Research Paper

The effectiveness of night ventilation for the thermal balance of an aquifer thermal energy storage

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HIGHLIGHTS

• The ATES system achieved a thermal balance of 11–12% using regeneration strategies.
• Co-simulation method was applied using MATLAB, TRNSYS and COMSOL.
• Night ventilation was determined as a prominent option for thermal balancing methods.
• The system COP was improved by 26.4% by using night ventilation.

ARTICLE INFO

Keywords:
Aquifer thermal energy storage
Aquifer thermal
Thermal imbalance aquifer
Regeneration aquifer thermal

ABSTRACT

Aquifer thermal energy storage (ATES) is a significant source of heating/cooling systems due to its energy and cost efficient operation. To ensure environmental and energy sustainability, the use of ATES is governed by strict regulations, one of which is the requirement of maintaining a balance in the amount of heat transfer into the ground. In general, the combination of a heat pump (HP) and an air handling unit (AHU) are commonly used to achieve this thermal balance through regeneration strategies for cooling dominated loads. However, this approach increases the operational cost and energy consumption of ATES heating/cooling systems. In this paper, an alternative approach that makes use of night ventilation (NV) for regeneration is evaluated. In addition, the operational cost and energy efficiencies of the commonly used combination of an HP and AHU are compared to those associated with NV operation. The results show that using NV for the regeneration of the cold well could reduce energy consumption by 19.3 MWh/year, which amounts to a 26.4% increase in system coefficient of performance (COP).

1. Introduction

To reduce the energy consumption of heating and cooling systems in the built environment, the ground has been identified as an efficient energy storage source in areas where ground conditions are suitable for the availability of the underground water [1,2]. Thermal systems, such as an aquifer thermal energy system (ATES) that make use of groundwater for long-term storage of thermal energy, are now in coastal areas becoming common features of modern large buildings due to the cost effectiveness of the system due to suitable ground and weather conditions. When used in a building, an ATES system removes heat from the building during cooling periods and provides heat during periods of heating. The cold and heat extracted from the building are stored in separate warm and cold wells underground with temperatures between 16 and 18 °C in the warm well and between 6 and 8 °C in the cold well [1,3]. The economic and technical advantages of ATES over traditional cooling/heating system have been already proven [4]. Due to the highly efficient energy storage capabilities of ATES, these systems are a good option for achieving the goals of carbon emission reduction and improving the energy efficiency of the built environment.

Similar to many other technical solutions, the use of ATES is controlled by governmental regulations [1]. Specifically, in locations where ATES systems are densely installed, regulations are strict with regard to installation of new systems and the preservation of their long-term efficiency. One of these regulations is the maintenance of thermal balance in the amount of the heat injected into and extracted from the ground. Achieving thermal balance in the ground prevents future thermal interaction between the well groups. The imbalance between heating or cooling building loads in a particular system results in dominance of either the warm or cold well, which degrades the other well over the long term as a result of thermal interaction [5]. According to the regulative framework for the Netherlands, an ATES system...
should be in a thermal balance range of 0–15% over a period of 5–10 years [6].

For a cooling dominated building load, in order to maintain the thermal balance of a well within the required range, heat pumps (HPs) [4,7,8], cooling towers (CTs) [9,10], and air handling units (AHUs) [4,7] are used to compensate for the surplus heat in the ground. Thermal balancing methods are also known as “regeneration” methods. Fig. 1 illustrates the system studied in [9]. In order to balance the surplus heat injection to the warm well, an AHU is activated when the ambient air temperature falls below 4 °C to expel the heat from the warm well to be injected in the cold well as cold source. It is common practice to use the heating/cooling coil of an AHU and HP together as cold compensators [8,7]. In an experimental study of a functional ATES system by Vandhout et al. [4], it was demonstrated that the AHU was used for cold compensation. The AHU was activated for thermal balancing when the ambient air temperature was lower than 4 °C during non-office hours to expel additional heat from the ground. This approach is called direct compensation (DC) from an AHU [4]. In cases where cold compensation is not sufficiently achieved by the AHU, the HP is activated to compensate for the remaining thermal imbalance ratio. This approach is called direct compensation from heat pump (HPC). Unlike an AHU, the operation of HPs is not limited to the ambient air temperature, which makes an HP a reliable cold/heat compensation unit.

Another approach that can be used for cold compensation is night ventilation (NV). Night ventilation is used in buildings to increase the efficiency of cooling and decrease the cooling load in the building [11–13]. Night ventilation is capable of removing a portion of accumulated heat from a building by utilizing the lower outside temperatures present at night. Thus, the quantity of heat injection into the ground decreases due to the decreased cooling and peak cooling demand on the ATES system, which assists the system in eliminating HP operation in the cooling mode from the ATES system, while at the same time, reaching a thermal balance between the heating and cooling demand.

So far, the studies concerning ATES are limited to the advanced thermal modelling of underground [14–18] and few simulation on the system level, where ATES is connected to HVAC system [10,19]. Those studies [10,19] were based on some parametric studies for operational settings without taking into account the influence of the dynamic building load. However, in the real applications, the thermally unbalanced building load is inevitable and has significant influence on the performance, which was proven in experimental analysis [8,4]. Although the use of AHUs and HPs for cold compensation is very common in practice [3,4,8,20] for ATES system, the use of NV as a viable alternative has been limited. Therefore, this study aims to evaluate the performance of these two thermal balancing strategies. The performance of the strategies is evaluated based on two metrics: the efficient operation of ATES and the operational costs for thermal balancing. In this study, the operation, cost, and energy effectiveness of the two thermal balancing strategies are analyzed. One of these thermal balancing strategies is utilizing AHU in DC mode and utilizing HP in HPC mode as was applied in [4]. In the other strategy, HPC is replaced with NV using AHU; thus, air handling unit is utilized in DC and NV mode. It is the aim of this study to determine the effectiveness of NV as the cold compensation method. The cost of the compensation methods is analyzed numerically. A cooling dominated building is considered as a case study based on the fact that buildings are becoming more cooling dominated due to improved air tightness and advanced insulation techniques [1,9].

The remaining sections of the paper are structured as follows: First, the base case with cooling dominancy is presented, followed by two compensation control strategies applied to this case. Correspondingly, the heat transfer characteristics and the influence on the temperature of the ATES system are presented. Finally, the energy performance and operational costs are calculated.

2. Previous studies

Since ATES systems are commonly applied in commercial buildings, the majority of these systems are exposed to cooling dominant building loads [10]. Aquifer thermal energy storage is an energy efficient system [3,10]. However, thermal imbalances should be accounted for in
overall system performance due to the extra cost of cold regeneration. As thermal imbalance grows, the system will incur additional costs for the compensation of this thermal imbalance \[1\].

ATES systems have been popularly used in Canada \[21,22\], USA \[23–25\], Asia \[26–28\] and Europe \[26–30\]. Due to the lack of simulation tools for ATES, most previous studies have been based on experimental studies with a focus on groundwater quality \[26\], feasibility studies \[29\] and performance analysis \[1,4,7,13,23,27\]. Table 1 shows a list of experimental studies in which thermal imbalances are addressed. The Technical University of Eindhoven utilizes the largest size ATES system on its campus, and this produces more than 20 MWh of energy in the Netherlands \[31\]. Due to the internal heat gain in the buildings and high cooling demand of laboratories, the university has a cooling dominated load profile. Therefore, cooling supply from the ATES system is supported by a cooling tower (CT), which balances the amount of heat underground by acting as supplementary heat rejector \[37\]. Similarly, Stockton College in New Jersey utilizes ATES connected to a CT for additional heat rejection \[10\]. A commercial building located in Utrecht employs AHU to charge the cold well when the ambient temperature is suitable and an HP when AHU are not utilized \[10\]. Related to this, Vanhoudt et al. \[4\] and Kranz et al. \[6\] analyzed how the ATES system uses AHUs to regenerate cold wells.

Vanhoudt et al. \[4\] conducted an experimental study of an ATES system for a Belgian hospital and concluded that the system utilizes AHU and an HP depending on the thermal imbalance ratio. The HP operates at peak hours when ATES is not sufficient for direct cooling. In order to eliminate HP operation, either ATES temperatures can be lowered through additional cold storage or the cooling demand can be decreased. One office building in the Netherlands is utilizing NV to decrease HP operation time by decreasing the cooling demand within the building. In addition, NV assists the building in decreasing the peak cooling demand hours that further decreases the HP operation required by the ATES system. The effectiveness of NV in decreasing peak cooling and cooling demand has been proven in many studies.

Current simulation studies concerning ATES systems are limited to performance analysis integrated with solar thermal \[10\], combined heat and power (CHP) \[32\] cooling tower \[10\] and AHU \[8\]. Ghaeibi et al. \[10\] investigated the performance of ATES in different modes, physical parameters of the underground and operational settings such as injection temperature and flow rate to the ATES, and concluded that the COP of ATES could be as high as 17.2 in cooling mode in combination with HP. Zeghici et al. \[32\] compared the high temperature ATES integrated district heating system with an existing traditional district system connected to a power plant. The ATES system showed energy savings of 44%. Kranz et al. \[8\] made a sensitivity analysis of operational settings of an ATES system to determine the optimal design settings. It was observed that none of those studies \[10,8,32\] included the thermal imbalance influence on the system performance. However, practically, thermal imbalances on the building load should be taken into account since the building load profile has direct influence on the temperature profile. In addition, the operational cost from the thermal compensation methods needs to be evaluated as well since they are caused by the extra energy consumption within the system.

In practical applications \[4\], thermal balance of ATES has been achieved only through increasing the amount of charged cold in the ground by utilizing DC and HPC methods. The alternative solution presented in this paper achieves thermal balance by increasing the amount of charged cold using DC, while simultaneously decreasing the cooling demand using NV, which results in less heat injection to the ground, in the building. Therefore, this paper intended to explore the performance of NV as cold compensation strategy in substitute for HP.

3. Methodology

3.1. Case study building and system description

The building model in the case study is an office building in the Netherlands. The building has a total area of 3520 m² and volume of 9370 m³. It is a modern building with a cooling dominant building load due to advanced insulation techniques and a high amount of internal heat gain. The building requires an annual heat injection of 426 MWh and heat extraction of 86 MWh. The ATES system works in a cyclical mode. The injection temperature was designed at 16 °C for the warm well and 8 °C for the cold well. The maximum heating or cooling capacity also changes depending on operation. While heat is supplied to the building, in the building. Therefore, this paper intended to explore the performance of NV as cold compensation strategy in substitute for HP.

Table 1

<table>
<thead>
<tr>
<th>Ref. Location</th>
<th>Cooling dominated</th>
<th>Heating dominated</th>
<th>Cold-warm well injection temp.</th>
<th>System components</th>
<th>Building type</th>
</tr>
</thead>
<tbody>
<tr>
<td>[31] Eindhoven, Netherlands ✓</td>
<td>✓</td>
<td>6/16</td>
<td>ATES + HP + CT</td>
<td>University</td>
<td></td>
</tr>
<tr>
<td>[7] Utrecht, Netherlands ✓</td>
<td>✓</td>
<td>8/14</td>
<td>ATES + HP + AHU</td>
<td>Office building</td>
<td></td>
</tr>
<tr>
<td>[10] Tehran, Iran ✓</td>
<td>✓</td>
<td>3/14, 43/65</td>
<td>ATES + HP + CT + solar thermal</td>
<td>Residential building</td>
<td></td>
</tr>
<tr>
<td>[32] Bucharest, Romania ✓</td>
<td>✓</td>
<td>5/15, 35/50</td>
<td>ATES + HP + CHP</td>
<td>Community building</td>
<td></td>
</tr>
<tr>
<td>[9] Hamburg, Munich, Berlin, Germany ✓</td>
<td>✓</td>
<td>8/14</td>
<td>ATES + CT + HP</td>
<td>Data center</td>
<td></td>
</tr>
<tr>
<td>[13] Rostock, Germany ✓</td>
<td>✓</td>
<td>10/50</td>
<td>ATES + HP + solar thermal + boiler</td>
<td>Collective system</td>
<td></td>
</tr>
<tr>
<td>[33] Oslo, Norway ✓</td>
<td>✓</td>
<td>18</td>
<td>ATES + AHU</td>
<td>Airport</td>
<td></td>
</tr>
<tr>
<td>[34] Merin, Turkey ✓</td>
<td>✓</td>
<td>9/20</td>
<td>ATES + AHU</td>
<td>Hospital</td>
<td></td>
</tr>
<tr>
<td>[35] Adana, Turkey ✓</td>
<td>✓</td>
<td>/40</td>
<td>ATES</td>
<td>Commercial building</td>
<td></td>
</tr>
<tr>
<td>[27] Shanghai, China ✓</td>
<td>✓</td>
<td>11–17/25–30</td>
<td>ATES</td>
<td>Exhibition Hall</td>
<td></td>
</tr>
<tr>
<td>[29] Ottowa, Canada ✓</td>
<td>✓</td>
<td>–</td>
<td>ATES</td>
<td>University</td>
<td></td>
</tr>
<tr>
<td>[23] Alabama, USA ✓</td>
<td>✓</td>
<td>/35–81</td>
<td>ATES</td>
<td>Commercial building</td>
<td></td>
</tr>
</tbody>
</table>
reject heat directly using the ambient air. The coil of the AHU can be used for both heating and cooling (Fig. 2).

3.2. Principle of the AHU-HP-ATES system

The office building operates between 7 a.m. and 7 p.m. on workdays and is not operational during the weekends. There are four different operation modes within the system: the heating mode, the direct cooling mode, the chiller mode, and the regeneration mode. The ATES system is either directly connected or connected through the HP to the heating/cooling coil. In the heating mode, the system activates the HP and the ATES system. Since the warm well temperature is not high enough for direct supply, the ATES system extracts heat from the warm well and ejects it into the evaporator of HP. Heated water exchanges heat with the building through the heating/cooling coil. In the cooling mode, the control system activates the ATES system for direct supply when the indoor temperature exceeds 23 °C. The ATES system can provide sufficient cooling depending on the availability of the cold source and the building load. The ATES system directly exchanges heat with air through the AHU, where the return water temperature reaches 16–25 °C. The HP operates in chiller mode to further chill the water coming from the ATES system in cases when the indoor temperature exceeds 25 °C, which means that direct cooling supply through ATES is insufficient. In chiller mode, the water from the cold well rejects heat first from the air returned from the building and then from the condenser, where the return water temperature is further increased and can be as high as 25–30 °C. Detailed information about the regeneration mode is provided in the section below.

3.3. Regeneration strategy

Due to the dominant cooling load, the building operates various regeneration strategies for achieving thermal balance. As is also applied in this study, ATES systems typically operate in conjunction with the HP and air water heat exchanger of the AHU to regenerate their cold well [4,8]. The water coming from the warm well is cooled by ejecting its heat into the air using a fan connected to the heating/cooling coil, when the ambient temperature goes below 4 °C to inject the water temperature in the desired values to the cold well. When the ambient conditions are suitable, the operation of the AHU is prioritized, since the COP of an AHU is higher than the COP of an HP. The warm well is directly connected to the AHU for direct cold compensation. Since the AHU is responsible for distribution of conditioned ventilation air, it is only possible to operate the system in the regeneration mode during non-working hours. Unlike the AHU, the HP has no limitation with regard to ambient conditions and can operate to reject additional heat from the warm well if thermal balance is not reached [4]. In addition, the AHU can be used with NV mode during the cooling period, which enables the system to remove a portion of heat from the building, therefore, contributing to decreasing the heat injection into the ground and eliminating heat pump operation for cooling.

The following regeneration strategies were applied to achieve thermal balance in the ATES system. The regeneration strategies were presented in Fig. 3A–C (dashed line represents inactive line, normal line represents active lines):

Base case: The building utilizes no regeneration strategy.

Fig. 3. (A) Heat pump compensation. (B) Direct compensation. (C) Night ventilation.
Case 1. The building utilizes AHU regeneration and NV. The AHU operates in two modes: DC and NV mode. First, the system utilizes the AHU to reject heat when the ambient temperature ($T_a$) is below 4 °C in DC mode, while NV mode is activated during the cooling period. (Fig. 3B and C).

Night ventilation strategy in the building is applied with the following rules [36]:

- The building is cooled to a set point of 19 °C before the day begins;
- Night ventilation begins if the indoor temperature ($T_i$) is above 22 °C;
- There should be at least 4 °C difference between the indoor and outdoor temperatures;
- Operation time is between 2 a.m. and 5 a.m. when the ambient air temperature reaches its lowest point.

Case 2. The building utilizes DC and HPC. The HP operates in conjunction with the AHU during non-office hours. AHU operates with DC mode to compensate the maximum possible amount of heat when the ambient temperature is lower than 4 °C during non-office hours. The HP compensates for the remaining thermal imbalance ratio (Fig. 3A and B).

The quantity of operation hours for regeneration is calculated based on the thermal imbalance in the first year of operation. First, the thermal balance for Case 1 is calculated using NV and DC. Later, the amount of HPC needed to achieve the same thermal balance ratio is calculated. In both cases, the AHU operates as much as possible in DC mode. The remaining heat is compensated for with NV mode in Case 1 and with HPC in Case 2 (Fig. 4). In this way, it is possible to create a reliable comparison between HPC and NV.

3.4. Building and HVAC models

The entire energy flow network for this study was built in TRNSYS. A numerical model was developed for ATES using the finite element method in COMSOL and integrated into the TRNSYS network using the type 155-MATLAB component. TRNSYS has been popularly used to simulate BTES and ATES integrated HVAC systems, [8,37,38]. Type 927 was used for the HP model [39]. Type 927 represents a single stage water-to-water HP based on user supplied data files containing catalog data for the normalized capacity and power draw. Two fan coil components (type 928) were used to model the air water heat exchanger. The building was separated into nine air nodes. Multi-zone building model (type 56) was used to simulate the building load. Air cooling/heating supply was integrated into each node and the supply air was linearly interpolated depending on the volume of each node. All the parameters were adjusted in accordance with the actual technical datasheets of the units. Variable discharging pumps (type 110) were connected to heat exchanger-type 761 to maintain a certain amount of temperature difference between entering and exiting temperature so that the system operates when the temperature difference is greater than 2 °C. Control of the system is implemented under set point based controllers in the building. Type 2-AquastatC and Type2-AquastatH were used to control the indoor temperature and Type 2d (differential controller) was used to control the HVAC components in the system.

3.4.1. The ATES model

The ATES model was numerically solved using the finite element method. The flow of water in porous media was solved based on the Darcy law and coupled with a heat transfer function to determine the temperature distribution throughout the meshed domain. The model was validated with an experimental data from an operational ATES in Amsterdam. The model used in [40], where detailed information can be found, is employed in this paper as well. The parameters in Table 2 was applied for the model.

3.4.2. Heat pump model

Manufacturer’s specification of the HP, including power, cooling/heating capacity, and the rated load/source flow rates are shown in (Table 3). Two external files (for cooling and heating) were incorporated into the HP model in which the model reads the catalog data...
Fig. 4. Control algorithm for thermal balance (IR: imbalance ratio, $T_a$: Ambient temp., $T_i$: Indoor temp.)

Table 2
Physical parameters of ATES.

<table>
<thead>
<tr>
<th>Physical conditions</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity</td>
<td>$5 \times 10^{-4}$</td>
<td>m/s</td>
</tr>
<tr>
<td>Thermal conductivity of aquifer</td>
<td>2.5</td>
<td>W/(m°C)</td>
</tr>
<tr>
<td>Initial ground temperature cold well</td>
<td>12</td>
<td>°C</td>
</tr>
<tr>
<td>Mean ambient temperature</td>
<td>10.4</td>
<td>°C</td>
</tr>
<tr>
<td>Effective porosity</td>
<td>35</td>
<td>%</td>
</tr>
<tr>
<td>Thickness of the aquifer</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Volumetric heat capacity of aquifer</td>
<td>2.45</td>
<td>MJ/(m$^3$K)</td>
</tr>
</tbody>
</table>

Table 3
Physical parameters of HP.

<table>
<thead>
<tr>
<th>Physical conditions</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>The rated source/load flow rate</td>
<td>50/50</td>
<td>m$^3$/h</td>
</tr>
<tr>
<td>The rated cooling capacity/power</td>
<td>200/38.4</td>
<td>kW</td>
</tr>
<tr>
<td>The rated heating capacity/power</td>
<td>216/46.3</td>
<td>kW</td>
</tr>
<tr>
<td>The rated cooling COP</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>The rated heating COP</td>
<td>4.67</td>
<td></td>
</tr>
</tbody>
</table>
for the capacity varying with entering water temperature to evaporator and condenser. The model receives the data either from the cooling or heating file based on the control signal that activates HP operation in cooling or heating mode.

### 3.4.3. Pump model

The power consumption of the well pump varies linearly with the flow rate. Flow rate varies based on the temperature difference between the warm and cold wells and the amount of heat transfer to the building.

\[
W_{\text{pump,ww}} = \left(\frac{Q_b}{C_p\text{water}(T_{\text{ww}} - 3)}\right)\left(V_{\text{max}}\right)W_{\text{max}}
\]

(1)

\[
W_{\text{pump,cw}} = \left(\frac{Q_b}{C_p\text{water}(16 - T_{\text{cw}})}\right)\left(V_{\text{max}}\right)W_{\text{max}}
\]

(2)

where, \(Q_b\) is the heat transfer to the building, \(C_p\text{water}\) is the specific heat capacity of the water, \(T_{\text{ww}}\) is the extraction temperature from the warm well, \(T_{\text{cw}}\) is the extraction temperature from the cold well, \(W_{\text{pump,ww}}\) is the supplied power for the warm well pump, and \(W_{\text{pump,cw}}\) is the supplied power for the cold well pump.

### 3.5. The Co-simulation for TRNSYS-MATLAB-COMSOL

Co-simulation between the three software MATLAB, COMSOL, and TRNSYS was used for this evaluation. Combining different software allows the user to utilize the differing strengths of the simulation tools. For instance, COMSOL allows users to accurately analyze the behavior of ATES using finite element method [40], while TRNSYS is a powerful simulation tool for simulating complex HVAC systems within a building. Due to the lack of tools used to simulate ATES integration into a building, this study developed a co-simulation tool for the ATES and HVAC systems. Unlike the known co-simulation approaches from past studies, such as Energy plus with Java [41], Energy plus with MATLAB, and Energy plus with CFD [42], a co-simulation approach towards CFD in connection to TRNSYS is a relatively new concept. Which has proven to be effective in predicting the behavior of complex models in comparison to the TRNSYS model [43].

With the MATLAB component (type 155) of TRNSYS, it is possible to call external functions written in MATLAB script. There is also a toolbox called COMSOL live-link MATLAB that is able to link MATLAB to COMSOLMATLAB, which is responsible for information exchange and acting as the master connecting COMSOL and TRNSYS. MATLAB is responsible for transmitting the necessary information between COMSOL and TRNSYS. COMSOL required information from TRNSYS, including inlet water temperature, inlet flow rate, and the percentage of pump discharge (flow rate) to calculate the heat transfer in the aquifer. The warm well and cold well signals were used to decide which well was in charging or discharging mode. Eventually, the warm and cold well models simultaneously implemented the input variables and sent the outputs, including the outlet water temperature and flow rate, back to TRNSYS through type 155-MATLAB component. It is possible to increase the number of inputs and outputs as many as needed using type 155.

### 3.6. Energy performance evaluation

Electricity consumption differs depending on the mode of operation. For an AHU in DC mode, the system operates the fan of the AHU and the pump of the ATES system, while an AHU in NV mode employs only the fan of the AHU. The performance indicators for the regeneration method are calculated separately. \(\text{COP}_{\text{IP,reg}}\) is calculated to determine the performance of an HP in HPC mode, while \(\text{COP}_{\text{DC,reg}}\) is the performance indicator of an AHU in DC mode.

\[
\text{COP}_{\text{DC,reg}} = \frac{Q_{\text{sup,a}}}{P_{\text{fan}} + W_{\text{pump,ww}}}
\]

(3)

\[
\text{COP}_{\text{HP}} = \frac{Q_{\text{sup,a}}}{P_{\text{fan}} + P_{\text{HP}} + W_{\text{pump,ww}}}
\]

(4)

\[
\text{COP}_{\text{direct cooling}} = \frac{Q_{\text{sup,a}}}{P_{\text{fan}} + W_{\text{pump,cw}}}
\]

(5)

\[
\text{COP}_{\text{HP,\text{cw}}b} = \frac{Q_{\text{sup,b}}}{P_{\text{fan}} + P_{\text{HP}} + W_{\text{pump,ww}}}
\]

(6)

\[
\text{COP}_{\text{HP,\text{cw}}b} = \frac{Q_{\text{sup,b}}}{P_{\text{fan}} + P_{\text{HP}} + W_{\text{pump,ww}}}
\]

(7)

\[
\text{COP}_{\text{sys}} = \frac{Q_{\text{cool}} + Q_{\text{heat}}}{W_{\text{fan}} + W_{\text{pump,cw}} + W_{\text{pump,ww}} + W_{\text{hp}}}
\]

(8)

where \(Q_{\text{sup,a}}\) is the extracted heat from the ATES system, \(Q_{\text{sup,b}}\) is the supplied heat to the building, \(P_{\text{fan}}\) is the power consumption of the fan of the AHU, \(P_{\text{HP}}\) is the power consumption of the HP, and \(\text{COP}_{\text{sys}}\) is the system COP.

### 4. Results

In this section, the thermal imbalance ratio and temperature variation of the ATES are analyzed first. Then, the heat transfer to the ground and the COP of components for each time step are calculated. Last, the total energy consumption under different modes of operation is determined. Results were derived based on the last year of operation, in which the temperature in the ATES system became stable [10].

#### 4.1. Temperature

As shown in Fig. 5, the temperature change in ATES was projected over a period of five years. After five years of the operation, the heat recovery was found to have a negligible change [5]. It was observed that while thermal balancing significantly improved the temperature in the cold well, the warm well temperature was not heavily influenced, since it was already close to the maximal extraction temperature of 16 °C in the base case. However, the average extraction temperature from the cold well was improved significantly from 11.1 to 8.6 °C at the end of the five-year period, as the average extraction temperature from the cold well in the base case was far from the minimal extraction temperature of 8 °C.

#### 4.2. Operation time

As can be seen in Fig. 6, the number of operation hours for cooling dominates the heating hours for the base case due to the cooling dominated load. For Case 1 and Case 2, the AHU operates with DC mode more frequently during December, January, and February since the ambient temperature was low enough, which amounted in total to 745 h/year. It was observed that ambient conditions are quite suitable for NV. The highest amount of NV operation was in July, which amounted to 54 h/month, whereas the lowest operation was in April, with 17 h/month. As ambient temperatures and solar radiation increase, the heat accumulation in the indoor environment increases as well, which triggers the operation of NV more frequently. The total amount of NV operation was 306 h/year for Case 1. For Case 2, whenever the ambient conditions were not suitable for DC, HPC operated during the winter season until the calculated thermal balance ratio for Case 1 was achieved. The total amount of HPC operation was calculated as 348 h/year.
4.3. Heat transfer

The monthly accumulated and hourly heat transfer rates to the ground for the base case, Case 1, and Case 2 are represented. As the operation hours of the system components vary (Fig. 6), it can be seen that rates of heat transfer to the ground vary (Figs. 8 and 9). The base case represented the thermal imbalance of 80%, which amounts to injected heat of 426 MWh and extracted heat of 86 MWh.

Both Case 1 and Case 2 reached the thermal imbalance ratio of 11–12%. The heat extraction rate of DC and base heat extraction were at a maximum in January due to the low ambient temperature. The heat injection rates were mainly influenced by parameters such as ambient temperature and solar radiation, which affect the building cooling load. Although there was a certain correlation between ambient temperature and injection rates, solar radiation played a significant role; the injected heat was higher in June and July compared to August due to the relatively lower solar radiation in August.

The hourly heat transfer from DC is highly influenced by the ambient temperature (Fig. 8), since the heat is directly removed with the use of ambient air. The highest extraction rate was as high as 491 kWh.
when the ambient temperature was \(-7.8\) °C. For Case 1, besides DC, NV assisted in the reduction of the annual heat injection of 87 MWh since NV eliminates a portion of the cooling demand by removing accumulated heat during the night. Night ventilation was especially effective during June, July, and August, when the heat accumulation within the building was high. The influence of NV on the indoor temperature was clearly presented (Fig. 7), which ultimately lowers the heat rejection into the ground (Fig. 9) and the peak thermal load of the building by lowering the indoor temperature. The yearly accumulated injected heat and the extracted heat reached 339 and 301 MWh/year, respectively. In Case 2, HPC extracted 74 MWh/year of heat, while DC extracted 215 MWh/year. The annual extracted and injected heat values were calculated as 376 and 426 MWh/year, respectively.

4.4. Ground pumping

The energy consumption of the pump in the wells was mainly influenced by the temperature of the source from the wells and the amount of heat transfer to the building (Eqs. (1) and (2)). Therefore it was possible to see similarities in the trends of heat transfer to the ground and the electricity consumption of the pump (Fig. 10). In all cases, power consumption is the highest during the cooling mode (Fig. 10) due to the relatively higher cooling power capacity in comparison to the heating power capacity. In addition, the average power consumption of the pump was the highest in HP cooling mode, due to the fact that the ATES system with HP reached the highest cooling capacity. There was an apparent difference between the base case and the other cases in power consumption in the cooling mode since the thermal quality of the cold well was the lowest for the base case. In addition, it was possible to observe a difference between Case 1 and Case 2 in the cooling mode. Although the supply temperature is the same for both systems, NV assists the system in decreasing the peak cooling demand, which results in lower average electricity consumption by the pump. In comparison, no significant difference was observed in the heating mode since there was no significant change in the average supply temperature from the warm well (Fig. 5). It is possible to see
such similarities in the trend of pump electricity consumption in another study [4] that conducted an experimental analysis with an ATES system.

4.5. Coefficient of performance

Coefficient of performance differs depending on the mode of operation. Fig. 11 indicates the difference between the COP values of each operation mode. As mentioned in Section 2, AHUs provide energy efficient cold compensation in comparison to HPs. Therefore, the AHU was given priority to operate in DC mode before HPC mode, which is also commonly applied in the real world applications [4]. Coefficient of performance values of the units were presented starting from cooling season. The COP of DC can be as high as 16.7 when the ambient temperature is at its lowest. The average COP for DC and HPC was calculated as 11.6 and 4, respectively. The COP of direct cooling can be as high as 35.5 and fluctuates often depending on the incoming air temperature and the supply water temperature. The COP difference between direct cooling and the HP cooling mode is apparent. The average COP for direct cooling and HP in chiller mode was determined as 22.7.
and 3.1, respectively (Eqs. (3)–(8)).

4.6. Energy performance

As shown in Section 4.1., the cold well temperature is more noticeably influenced by regeneration and additionally, the temperature change in the cold well can potentially influence the performance of the system due to the direct cooling option. Motivated by this, analyses of the cooling supply specifically and the entire system performance are presented in this section.

Fig. 12 clearly presents the differences in HP operation for cooling. In the base case, the maximum NP operation accounts for 492 h/year of operation. The deviation was relatively higher during June, July, and August in comparison to Case 1 and Case 2, due to the increase in cooling and peak cooling demand. Due to the improvement of the cold well temperature, where the average extraction temperature decreased from 11.1 to 8.6 °C, Case 2 was able to eliminate HP operation by 85 h/year. For Case 1, the cold well temperature was improved as in Case 2, and the peak hours were additionally decreased using NV. As a result, Case 1 eliminated 144 h/year of HP operation for cooling in comparison to the base case. The influence of NV was quite apparent during June, July, and August, since NV was able to eliminate a high amount of cooling load.

As mentioned in the introduction [1], thermal balancing strategies are considered to be extra operational costs for the system. For the last year of operation, the annual electricity consumption was determined to be 70.6, 78.9, and 98.2 MWh for the base case, Case 1, and Case 2, respectively. The traditional regeneration strategy (Case 2) increased electricity consumption by 40%, while Case 1 increased the electricity consumption by only 11.8% (Fig. 13). Eventually, COPsys were calculated as 7.5, 6.7, and 5.3 for the base case, Case 1, and Case 2, respectively. The deviation in energy consumption stemmed from the effectiveness of the cooling supply. The electricity consumption for heating differs slightly due to the minor change in supply temperature year.

Fig. 11. Coefficient of performance values for the operation modes for Case 2.

Fig. 12. The number of chiller operation hours.
from the warm well. Energy performance differs significantly for the cooling supply due to the participation of the various operation modes, specifically for HP cooling. Cooling performance was mainly improved by decreasing the number of HP cooling operation hours (Fig. 12) from 492 to 348 h/year. Another significant difference between Case 1 and Case 2 was the utilization of the HP for HPC operation. In comparison to NV operation, HPC operation was a costly cold compensation method and resulted in the highest additional cost.

5. Discussion

Currently, the investigation of thermal imbalance has been mostly investigated for BTES, where heat is injected and extracted to/from the same field [38,37,44–46]. In those studies [38,37,44–46], it was concluded that reaching thermal balance was capable of improving overall performance and reducing the operational and initial costs of the system in the long term due to the severity of the effect of thermal imbalance on the source temperature. The change in source temperature ranged from −10 to 13 °C, depending on the thermal imbalance ratio. Due to the fact that heat and cold sources are separated in an ATES system, the influence on temperature is relatively small. In this study, the temperature variation was 2.5 °C over a period of five years for the cold well. The temperature change was limited by the improvement in the heat recovery, which was negligibly small after the fifth year of operation [10]. While the thermal imbalance of 80% in this study resulted in 2.5 °C deviation in the extraction temperature of the cold source temperature of the ATES system, in the BTES system, thermal imbalance of 80–90% resulted in an average temperature decrease of 10.9 °C [38] and 9.8 °C [47] for the source temperature.

In some previous numerical studies [7–9], ATES has been considered as an isolated storage system without connecting with buildings and the system has been analyzed based on different operational parameters, such as injection, extraction temperature, and the volume of cold/heat source. ATES systems offer great opportunity for energy reduction in cooling supply due to the suitable source temperature, the cooling COP can be as high as 17.2 [10] and 16 [9] depending on the amount of cold preserved in the cold well. However, it is not possible to fix the supply temperature from the cold well by isolating ATES from the building load since the dynamic building load profile has a direct influence on the amount of cold in the cold well. This study has shown that the thermal potential of an ATES is highly influenced by the thermal load. In the case with thermally unbalanced load, the cold well temperature was as high as 11.1 °C while in the case with thermally balanced load the temperature was 8.6 °C. In addition, when regeneration applied, it is observed that the performance of the ATES system was further decreased (from the system COP of 7.5 to 6.7).

These findings are novel which can only be obtained when buildings and ATES are modelled as a whole.

In this study, we evaluated the system with 80% thermal imbalance ratio and the findings proved the advantage of NV over HPC mode for reaching a balance. Without a doubt, the performance of the components varies depending on the ambient conditions and some physical parameters within the system. For this specific case study, night ventilation was capable of reducing the cooling load by 20% (from 426 MWh to 339 MWh). This is in line with existing studies [48–50] concerning NV, which have shown that cooling load reduction vary between 18 and 50%. As the efficiency of NV increases, the system gets more economical benefit. For instance, the location that has relatively higher outdoor temperature swing can get more benefit from NV. Besides, in reality, the weather conditions varies from season to season which might result in major changes in the system performance. For instance, if the weather condition is colder for a cooling dominated load, the thermal load will get closer to a thermal balance, which results in less additional cost of operation. In addition, low ambient temperature results in energy efficient operation of DC mode. As a result, the system performance is highly influenced by the ambient conditions.

Considering the dynamic relationship between the ATES performance and the ambient conditions, the fixed control strategies as in this study are not applicable for the real cases to maintain a high performing ATES system. There is a need for adaptive control strategies such as model predictive control. This is study is limited to the fixed control settings in order to determine the potential influence of NV over HPC. Further studies can be conducted for the building under various climate region and with various control strategies.

6. Conclusions

In this paper, the ATES system performances of two thermal balancing methods were presented. One method uses an HP in HPC mode and an AHU in DC mode. The other method uses NV and an AHU in DC mode. The following conclusions can be drawn from this study:

- While the base thermal load represented a thermal imbalance of 80%, the system managed to reach a thermal balance of 11–12% for both cases using the regeneration strategies.
- With the operation of NV, heat injection into the ground was decreased by 87 MWh, which amounts to 20.4% of the total annual injected heat.
- With the operation of NV, the duration of HP operation in cooling mode was decreased by 29%, from 492 h/year to 348 h/year in comparison to the base case.
- By replacing HPC with NV operation, the system COP was improved.
by 26.4%, with a COP increase from 5.3 to 7.6.

Night ventilation promises to be an effective method of increasing the cooling performance of ATES systems. As such, it has high potential for lowering the extra cost of cold compensation methods in comparison with HPC. In this paper, it is clearly demonstrated that NV should be given priority over HP operation for the regeneration of the cold well.

Acknowledgements

The authors would like to acknowledge EuroTech, WOI, OTIB and BAM Techniek for their financial support.

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