The energy efficient use of an air handling unit for balancing an aquifer thermal energy storage system

Citation for published version (APA):

Document license:
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DOI:
10.1016/j.renene.2019.07.111

Document status and date:
Published: 01/02/2020

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
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Download date: 08. Jan. 2020
The energy efficient use of an air handling unit for balancing an aquifer thermal energy storage system

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Abstract

Aquifer thermal energy storage (ATES) systems, which utilize underground water for heat exchange with buildings, have been proven to be an excellent heating and cooling source. However, their operation is limited by strict regulations, one of which is the requirement for balance in the amount of heat transfer to the ground. Systems are highly exposed to cooling dominated loads, which results in excess heat injection into the ground. Commonly, an air handling unit is utilized to expel heat from the ATES system. This is known as the direct compensation (DC) method. In this study, an alternative approach that uses night ventilation (NV) was presented as a promising solution in combination with DC. Night ventilation can be used to decrease the cooling load and by using NV the system can avoid excess heat injection into the ground. The DC method was combined with NV under various control settings and compared with a system that uses only DC. The optimal operational setting between DC and NV operation was determined based on simulating a case study building. The study determined that the energy performance of the system can be improved by 16% by optimally adapting NV to the DC method.

1. Introduction

Maintaining a comfortable temperature inside a building requires a significant amount of energy usage by heating and cooling systems. The energy required to operate these systems generally comes from fossil fuels. Energy consumption within buildings is a major contributor to environmental concerns and global warming. Numerically, buildings are responsible for 40% of primary energy use in the EU and US, and 27.3% in China [1]. To reduce carbon emissions, aquifer thermal energy storage (ATES) systems have been introduced as an alternative energy source to decrease energy used in heating/cooling supply in buildings. Specifically, ATES systems are excellent cold suppliers due to the suitable temperature range of groundwater, which in the Netherlands has a natural temperature of around 12–14 °C between depths of 15–100 m. Therefore, ATES systems are increasingly applied to buildings with high cooling requirements, which results in excess heat injection to the ground. 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 [2]. However, in practice this thermal balance is seldom reached.

To compensate for the deficient cold in the ground, there are regeneration methods available that are practically applied in buildings [3–7]. Cooling towers (CTs) [3,5], air handling units (AHUs) [4,6,7] and heat pumps (HPs) [6,7] are popularly used as cold compensation units. An AHU and a CT in direct compensation (DC) mode expel the heat from water from the warm well using outside air, chilling the water. The chilled water is injected back into the cold well. Drenkelfort et al. [3] present three ATES systems that use CTs for the regeneration of cold wells. The CT operates when the wet bulb ambient temperature is lower than 4–6 °C depending on the ground temperature.

The Technical University of Eindhoven utilizes very large size ATES system on its campus, which produces more than 20 MWh of energy [5]. Due to the internal heat gain in the buildings and the high cooling demand of laboratories, the university has a cooling dominated load profile. Therefore, cooling supply from the ATES system is supported by a CT to reach a thermal balance, which is

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https://doi.org/10.1016/j.renene.2019.07.111
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also utilized when the ambient temperature is lower than 2 °C. The authors in Ref. [4] created a sensitivity analysis of an ATES system based on the operating settings. The system was tested for various regeneration set-points ranging between −2 and 10 °C. Since the availability of ambient conditions increases, the amount of cold storage is increases, which resulted in an increase in the coefficient of the performance (COP).

Authors in Ref. [7] studied an ATES system that utilizes an AHU when the ambient temperature is below 4 °C. Vanhoudt et al. [6] conducted an experimental analysis of a Belgian hospital connected to an ATES system. An AHU was employed when the ambient temperature was below 4 °C. In cases when the AHU alone could not generate sufficient cooling compensation, the HP operated to supply the remaining necessary cold water to the ground. From the existing experience [3–7], cold compensation methods are popularly applied to compensate for deficient cold in the cold well. The operation temperature for CTs and AHUs ranges between 2 and 6 °C. However, it is also possible to reach a thermal balance by decreasing heat injection into the ground by decreasing the cooling demand supplied by ATES systems. Night ventilation (NV) can be a promising technique to address the thermal imbalance problem, since NV can be used to reduce the cooling demand [6–11]. In cases where the thermal balance is not reached with NV, an AHU can be utilized to compensate and generate the remaining cooling necessary. Night ventilation was introduced as an alternative method for cold compensation [12]. Air handling unit was utilized in night ventilation mode in substitute for heat pump operation. It was shown that the system could improve the performance by 26% [12].

The use of CTs and AHUs in DC mode and HPs is very common [3–7,12]. NV was proven as effective thermal balancing method; however, it has not yet been studied as an alternative option in substitute for DC operation. In this study, NV is activated based on various temperature difference values for indoors and outdoors as a substitute for DC mode. Depending on the operation settings, the share of NV in generating cold compensation changes, which also changes the amount of cold generated using DC. The correct synergy between NV and DC mode eventually results in overall high energy performance. Ultimately, the most energy efficient operation was determined for NV and DC combined through testing various control settings of NV. In this study, First the thermal imbalance ratio of a cooling dominated building was investigated. Next, the potential of NV together with DC mode at various operational temperatures was assessed. Finally, the energy performance at the best performing operational setting was determined.

The remaining sections of this paper are structured as follows: First, the base case with cooling dominancy is presented, followed by compensation strategies applied to this case. Correspondingly, temperature, heat transfer characteristics and energy performance are analyzed.

2. Literature review

Studies [2–9] that investigate the energy performance of an ATES system in a building integrated concept were found to be limited. Although there are available practical applications [3–7], there have been few studies concerned with ATES system performance connected to building load. Past studies mainly focused on thermal modelling of ATES systems [13–17] to determine the influence of physical parameters on the efficiency of the ATES system itself. However, the efficiency of ATES is not only influenced by physical surroundings but also by dynamic interaction with the building load. Bozkaya et al. initiated the thermal imbalance investigation and analyzed the effect under various thermal imbalance rates [18]. The findings showed that thermal imbalance could decrease the system performance up to 13.7% depending on thermal imbalance rate.

Optimizing operational settings for charging a thermal energy storage system connected to building load is an approach used in existing studies [19] to achieve high energy performance. This approach has been considered for ATES systems as well. Studies considering this approach [4,20] have mainly focused on the sensitivity of the system performance to operational settings such as injection temperature [20], injection flow rate [20], charging set-point temperature [4] and temperature level in the cooling network [4]. Kranz et al. [4] analyzed various settings for charging the cold well. The air-water heat exchanger was utilized between 4 and 8 °C. Charging the cold well with a lower ambient temperature has shown a significant increase for the cooling COP. It was demonstrated in the study [4] that the cooling can be supplied with various operational temperature settings and, eventually, COPs significantly differ from each other. Similarly, Ghaebi et al. [20] adapted various operational settings for ATES systems where the same amount of cooling energy was stored at various injection

<table>
<thead>
<tr>
<th>Ref.</th>
<th>System</th>
<th>Heating Dominant</th>
<th>Cooling Dominant</th>
<th>Thermal Balancing Unit</th>
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temperatures, and a corresponding performance analysis was made.

Although the influence of operational settings has a significant effect on ATES system performance, it has not yet been analyzed under the thermal imbalance concept. Thermal balancing methods have been frequently applied for borehole thermal energy storage (BTES) systems. Due to the similarities in operation between BTES and ATES systems, applied methods for BTES systems can be used for ATES systems. As listed in Table 1, AHUs and CTs have been popularly used for BTES and ATES systems for cooling dominant loads. In ATES systems in the Netherlands and Belgium [6], it is common that an AHU is prioritized to generate necessary additional cooling for the cold well when the ambient temperature is below 4 °C. An air handling unit can provide energy efficient solution for cold compensation since the cold is compensated in the cost of the power consumption of a fan. If the capacity of the AHU alone is not enough to generate the necessary cold, an HP is utilized as a secondary option to compensate the remaining cold [6]. Since the operation of the HP is not limited by ambient conditions, HPs are a reliable source of cold generation in the thermal imbalance concept. However, HPs have lower energy efficient operation in comparison to AHUs and are therefore considered a secondary option.

As an alternative option, NV can be used for balancing purposes by lowering the cooling demand for the cooling dominated load [12,18]. The effectiveness of NV in decreasing cooling and peak cooling loads has been proven in many studies [8–11]. Depending on physical and operational parameters, NV can decrease the cooling demand by 18–50% [8–11]. In addition, NV lowers the average annual indoor temperature between 3 and 6 °C for heavy-weight buildings [39,40], which also leads to a decrease in peak cooling demand. Decreasing cooling and peak cooling demands results in the elimination of HP operation in the cooling mode for ATES systems due to the fact that in cooling mode, the HP operates based on the peak cooling demand where the ATES system’s capacity is not sufficient to meet the cooling demand [6].

However, like many other heating/cooling operation modes, NV is also influenced by physical and operational parameters. One such operational parameter is the temperature difference between the outdoor and indoor temperature. The range of temperature difference varies between 2 and 10 °C [41–43] depending on the ambient day and night temperature values for the location of interest. As the temperature difference increases, the NV fan operates more energy efficiently. However, it also decreases the amount of heat removal from the building due to the less availability of the outdoor conditions.

2.1. Contribution of this paper

The ATES systems are widely recognized as a very energy efficient cooling source. The majority of the installed ATES systems have been exposed to cooling dominated building load since the system is usually applied for the cases with a high cooling demand. Maintaining a thermal balance system by applying the balancing methods brings extra cost for the user; thereby, undermining the performance of the system. In order to reduce the energy consumption of the system, it is necessary to assess the potential of various balancing methods to optimize the system operation.

Previously, the potential of NV for an exchange of heat pump operation in cold compensation was studied [12]. In this study, the DC method with NV was compared. Because, determining the potential of each method eventually enables users in which order the methods should be given priority in the existing applications. This information can be also implemented for advanced control methods such as model predictive control in smart grid concept to schedule in advance the operation modes for the predicted thermal imbalance ratio. In addition, the output of this paper helps users to size and determine the HVAC system components for cost and energy efficient design for future applications.

3. Case study building and system description

This case study analyzed a commercial building with a total area of 3520 m² located in the Netherlands. According to results from the TRNSYS multi-zone building model (Type 56), the heating and cooling demands are 105 MWh and 295 MWh, respectively. The building required cooling from March 10 to November 1, which totaled 230 days of cooling and 135 days of heating. The building operates from 7 a.m. to 7 p.m. during the weekdays and is not operational during weekends.

The building’s heating and cooling demands are met by an ATES system and a serially connected HP. The ATES system functions on a cyclical mode; this means that the heat and cold extracted from the building are stored separately in cold and warm wells. Typically, the design operating temperature for the cold well is 6–8 °C and 16–18 °C for the warm well [44,45]. For this study, the injection temperature for the warm and cold well was designed as 16 °C and 8 °C, respectively. Practically, ATES is initially employed to deliver the cooling demand before HP operation, which was also applied for this study. The water from the cold well is directly utilized to cool the building. In cases where ATES cannot supply sufficient cooling, the HP operates to further chill the water coming from the ATES system, which is also known as HP in chiller mode [6]. The cooling network feed temperature was designed to be between 13 and 14 °C from the ATES and 8–10 °C from the HP in chiller mode. To ensure that the HP was utilized when ATES cooling was not sufficient, the cooling set-point temperature for ATES was lower than HP. As usually practically applied in the Netherlands, the set-point temperature for ATES was 23±2 °C, and 25±2 °C for the HP. Typically, ATES systems are designed such that 70–80% of the cooling demand is directly met through ATES [6]. The warm well is used as a source for the evaporator of the HP, thus, the HP is solely responsible for the heating supply. The system regenerates the cold well using an AHU in DC mode (Fig. 1). During DC mode, the building is disconnected from the HVAC (heating, ventilation, air conditioning) system and the heat in the warm well directly exchanges heat with the heating-cooling coil. Fans are employed to expel the heat from the coil to be discharged outdoors using the ambient air. In NV mode there is no use of water flow within the system, and the ambient air is used to directly expel heat from the building.

3.1. Description of the AHU

The heating and cooling needs of the building are managed through an AHU that exchanges heat with ATES or the HP through a heating/cooling coil. The fan power used by the AHU is constant since air flow rates are not variable and provide air at a 13.3 ACR. The AHU is used in two bypass options: recirculation and regeneration. In recirculation mode, V6 and V5 are closed and V1 is opened to recirculate the return air from the office without mixing any fresh intake air in order to preserve energy for heating. In regeneration mode, regeneration bypass (V2) is opened, and V3 and V4 are closed; thus ambient air is completely isolated from the building. The heat is exchanged between the intake air and the warm well water through the heating/cooling coil. The supplied water from the warm well is cooled and return water is injected.
Fig. 1. Schematic diagram of the energy flow network in various modes.
back into the cold well. After the heat extraction, the air exits the building through regeneration bypass, the return fan and V5. In NV mode, neither regeneration nor recirculation bypasses are used; thus, V1 and V2 are closed and the coil is not active. Fresh air is supplied to the building through V6 and V4 and exits the building through V3 and V5. The pumps of the ATES and fans are active in DC mode, but in NV mode only fans are active since there is no heat exchange with ATES (See. Fig. 2).

4. Methodology

4.1. Regeneration strategy

A parameters study was carried out by adapting various control settings of the AHU in NV and DC modes in order to reach a thermal balance between the amount of injected and extracted heat. The AHU was initially utilized in NV mode during the cooling period under various temperature differences ($\Delta T^\circ C$) between the ambient temperature and the indoor temperature. Depending on the availability of the suitable conditions for NV, the system had a decreased cooling load supplied from ATES. The remaining cold was compensated by AHU in DC mode.

Night ventilation strategy in the building was applied according to the following rules [46]:

- The building is cooled to a set-point of 19°C before the day begins;
- Night ventilation begins if the indoor temperature ($T_{in}$) is above 22°C;
- Operation time is between 7 p.m. and 6 a.m., when the ambient air temperature reaches its lowest point;
- There should be a temperature difference of at least $\Delta T^\circ C$ (Table 2) between the indoor and outdoor temperatures.

For each different temperature difference ($\Delta T^\circ C$) values between indoor and outdoor temperatures, case scenarios were generated. As the temperature difference increases between indoor and outdoor temperature, which ranges between 2 and 10°C [41-43], NV works more energy efficiently. However, at the same time, the number of operation hours decreases as the temperature difference ($\Delta T^\circ C$) increases, which results in higher cooling requirements from DC mode to compensate the remaining cold. The AHU was utilized in DC mode when the ambient temperature was below 4°C and modulated based on the remaining amount of cold to be compensated. In this way, the optimal tuning between NV and DC operation was determined. Case 1 can be used as a reference case where there is no participation of NV, and it can be compared to other cases (Cases 2–7) to determine the influence of NV in energy savings.

4.2. Simulation models

4.2.1. The ATES model

The ATES model was developed in COMSOL (software) using the finite element method and integrated into the whole HVAC network in a time-dynamic manner. The model was previously used in a validation study [47], which proved that the model can integrate into the building load and simulate the changes imposed by the building load. The model applies Darcy and Fourier law for heat transfer within subsurface porous media. Natural groundwater flow and thermal interaction between wells were neglected for this case. The parameters for ground conditions were derived from the previous study [47], which took place in the Netherlands.

4.2.2. HVAC models

The entire energy network, including the building model, was built in TRNSYS 17, which is a software popularly used to simulate and analyze the performance of ground-sourced applications such as BTES and ATES systems [4,48-51]. Based on existing studies [49,52] and the validation study [53], Type 927, which represents the groundwater-sourced HP, was proven to be a reliable HP model and therefore was used in this study. In Type 927, the capacity was read from the catalog data (Table 3), which varied with entering water temperature to evaporator and condenser. It was controlled based on the control signal to determine whether to operate in cooling or heating mode. The AHU was modelled after a two-fan
coils model (Type 928) in which heating and cooling energy are delivered to an air stream from a source liquid stream. The heat dissipation from the fan motor is also taken into account in the model. Based on the efficiency of the motor, an amount of heat was transferred into the air. Pumps were modelled based on the linear relationship between the water flow rate and power consumption (Eqs. (1) and (2)). Based on the amount of heat transfer, the flow rate of water was modulated to inject the water at the set-point temperature of 16 °C to the warm well and 8 °C to the cold well.

\[
W_{\text{pump,ww}} = \left( \frac{Q_b}{C_p\text{water}(T_{ww} - 8)} \right) / V_{\text{max}} \times W_{\text{max}} \quad (1)
\]

\[
W_{\text{pump,cw}} = \left( \frac{Q_b}{C_p\text{water}(16 - T_{cw})} \right) / V_{\text{max}} \times W_{\text{max}} \quad (2)
\]

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

### 4.2.3. Control models

In order to control such a complex heating/cooling system with various operation modes, many control signals were generated based on the operational settings in the system. The rule-based control was implemented using polynomial Boolean algebra. Control signals are produced with aqua-stats for heating and cooling and differential control components (Type 2C-2D) for temperature. Generally, Type 2 was intended to generate an ON signal when the monitored value rose above the user-specified set-point by a certain value (upper dead-band) and then turn off when the variable fell to within a specified value of the set-point (lower dead-band). Differential controllers generated a signal with a value of 1 or 0 from different components. At that point, a more detailed form of control is desired where all control signal are combined in the form of the equation. Those controllers were described as a polynomial equation and written in the equation tool in TRNSYS, and ultimately used to control system components such as pumps, valves, fans and the HP.

## 5. Results

### 5.1. Operation time

The operation time of AHU in NV mode is illustrated in Fig. 3 for each case. Night ventilation operated during the cooling period and non-office hours. Depending on the surrounding conditions, the annual NV operation varied significantly, which amounted to a maximum of 1012 h for Case 7 and a minimum of 83 h for Case 2 (Fig. 4). It was observed that NV operated more frequently during the hot period (Fig. 3), specifically, between June and July, when the internal heat gains increased significantly due to relatively high

![Fig. 3. The operation times of AHU in NV mode.](image-url)

![Fig. 4. Annual AHU operation in DC and NV mode.](image-url)

<table>
<thead>
<tr>
<th>Physical Conditions</th>
<th>Values</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>The rated source/load flow rate</td>
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<td>m³/hr</td>
</tr>
<tr>
<td>The rated cooling capacity/power</td>
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<td>kW</td>
</tr>
<tr>
<td>The rated heating capacity/power</td>
<td>216/46.3</td>
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<td>The rated cooling COP</td>
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<td>—</td>
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<tr>
<td>The rated heating COP</td>
<td>4.67</td>
<td>—</td>
</tr>
</tbody>
</table>

Weather data for Amsterdam, the Netherlands was used in the simulation.
ambient temperatures and solar radiation. Direct compensation operation was at a maximum for Case 1 since there was no NV operation to decrease the cooling load on the ATES system. As NV participation increased, the share of DC decreased to achieve thermal balance. In Case 7, NV operation was maximal, where DC operation was as low as 195 h. Without any participation of NV, DC operation was maximal in Case 1 and sufficient alone to compensate the entire thermal imbalance (See. Fig. 5).

5.2. Temperature

5.2.1. Ground temperature

When the thermal balance is achieved, the temperature for both the warm and cold wells reaches approximately the injection temperature (16°C for the warm well and 8°C for the cold well) year after year. Since thermal interaction between well groups was neglected, the temperature for both wells increased as the accumulated heat and cold assist wells preserved heat more efficiently. After the 5th year of operation, there was a stable temperature change. At the end of the 10th year of operation, the cold well temperature improved significantly, and the average cold well extraction temperature decreased from 11.1°C to 8.6°C. While, at the same time, the heat was rejected from the warm well, which resulted in a decrease of warm well extraction temperature from 16°C to 15.5°C.

5.2.2. Indoor temperature

Another aim in applying NV was to lower the indoor temperature, which would ultimately decrease the HP operation for cooling by decreasing the peak cooling demand within the building. As can be seen in Fig. 6, the indoor temperature was highly influenced by NV operation, specifically during June, July and August when the internal heat accumulation was relatively higher. The peak average weekly temperature difference was as high as 6°C between the case with the highest amount of NV operation (Case 2) and the case with no NV operation (Case 1). The average indoor temperature decreased corresponding to the amount of NV operation change. The annual average indoor temperature decreased by 3.9°C (from 24.7°C to 20.8°C). The indoor temperature showed a decreasing trend as the amount if NV operation increased.

5.3. Heat transfer

The goal of using AHU in DC and NV mode was to reach thermal balance by decreasing the heat injection during the cooling period and increasing the cold injection into the ground. All cases apart from the base case reached a thermal balance of 0–1%. The cooling demand decreased corresponding to the amount of NV operation, which resulted in less heat injection into the ground. It was observed that the heat injection was decreased by 46% in comparison to the base case and Case 7, where the heat injection decreased from 306 MWh to 164 MWh (Fig. 8). Correspondingly, the amount of cold that was needed to be compensated from DC decreased. In Case 1 DC injected the maximum amount of cold, which amount to 216 MWh. Night ventilation operation was substituted with 5%, 25%, 47%, 55%, 57% and 66% DC operation for Cases 2, 3, 4, 5, 6 and 7, respectively.

5.4. Energy performance

This section illustrates how the system energy performance was influenced by the substitution of NV operation with DC operation. Since NV decreased the cooling and peak cooling demand within the building, the HP operation in cooling mode was significantly influenced. The cooling demand and the amount of HP operation in cooling mode decreased by 46% and 58% (Fig. 9), respectively. The share of direct cooling increased from 73% (Case 1) to 80% (Case 7), which was mainly influenced by a relatively lower indoor temperature profile (Figs. 6 and 7). The decrease in HP operation had a substantial influence on the cooling performance because the remaining components, such as a fan for the AHU or a ground pump for ATES, were both working with relatively higher COP. Therefore, although a small percentage (27%) of cooling was supplied using HP for Case 1, HP had a large share (51%) of the electricity consumption for cooling (Fig. 10). This is due to the relatively higher COP of HP in comparison to direct cooling and DC operation, which were operated by units with low operation costs such as fans and pumps. As a result, eliminating some of the HP operations substantially decreased electricity consumption. However, the electricity consumption increased noticeably for NV mode due to the significant increase in its operation (Fig. 4). Eventually, the optimal balance between the NV and DC modes was determined for Case 4.
comparison to Case 1, the system COP was improved by 16%, from 5.6 to 6.5 (Fig. 11). For each case, the system benefited from any amount of substitution between NV and DC.

6. Discussion

Due to the fact that buildings are increasingly constructed with advanced insulation techniques and air strictness, there is an increasing trend in the cooling demand worldwide. The ATES system is proven [4,6] to be an energy efficient cooling source to address this growing cooling demand. However, the necessity for thermal balancing is undermining the high energy performance of these systems due to the extra energy cost of cold compensation. Existing research has been mostly limited [4,20,55] to performance analyses based on fixed injection temperatures, flow rates and the amount of heat/cold. In practice, ATES is a dynamic heat storage system and influenced by the thermally unbalanced building load.

Fig. 6. The temperature change of indoor temperature.

Fig. 7. The average indoor temperature for each cases.

Fig. 8. Heat transfer to the ground for each case.
as a function of weather conditions. Therefore, this study is novel in that ATES is fully integrated into the dynamic building load.

In this study, an ATES system operating under a 70% thermal imbalance rate was evaluated. It was sufficient to solely use an AHU to compensate the entire deficient cold in the cold well. However, depending on the amount of thermal imbalance, there may be cases where there is a need for HP operation to fully compensate the thermal imbalance, which would decrease the overall performance by considerable amounts. The thermal imbalance ratio and the cold compensation are heavily influenced by dynamic weather conditions. For instance, a mild summer would not increase the cooling demand substantially, and, at the same time, a very cold winter can assist the thermal balance by increasing heating demand. Cold winters would also create more opportunity for efficient DC operation for the AHU. Inversely, a very hot summer and mild winter would result in poor performance of the ATES system because there would be a higher cooling dominated load than usual and less suitable time for AHU operation for DC mode. Such dynamics must be taken into consideration in the design and operation of the existing and future applications of ATES systems.

In the previous study [12], night ventilation was showed as an energy efficient component in comparison to heat pump for achieving a thermal balance. This study revealed that any inclusion of NV as a substitute for DC could offset the additional cost of cold compensation DC operation (case 1). Without a doubt, such comparison is influenced by the effectiveness of NV and DC, which is influenced by many physical parameters in the building and weather conditions. Depending on the control settings, the operation of NV could decrease the cooling demand by a maximum of 46% and the average indoor temperature by 3.9 °C, which is in line with previous studies where cooling loads were reduced by 18–50% [9,10,11], and the average indoor temperature was reduced by 3–6 °C [39,40]. In addition, the weather conditions during the summer and winter period would also influence the optimal balance between NV and DC operation, since both operations heavily depend on the outdoor temperature. However, this
consideration is not within the scope of this study, and further studies can be conducted to explore the sensitivity of NV and DC in various climate regions and under various physical parameters for the building.

7. Conclusions

The effectiveness of NV operation compared to DC operation was compared. The amount NV participation in cold compensation was controlled based on the temperature difference between the indoor and outdoor temperature. In this way, the optimal balance between DC and NV was determined and the following conclusions were drawn:

- The ATES system under 70% thermal imbalance was entirely compensated using an AHU in NV and DC mode;
- The ATES system exhibited higher energy performance by combining DC and NV in comparison to cold compensation using only DC;
- The use of NV could limit the operation of the HP in cooling mode by a considerable amount;
- System COP was improved by 16% using the optimal combination of DC and NV (Case 4) in comparison to sole DC operation (Case 1).

Night ventilation has been identified as a promising technique to address a cooling dominated load in ATES systems. Direct compensation is a practically applied method to reach thermal balance within the system; however, introducing NV in combination with DC could potentially lead to higher performance. The optimal combination between DC and NV should be determined for each individual building, as this varies depending on the building characteristics and climate region.

Acknowledgments

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

References


[34] A. Capozza, A. Zorrella, M. De Carli, Long-term analysis of two GSHP systems using validated numerical models and proposals to optimize the operating parameters, Energy Build. 93 (Apr. 2015) 50–64.


