becoming increasingly important due to the rising cost of fossil fuels, environmental concerns and the flexibility towards the electricity network.

Since the idea of an aquifer thermal energy storage (ATES) system was launched, a significant amount of theoretical and experimental studies have been reported in the literature. The design, performance and economic analysis of these systems were extensively described [7–9]. Case studies, textbooks and standards that discuss installation procedures for ATES systems are available [10–13]. Paksoy et al. [14] reported a feasibility study for an ATES system in a Turkish hospital in Adana. They concluded that a significant potential exists for the reduction of the energy consumption (electricity and fuel oil) and replacement of chillers. An overview of ATES techniques by Andersson [15] showed that the energy savings can amount to 90–95% for direct heating and cooling, 80–85% for heat pump assisted heating and cooling, 60–75% for heat pump assisted heating systems, 90–95% for cooling of industrial processes, and 90–95% for district cooling.

While a large number of ATES systems are already operational at the moment, long-term monitoring data are not often published. To the meaning of the authors, too little attention has been paid to the monitoring of ATES installations, mainly because of the high cost of the measuring equipment (flow meters, temperature sensors, data logging instruments). Monitoring and commissioning of a building's heating and cooling installation is however essential for the market growth of innovative techniques as ATES [16]. Michopoulos et al. [17] described a three-year monitoring campaign of a

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borehole thermal energy storage (BTES) system in Northern Greece. However, unlike ATES, this is a closed system whereby heat of the ground is exchanged by means of vertical ground heat exchangers.

The seasonal coefficient of performance (COP) for heating of this installation increased from 4.4 to 5.2 during three years of monitoring, while the seasonal COP for cooling decreased from 4.5 to 4.4. This is explained by the increasing ground temperature due to a much higher cooling load compared to the heating load. After three years of operation no stabilization was achieved yet. Schmidt and Müller-Steinhagen described [18] a four-year monitoring campaign on an ATES installation coupled with thermal solar panels. The ATES is used to store heat of the sun in summertime, and therefore, the storage allows to increase the solar fraction to heat the building. Unlike the ATES described in this paper, the installation described works at far higher temperatures. Sanner et al. [19] presented the results of a monitoring campaign on an ATES system for heating and cooling of the Reichstag in Berlin. The installation consists of a high temperature ATES for heating and a low temperature ATES for cooling, while in this paper one ATES for both heating and cooling is described. Studies on GSHP systems in Belgium are very scarce, although the temperature of the soil is stable in most areas and suitable for GSHP applications.

This paper reports on a monitoring study of a low temperature ATES system coupled to reversible heat pumps for heating and cooling a new hospital in near Antwerp over a three years period [20]. The energy and temperature data recordings, the COPs of the system and the heat pump in the heating and cooling mode are determined. Furthermore, primary energy savings and CO_2 reductions are included. This paper equally provides an economical analysis that compares the ATES based system with a conventional HVAC installation, consisting of a gas boiler and compression cooling machine.

2. Methods

2.1. System description

The ATES and heat pump system is installed at the “Klina” (“Klinieken Noord Antwerpen”) hospital in Brasschaat, Belgium. It is located at a distance of 12 km north-east from the centre of Antwerp. The building was designed in the early 90s and the construction works were completed in 1999. The ATES system went in operation in August 2000. The building consists of 4 floors, covering 440 beds, surgery, technical and consultation rooms and a large atrium in between these zones. The hospital was one of the first in Belgium to incorporate comfort cooling in the patient rooms. To avoid expensive cooling with traditional refrigeration systems, a long-term energy storage system with groundwater was installed. The hospital operates 365 days a year on a 24 h a day basis.

The heat distribution in the building is provided by radiators designed to operate at a high temperature regime (80/50 °C) which is not suitable for a heat pump installation. To meet this heat demand, gas-fired boilers were installed. Ventilation of the rooms is provided by in total 40 air handling units (AHU), containing water coils designed to work with low temperature heat (45/34 °C). This heat is provided by two heat pumps (195 kW_t) coupled with the ATES system. The same AHU’s provide cooling for the rooms in summertime. The design temperature regime for cooling is 11/21 °C, except for the surgery rooms where the AHU’s are designed to work at 6/12 °C. The lower temperature allows to dehumidify the supplied air.

Based on the data of a test drilling, the ATES system was designed, consisting of 2 wells, 65 m deep and 100 m apart to prevent hydraulic and thermal interferences. Groundwater is extracted by submersible pumps placed in the wells. The design specifications of the groundwater system are summarized in Table 1.

Table 1
Design specifications of the ATES system.

Parameter	Value
Maximum flow per well	100 m^3/h
Maximum cooling power	1.2 MW
Diameter drilling	0.8 m
Depth wells	65 m
Length filters	36–40 m
Thickness aquifer	30–40 m
Number of cold wells	1
Number of warm wells	1
Distance between cold and warm well	100 m
Undisturbed groundwater temperature	11.7 °C
Injection temperature warm well	18 °C
Injection temperature cold well	8 °C

The ATES system has three operation modes: a heating (winter) mode, a cooling (summer) mode and a regeneration mode. Once the ambient temperature rises above 14 °C, the installation switches to cooling mode. In this operation mode, groundwater is extracted from the cold well to cool down the ventilation air in the patient and surgery rooms (Fig. 1: solid line). The building’s heat is subsequently injected into the warm well. In case the cooling power is not adequate or if an insufficiently low temperature is reached, the heat pumps are switched on to assist. These heat pumps function as cooling machines (Fig. 1: dotted line), transferring the condenser’s heat by means of the ATES system to the warm well. The groundwater pumps are designed to follow the flow of water through the secondary system at any time. In this operation mode, the temperature of the warm well will increase over time.

If the ambient temperature decreases below 14 °C, the installation is automatically switched to winter mode (Fig. 2). In this scenario the direction of the groundwater flow is reversed: groundwater is extracted from the warm well which has been warmed up during summer mode. Its heat is transferred to the evaporators of the heat pumps, causing the flow to cool down. This cold flow is then injected in the cold well. The heat pumps increase the temperature level of the heat by which it becomes useful to warm up the ventilation air. The heat pump is used to heat the building in this mode, while simultaneously charge the cold well and cool down the warm well.

The third mode (regeneration) is automatically activated when the ambient temperature is below 4 °C (Fig. 3). Like in winter mode, groundwater is extracted from the warm well and injected in the cold well after delivering its heat to the secondary circuit. The warmed up flow in this circuit is led to the AHU’s, where it preheats the cold ambient air before this air is supplied it to the rooms. This means that at these low temperatures, the ambient air is cold enough to directly load the cold well.

2.2. Monitoring equipment

During the construction phase, a central building monitoring system (BMS) was installed to control all devices of the HVAC system and to provide monitoring facilities for the operation of the installation. An external data logging system was also added to the system, providing extra monitoring data of temperatures and energy flows. The aim of the monitoring system is to provide a complete overview of the operation of the installation. To obtain a full analysis of the ATES system the following data was recorded:

- The heat exchange by the groundwater circuit, as calculated by the flow rate of the groundwater and the inlet and outlet water temperatures of the groundwater circuit (measured before and after the ground heat exchanger).

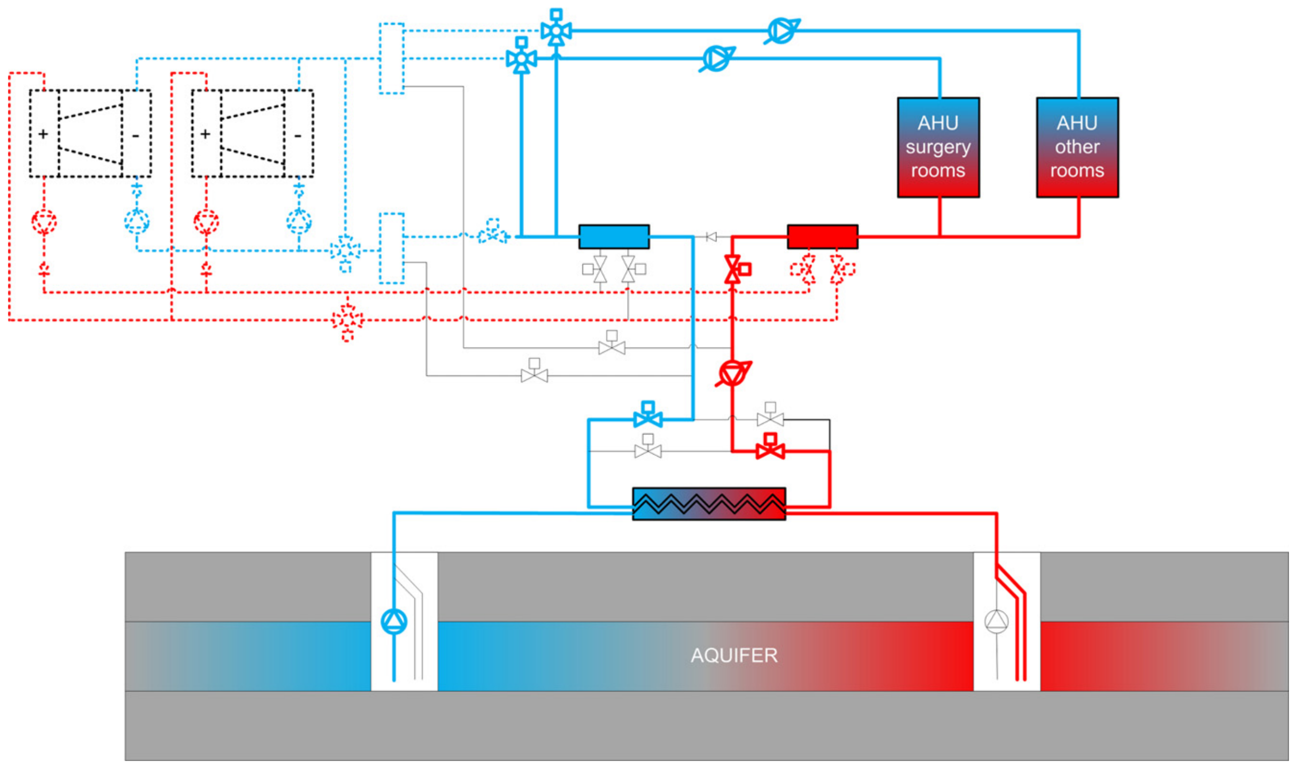

Fig. 1. Hydraulic scheme of the installation in cooling mode ($T_{ambient} > 14\,^{\circ}C$).

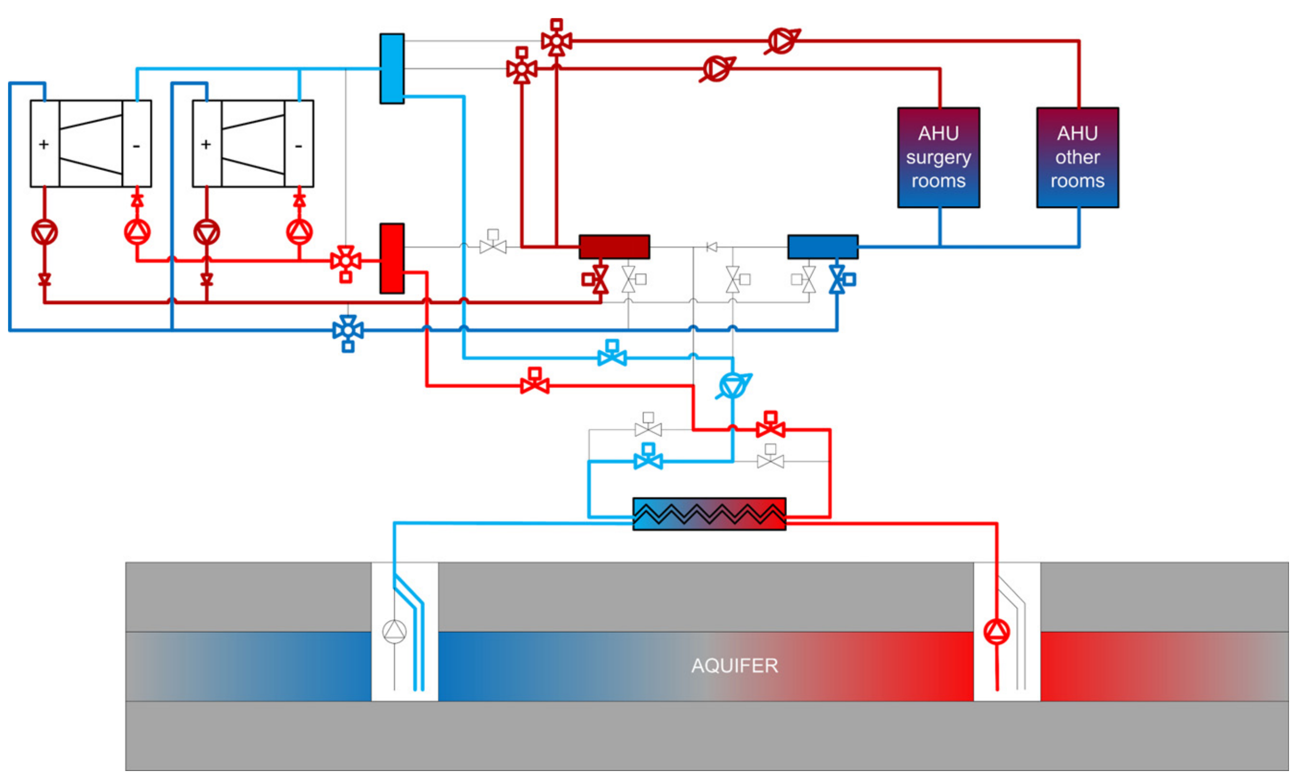

Fig. 2. Hydraulic scheme of the installation in heating mode ($4\,^{\circ}C < T_{ambient} < 14\,^{\circ}C$).

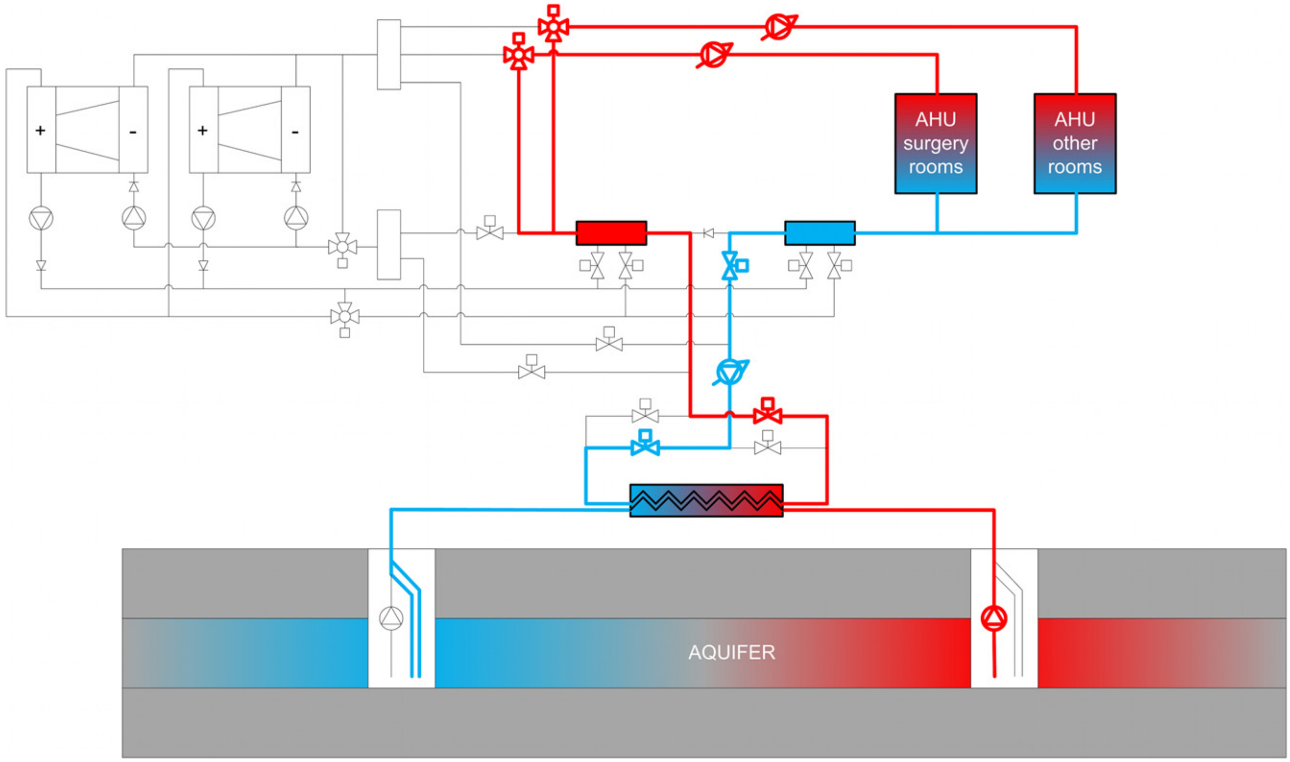

Fig. 3. Hydraulic scheme of the installation in regeneration mode ($T_{ambient} < 4\,^{\circ}C$).

- The heat (cold) supply by the condensers (evaporators) of the two heat pumps, which is determined by the operating time of the condenser pumps (fixed flow) and the inlet and outlet temperatures of the condensers (evaporators).
- The energy demand for heating and cooling of the hospital. This is calculated by the AHU's supply and return temperatures and the corresponding flows.
- Electricity consumption of the two heat pumps and the groundwater pumps.
- Ambient air temperature and relative humidity.

The flows were measured by an electro-magnetic flow meter. The accuracy of the flow measurement is ±0.2% of the flow rate plus or minus the zero stability. The temperatures were measured using paired 4-wire Pt-100 temperature sensors. The used sensors belong to a tolerance class "class A" with a tolerance of ±0.15 °C at 0 °C and ±0.35 °C at 100 °C. The flow and temperature sensors were connected to a calculation unit, which calculates the injected or extracted cooling and heating power. The electricity consumption was measured using energy counters. All data were recorded each half an hour on the data logger SD card (Datataker DT50). The results cover a monitoring period of three years (2003–2005) to assess seasonal effects of the ATES system.

3. Results and discussion

The results of the monitoring campaign were analysed to determine the technical, economical and ecological performance of the ATES and heat pump system. This allows to conclude on the operation and the economy of the system.

3.1. Ground water flow and temperatures

The first analysis examines the groundwater flow and groundwater temperatures during the operation of the system.

Fig. 4 shows the outside air temperature alongside to the groundwater flow of the ATES system in 2004. During summertime (June until September), a strong relationship between the groundwater flow of the ATES system and the outside air temperature is observed. During that period, most of the time the building is directly cooled by the groundwater, without assistance of the heat pumps. A variable flow pump allows to adjust the flow to the cooling demand. As the outside air temperature increases, more power has to be used for cooling of the hospital, leading to higher groundwater flows. In winter, the groundwater flow is more or less constant at 30–35 m^3/h. During wintertime, the heat of the warm well is merely delivered to the heat pumps. Because these heat pumps have constant flow pumps at the evaporators, the groundwater flow is also constant. As mentioned above, the ATES installation only provides preheating of the ventilation air, which is only a part of the total heat demand. The remainder of the heat demand is provided by radiators powered by a gas boiler.

Interestingly, our data reveal that the total extracted volume of groundwater during winter mode (heating) was about the same (4% less) as in summer mode (cooling), 515,000 m^3 versus 534,000 m^3, respectively, during the three-year monitoring period.

Fig. 5 shows the hourly average groundwater extraction temperature of the warm and cold well during the year 2004. Only when the groundwater system was in operation, the measurements were included in the graph. The figure shows a clear trend of an increasing cold well extraction temperature during summer (7 °C in June 2004 up to 10 °C in September 2004). Obviously, the available cold in the cold well decreases during summertime, however the groundwater temperature at the end of the cooling season was still low enough to cool down the building and lower than the natural groundwater temperature (~12 °C). This indicates that more capacity to cool the building is available at the end of the cooling season. Also in 2005 the cold well extraction temperature at the end of the cooling season was acceptable (10 °C). In 2003 however, this temperature was 12 °C. This is attributed to the fact that the

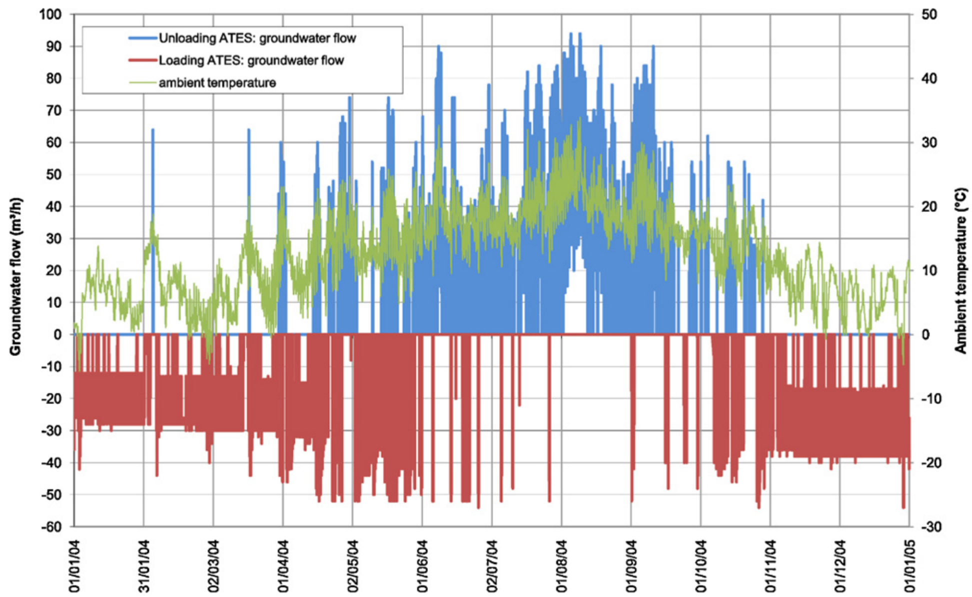

Fig. 4. Groundwater flow versus outside temperature (year 2004, positive groundwater flow: from cold well to warm well; negative groundwater flow: from warm well to cold well).

2003 summer was very hot. That year, all cold stored during winter was used to cool the building in summer, whereby at the end of the cooling season the extracted temperature became the natural groundwater temperature.

During the winter period, groundwater is extracted from the warm well at temperatures ranging between 16 °C and 18 °C and injected in the cold well at temperatures of 7 °C. This low temperature is ideal for cooling purposes when the cycle starts again in summer mode. As shown in Fig. 5, the groundwater extraction temperature of the warm well was very high at the beginning of the year (∼18 °C), while at the end of the year, the temperature dropped to approximately 15 °C. This phenomenon is also attributed to the hot summer of 2003, during which a lot of cooling was needed. The increased amount of condenser heat from the heat pumps in cooling mode warmed up the warm well more than usual. The summer of 2004 was a bit colder than average. As a result, the warm well was not loaded as high as usual. The autumn and winter were also slightly colder than usual. Consequently, the warm well temperature was low by the end of the year. In the beginning of 2003, the hot well temperature was 18 °C (due to the hot summer of 2002). By the end of 2005 the temperature was 16 °C (2005 had a normal summer followed by a warm winter).

3.2. Energy balance during three years of operation

A second analysis revealed the energy balance of the system. Fig. 6 shows the hourly average heating and cooling power delivered by the ATES system during the year 2004 and the average ambient temperature. The data show that the ATES system provides a cooling capacity up to 1.2 MW in summer mode. During winter mode, the capacity is a more constant but lower with an average of 350 kW (to provide heat to the building or to cold charge the cold well). The heat pump significantly helps in charging the cold well: without the heat pump, charging the cold well would only

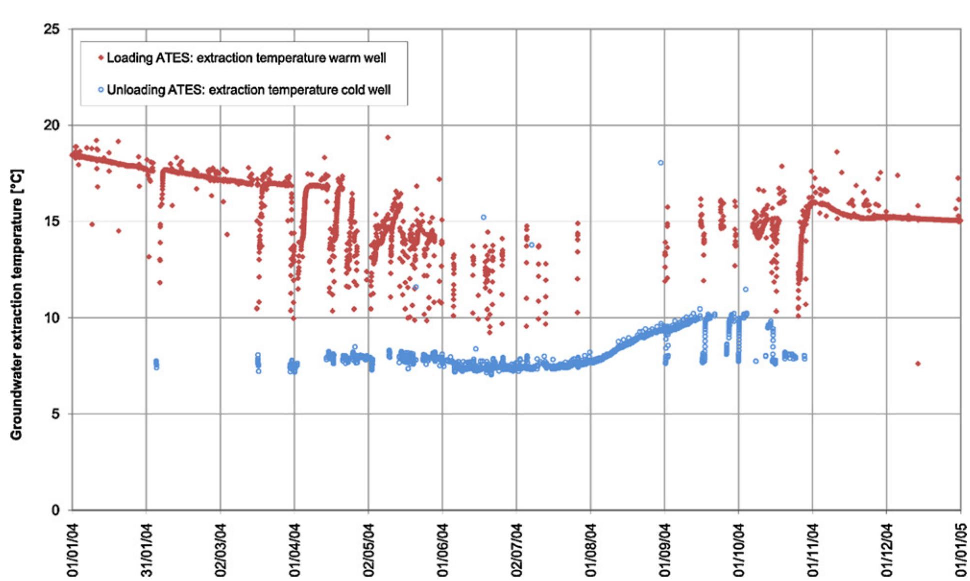

Fig. 5. Extraction temperatures of groundwater in warm and cold well (year 2004).

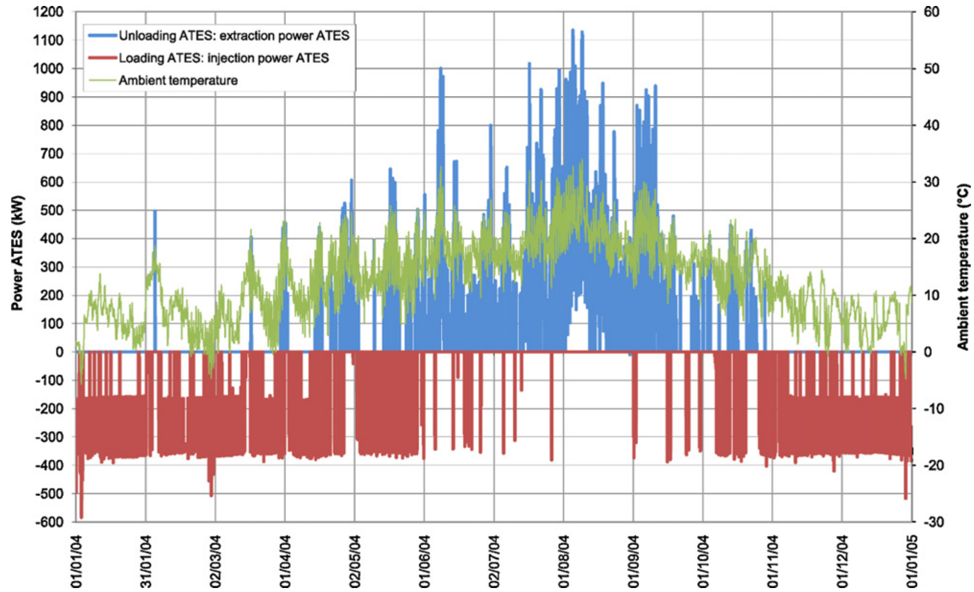

Fig. 6. Heating and cooling supply by the ATES system versus outside temperature (year 2004, positive power: cooling; negative power: heating).

occur at outdoor temperatures below 4 °C, while the heat pump allows to load the ATES even at ambient temperatures up to 14 °C. Consequently, the number of charging hours drastically increases.

The monitoring results allow to calculate the energy balance. Fig. 7 shows the monthly energy supplied by the ATES installation to heat and cool the ventilation air (histograms) and the average ambient temperature (solid line) over the whole monitoring campaign. As can be seen, there is a good correlation between the energy supplied by the installation and the average ambient temperature. During the winter months, the system delivers about 200–300 MWh/month of heat to the building, corresponding to the average power of 350 kW. About 150–200 MWh of cold is delivered to the hospital in an average summer month, although during the hot summer of 2003 this value peaked to about 280 MWh. It is also clear that in total the ATES system provided more heat than cold. There are two reasons for this. One is that the underground system is not fully in thermal balance, as will be discussed further on in this paper: overall more heat than cold is extracted from the ground. Another reason is that a large part of the heat supplied to the building is delivered by the heat pumps, whereby the electricity that they consume is also transferred to heat.

The Sankey diagram (Fig. 8) shows the total energy supply of the ATES system and the heat pump during the whole monitoring campaign. The largest part (7645 GJ or 81%) of the ATES cooling is applied directly for comfort cooling of the building. The remaining 19% (1776 GJ) of cooling is offered by the condensers of the heat pumps during summer (operating as a cooling machine). The resulting cooling power is mainly used to supply low-temperature cold to dehumidify of the surgery rooms. For heating, the warm well generally provides heat to the evaporator of the heat pump (78%). Only for limited periods of time, direct heating of the ventilation air is applied. This happens during the regeneration mode, where the cold well is charged while simultaneously the ventilation air is preheated.

To prevent thermal exhaustion of the wells and to guarantee the long-term operation of an ATES system, a good balance between the overall energy extracted from the ground and injected in the ground is important. The Sankey diagram reveals that the ATES system was not completely in thermal balance during the monitoring period. The groundwater system delivered 9.8 TJ of cooling (7.6 TJ by direct cooling and 2.1 TJ by the condensers of the heat pumps) versus 12.3 TJ of heating (2.7 TJ by direct heating and 9.6 TJ by the evaporators of the heat pumps), a difference of 26%. This is attributed to the manual control of the system and the lack of knowledge of the operator at the beginning of the operation of the system – the hospital was one of the first buildings to implement an ATES system with a heat pump for heating and cooling in Belgium. During the last year of the monitoring, the balance of the ATES system was improved, as there was only 16% difference in the energy balance. So, even after adjustment of the control strategy on an annual basis more cold is stored in the cold well than extracted. Consequently, the ATES system is always able to deliver enough cold. After all, the focus of the ATES system is on cooling and it is unarguably one of the most energy efficient cooling systems [4]. Nevertheless, the balance of the system is important. Cooling down of the warm well can cause problems in heating mode. Consequently, fine tuning the control strategy of the system is indispensable to prevent the depletion of the well in the future. Flexible control strategies for the HVAC systems could resolve the energy imbalance of the ATES systems. Therefore long term monitoring of the underground storage system is of significant importance. This should already be taken into account during the design of a project.

Also the COP for heating and cooling mode can be calculated from the diagram in Fig. 8. During the winter, the heat pump provide heat with an average $COP_{heating}$ of 5.6, while in summer, the heat pumps operate as cooling machines with an average $COP_{cooling}$ of 5.0. These high figures indicate that the working conditions (temperature levels of condenser and evaporator) are almost excellent because the secondary system (the AHUs) works at low temperature for heating and at high temperature for cooling. If also direct heating and cooling is taken into account as well as the electricity consumption of the different circulation pumps, the total SPF of the installation can be calculated. For heating, the SPFs were 5.5 (2003), 5.9 (2004) and 6.4 (2005), with an average of 5.9. For cooling, the values are 15.8 (2003), 57.9 (2004) and 43.9 (2005), with an average of 26.1. The relatively low value for 2003 can again be explained by the very hot summer. During this summer, active cooling by the heat pumps was much more prominent than usual. That summer only 69% of the cooling was supplied directly from the groundwater system, while on average over three years, this value was 81%. In conclusion, it is clear that this installation handles both cooling and heating in an efficient way.

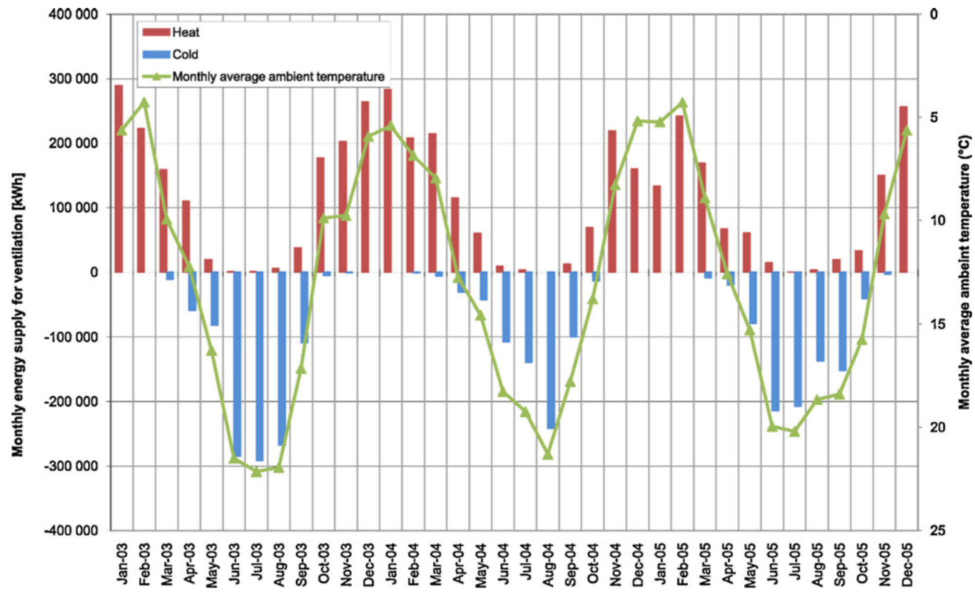

Fig. 7. Monthly heating and cooling supply by the installation during three years of operation (histograms) in relation to the ambient temperature (solid line).

3.3. Primary energy savings and CO_2 reduction

To determine the primary energy savings, the ATES and HP system is compared to a reference installation. As a reference situation, we consider that the cooling in the hospital is provided by a water-cooled cooling machine with a SPF of 3.5 and the heating by a gas-fired boiler with an efficiency of 85%. This is the typical setup for a conventional Belgian hospital. In this calculation, only the heating and cooling loads were considered. The energy requirements of the electrical circulation pumps of the HVAC system in the hospital were neglected (they are the same in the comparison). Next, the impact of the innovative installation on the CO_2 emissions over the monitoring period of three years is calculated. Primary energy use and CO_2 emissions are calculated according the European standard EN 15603:2008 [21] (Table 2).

The result of this comparison is shown in Table 3. The reference installation consumes considerably more primary energy than the ATES and HP system. In the ATES installation, gas consumption for conditioning the ventilation air is eliminated entirely and is replaced by electricity consumption of the source and heat pumps. However, because the heat pumps operate at a very high efficiency, even the total electricity consumption is only slightly above this of the reference installation over the total measuring campaign. In 2005 the electricity consumption of the ATES installation was even lower than that of the reference installation. Furthermore, the application of the ATES and HP system reduces CO_2 emissions by more than 1280 ton over the three years. There is a total primary energy saving of 71% for climatisation of the ventilation air. This corresponds to a CO_2-emission reduction of 73% as compared to the reference installation. As mentioned before, this installation only provides part of the total heating of the building. The rest of the heating is provided by gas boilers. Based on the annual gas bills of the hospital, one can conclude that the ATES installation delivers 46% of the total energy demand for heating of the hospital. If these gas boilers are taken into account, the CO_2-emission savings for the total climatisation energy of the hospital is 38%. Finally, the table shows that the efficiency of the system increased during the measuring campaign. The extensive active cooling in the summer of 2003 explains the lower value for that year. The difference between 2004 and 2005 is due to the difference in weather conditions: in 2005 more cooling was needed than in 2004, while for heating the opposite was true. Because the ATES installation is even more efficient for cooling than for heating in comparison with the reference installation, the relative primary energy savings were higher in 2005 than in 2004.

Table 2
Primary energy factors and CO_2 emission according EN 15603:2008 [21].

	Total primary energy factor	CO_2 emission factor (kg/MWh)
European electricity mix (UCPTE[a] countries)	3.31	617
Gas	1.36	277

[a] UCPTE: Union for the Coordination of the Transmission of Electricity.

3.4. Economic analysis

Also, the economic feasibility of the ATES installation and a reference installation has been assessed. For both installations, investment costs and energy costs (electricity and natural gas) were calculated based on the information obtained from the manufacturers and the owner of the hospital. An electricity price of €110/MWh and a natural gas price of € 35/MWh was used in the calculation. An SPF of 3.5 is assumed for the reference cooling machine and an average efficiency of the reference gas boiler of 85% is adopted. The results of the analysis are presented in Table 4.

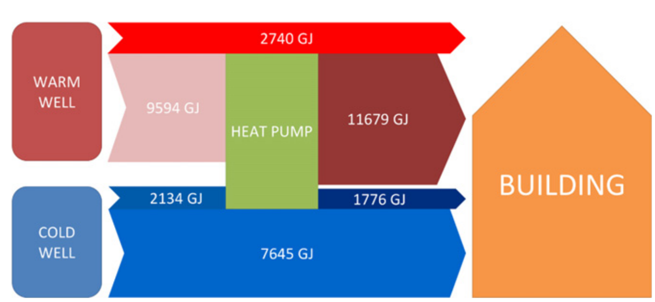

Fig. 8. Energy flows 2003–2005.

Table 3
Annual primary energy savings and CO_2 emission reduction.

		ATES system + heat pumps (installation Klina)				Gas-fired boilers + cooling machines (reference-installation)			
	Unit	2003	2004	2005	Total	2003	2004	2005	Total
Electricity consumption	MWh_e	343	242	198	782	313	193	242	748
Gas consumption	GJ	0	0	0	0	6340	5739	4884	16,964
Primary energy consumption	GJ_p	4082	2878	2362	9323	12,350	10,104	9527	31,981
Reduction primary energy consumption	GJ_p %	−8268 −67%	−7225 −72%	−7164 −75%	−22,658 −71%	–	–	–	–
CO_2-emissions	ton CO_{2eq}	211	149	122	483	681	561	525	1767
CO_2-emissions reduction	ton CO_{2eq} %	469 −69%	412 −73%	403 −77%	1284 −73%	–	–	–	–

Table 4
Economical analysis of the ATES system compared to the reference installation.

		ATES system + heat pumps (installation Klina)	Gas-fired boilers + cooling machines (reference-installation)
Investment costs	Underground installation (k€)	299	–
	Overground installation (k€)	266	241
	Heat exchangers	35	
	Pumps, ducts, appendages	46	
	Control equipment	116	
	Larger cooling coils	13	
	Frost protection cooling coils	32	
	Total installation costs (k€)	565	241
	Extra study and engineering costs for ATES installation (k€)	130	–
	Total, subsidies excluded (k€)	695	241
	Subsidies (k€)	244	–
	Total, subsidies included (k€)	451	241
Fuel costs	Cooling supply (MWh)	872	872
	Electricity consumption for cooling (MWh)	33	249
	Total cooling costs (k€)	3.7	27.4
	Heating supply (MWh)	1335	1335
	Gas consumption (MWh)	–	1571
	Gas costs for heating (k€)	–	55.0
	Electricity consumption for heating (MWh)	227	–
	Electricity costs (k€)	25.0	–
	Total heating costs (k€)	25.0	55.0
	Total fuel costs (k€/year)	28.7	82.4
Simple payback time	Subsidies excluded (years)	8.4	–
	Subsidies included (years)	3.9	–

The major cost of the ATES system is related to the underground installation. This includes wells, pumps, ducts, shut off valves and the heat exchanger. Since for the reference situation these components are not present, the reference installation is about k€ 450 cheaper than the more advanced installation. For the ATES system, a geological study and additional engineering costs need to be taken into account. Although the installation costs of the ATES system were a lot higher than those of a reference installation, to a large extent, these extra costs could be recovered by a subsidy of k€ 244.

The energy cost of the ATES installation is about k€ 54/year lower than the energy costs of the reference installation. The energy cost for cooling is about 85% lower than for a classical cooling installation, mainly due to the large share of natural cooling of the ATES installation. For heating, the difference is smaller. Still, 55% of the costs for heating are saved as compared to a gas-fired boiler installation.

The simple payback time, defined as the extra investment costs divided by the annual financial energy savings, is calculated. Even without subsidies the installation is economically feasible: the simple payback time is 8.4 years. Taking into account the subsidies, the payback time would even be less than four years.

4. Conclusions

The HVAC-installation in the Klina hospital consists of two heat pumps coupled to an ATES system. The installation is used for conditioning of the ventilation air. The system operated during three years without technical problems.

The results of the groundwater flow analysis show a good annual balance in pumped groundwater volumes. However, during the first years of operation, a large imbalance existed in energy transfer as more cold was injected into the ground than extracted. To date, the balance is more equilibrated, but to avoid depletion in the future adjusting the control strategy of the system could be necessary. This stresses the importance of long term monitoring of ATES systems, so that they can run over a long period of time.

The energy balance shows that the cooling was mainly provided by the direct use for groundwater (81% of the total cooling energy) while also 22% of the heating of the ventilation was provided by direct use of groundwater. This leads to high SPFs for the installation (5.9 for heating, 26.1 for cooling). The primary energy saving for the acclimatisation of the ventilation air reaches 71% as compared to a reference installation composed of gas-fired boilers and compression cooling machines. Furthermore, after three years of operation 1280 ton CO_2 was saved.

Our study also reveals that a well-designed ATES and HP system provides heating and cooling at a very high efficiency. The overall economic analysis indicates a payback time of 8.4 years without subsidies and an annual cost reduction of k€ 54 a year. These findings demonstrate that ATES systems are excellent environmentally friendly and economically feasible alternatives for heating and cooling supply in hospitals.

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