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Optimization of an aquifer thermal energy storage system through integrated modelling of aquifer, HVAC systems and building

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus prof.dr.ir. F.P.T. Baaijens, voor een commissie aangewezen door het College voor Promoties, in het openbaar te verdedigen op donderdag 13 juni 2019 om 10:00 uur

door

Basar Bozkaya

egenomen te Mersin, Turkije

Dit proefschrift is goedgekeurd door de promotoren en de samenstelling van de promotiecommissie is als volgt:
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Het onderzoek of ontwerp dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.
Erratum:

2.3.1.1 Governing equations

Page 24:
\[ \vec{q} = -K \nabla h \] (2) should be \[ q = -K \nabla h \]
\[ \rho_s \frac{\partial p}{\partial t} = Q_s \vec{V}(\rho q) \] (3) should be \[ S_s \frac{\partial h}{\partial t} = \nabla \left( AK \frac{\partial h}{\partial r} \right) \]

Where \( S_s \) is the storage coefficient, \( A \) is the thickness of the aquifer (m), \( K \) is hydraulic conductivity (m/s)

Page 25:
\[ \frac{\partial h}{\partial L} = \frac{Q}{2\pi K A} \ln \left( \frac{r_a}{r_f} \right) \] (4) should be \[ h(r_a) - h(r_f) = \frac{Q}{2\pi K A} \ln \left( \frac{r_a}{r_f} \right) \]
\[ [\overrightarrow{\nabla} (K \rho \overrightarrow{\nabla} h)] dV = Q_s \] (5) should be \[ [\overrightarrow{\nabla} (K \rho \overrightarrow{\nabla} h)] dV = Q_s \]
\[ (\rho c)_s \frac{\partial T}{\partial t} = \overrightarrow{\nabla} \left[ (\rho c)_aq (\lambda_{aq}) \overrightarrow{\nabla} T(r) \right] - (\rho c)_f \overrightarrow{\nabla} \left( q(r) T(r) \right) + Q_s \] (6) should be
\[ (\rho c)_s \frac{\partial T}{\partial t} = \nabla \left[ (\rho c)_aq (\lambda_{aq}) \nabla T \right] - (\rho c)_f \nabla \left( q T \right) + Q_s \]

Where \( \lambda_{aq} \) is the thermal conductivity of aquifer, \( (\rho c)_f \) specific heat capacity of fluid, \( (\rho c)_aq \) specific heat capacity of the aquifer, \( Q_s \) is the heat source term (J/m\(^3\)K\(^{-1}\)).

Page 27:
\[ H_{in} = \frac{Q}{2\pi B} \log \frac{r}{r_0}, \quad H_{out} = -\frac{Q}{2\pi B} \log \frac{r}{r_0} \] (7) should be
\[ H_{in} = \frac{Q}{2\pi K B} \ln \frac{r}{r_0}, \quad H_{out} = -\frac{Q}{2\pi K B} \ln \frac{r}{r_0} \]

Page 28:
\[ T_{in(\infty,t)} = -n(-k \nabla T) = 0 \] should be \[ T_{(\infty,t)} = -n(-k \nabla T) = 0 \]

3.2.1.3 COMSOL for aquifer modelling page

Page 56:
\[ \vec{q} = -K \overrightarrow{\nabla} h \] (1) should be \[ q = -K \nabla h \]

Page 57:
\[ \rho_s \frac{\partial p}{\partial t} = Q_s - \overrightarrow{\nabla} (\rho q) \] (2) should be \[ S_s \frac{\partial h}{\partial t} = \nabla \left( AK \frac{\partial h}{\partial r} \right) \]
Where \( S_s \) is the storage coefficient, \( A \) is the thickness of the aquifer (m), \( K \) is hydraulic conductivity \((m/s)\).

\[
[\nabla \cdot (K \rho \nabla h)]dV = Q_s \quad \text{(3) should be} \quad [\nabla \cdot (K \rho \nabla h)]dV = Q_s
\]

\[
(pc)_s \frac{\partial T}{\partial t} = -((pc)_{aq}(\lambda_{aq}) \nabla T(r)) - (pc)_t \nabla (q(r) T(r)) + Q_s \quad \text{(4) should be}
\]

\[
(pc)_s \frac{\partial T}{\partial t} = \nabla ((pc)_{aq}(\lambda_{aq}) \nabla T) - (pc)_t \nabla (q T) + Q_s
\]
Optimization of an aquifer thermal energy storage system through integrated modelling of aquifer, HVAC systems and building
SUMMARY

The heating and cooling energy needed in the built environment constitutes the majority of the total energy demand. It has become important to sustainably and cost-effectively reduce the growing energy demand in the built environment. Aquifer thermal energy storage (ATES) systems are potential solutions due to their energy-efficient storage of naturally supplied cold and heat energy. This is especially so in the countries where underground conditions are suitable for energy-efficient storage in aquifers such as in large parts of the USA, the Netherlands, China and other coastal countries where the groundwater is close to the surface. However, the ATES systems do not operate in line with performance expectations in practice. An ATES system is usually designed using a rule of thumb method that considers the system as a heat source with a constant water supply temperature. However, the temperature within the storage is not constant; there are heat losses to the surroundings. Furthermore, the total amount of stored heat significantly depends on the balance between the cooling and heating demand, which eventually leads to changes in the source temperature over time. Regulations are in place to enforce the thermal balance for the ATES applications over several years, which will maintain the sustainable use of sub-surfaces without any continuous heating or cooling of the soil. Therefore, it has become necessary to assess and control the ATES system to maintain the overall thermal balance.

ATES systems are frequently applied to buildings with high cooling demand. Therefore, most of the systems are exposed to a cooling-dominated load. For a cooling-dominated load, the deficient cold can be compensated by applying a cooling tower, an air handling unit (AHU), or a heat pump. However, achieving a thermal balance is burdensome for the user because the supply of deficient heat or cold to the aquifer brings additional energy cost. Therefore, ATES needs to be analyzed and controlled in a cost-efficient and energy-efficient way. To achieve this, the following tasks were completed throughout the research project: development of an integrated model of ATES and buildings, determining the influence of thermal
imbalance on the ATES performance, and development of new control strategies which were applied to energy-efficiently utilize an air handling unit for reaching a thermal balance within the ATES system along with heat pump.

A thermal dynamic ATES model was developed that handles the time-dynamic heat exchange to a building; this model integrates the ATES into building HVAC systems. The developed model was validated with real measurement data from an operational ATES in the Netherlands, and the model proved to be suitable for integration into the dynamic Heating, Ventilation, and Air-Conditioning (HVAC) network of the building.

Co-simulation is an effective method to assist with simulation of a complex system by thoroughly considering the physics of HVAC system, building thermal characteristics, and the aquifer layers. Well-known tools that are commonly used in HVAC system and building modelling were used: TRNSYS (Transient System Simulation) and COMSOL (Multiphysics modeling software). The control strategies that were already practically applied to the existing ATES applications were also used in the simulation platform. The developed model was used to explore the effects of different possibilities of restoring the thermal imbalance on the overall ATES system’s energy performance.

An air handling unit and a heat pump are traditionally used to reach a thermal balance. Night ventilation (NV) was substituted for a heat pump as an alternative solution to deal with the cooling-dominated building load. The use of NV causes the cooling demand that is supplied from ATES to decrease, which assists with reaching a thermal balance. Night ventilation proved to be a promising technique that cut off additional primary energy consumption. Optimizing the operation of an AHU was further explored. An AHU can be used in direct compensation (DC) mode, which is popularly applied in the existing applications. In the DC method, the surplus heat of ATES is expelled using ambient air conditions that are lower than 4°C to remove
the surplus heat stored in the warm well of ATES. The energy effectiveness of an AHU in combination of DC and NV mode was determined.

The results and discussion led to the following conclusions:

- The validation study for the ATES system and building’s HVAC model has demonstrated its potential for handling the dynamics and optimizing the overall energy performance control.
- The co-simulation method that used COMSOL-TRNSYS and MATLAB was successfully applied to investigate the influence of a thermally unbalanced building load on ATES energy performance.
- Night ventilation was determined as a promising solution for the compensation of thermal imbalance and could decrease the primary energy consumption by up to 26%.
- Optimal participation of an air handling unit for cold compensation improved the system energy performance by 16%.
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Chapter 1

INTRODUCTION

There is a steady increase in energy demand worldwide. It is important to sustainably and efficiently use available energy sources to meet the growing demand. In particular, the energy demand for the cooling and heating applications are responsible for major energy consumption. Aquifer thermal energy storage (ATES) has been identified as one of the most energy-efficient thermal storage systems. However, the operation of the ATES is not optimal in the existing applications. Therefore, this thesis aims to determine the possible solutions for the energy-efficient and sustainable integration of ATES with the building and its Heating, Ventilation, and Air-Conditioning (HVAC) systems.
1.1 Global Energy Demand

The growing population and demand for comfort has increased the energy demand in all sectors. The global primary energy demand is expected to increase by 60% by 2050 [1]. Rapidly growing energy demand brings environmental concerns due to the increase in carbon emissions and the rapid depletion of the fossil energy sources. As a result, growing environmental concerns and energy shortages have been driving forces for energy-saving solutions and renewable energy production in all sectors. Hence, there has been an increasing trend to use energy sources such as solar, wind, and geo-thermic energy.

The building sector is responsible for 40% [2] of the total energy consumption and 36% of carbon emissions in EU. Energy use within buildings mainly consists of heating, cooling, hot water usage, cooking, ventilation, electrical appliances, and lighting. Space heating and cooling represent 70% of the total energy consumption in buildings. In addition, there is an increasing energy demand within buildings due to growing global warming, which is expected to decrease global heating demand by 30% and increase global cooling demand by 70% [3].

In addition, strict energy regulations that have been imposed by the governments to deal with global warming have mandated the decrease of the primary energy consumption in building heating and cooling systems. According to the EU energy framework, greenhouse gas emissions must be cut by at least 40% by 2030 [4]. The United Nations signed the Paris Agreement to combat global warming; the agreement aimed to limit temperature rises by 1.5°C by 2050 [5]. In the last decade, there has been substantial interest in using energy storage systems to integrate renewable sources into the power grid and to efficiently supply thermal energy. Motivated by this, numerous thermal energy storage systems have been identified and used in buildings to increase the energy performance. This research focuses one of the less known but most efficient seasonal thermal energy storage systems: ATES.
However, ATES has attracted relatively less attention due to the lack of knowledge regarding potential and future applicability [6].

1.2 The energy potential of ATES

Aquifer thermal energy storage systems are globally applied but are particularly prevalent in Europe, North America, and the Netherlands [7]. In total, ATES has the highest amount of energy savings in North America at an estimated max of 490PJ(PetaJoule)/year, which amounts to 7% of energy use in the commercial buildings. The highest potential share of ATES’ energy saving is in Western and Eastern Europe: 8-12% of the energy use in commercial buildings. Although the system is less popular in China, it is estimated that ATES could decrease the energy use by 420PJ/year there [8]. In the Netherlands, ATES systems offer high primary energy saving potential that amounts to 11% of the total energy usage in the built environment [9].

The energy saving potential of ATES systems is 40-90% compared to traditional HVAC systems. Due to ATES’ high energy reduction potential, it is expected that it must have a major share in the energy supply to reach the 2050 target [5] of a 75% reduction of heating and cooling demand [9]. Due to the relatively low installation cost, ATES systems are economically viable systems because their payback period is mostly less than 5 years [10]. However, the usage of ATES is limited in most countries by a number of obstacles such as suitable geo-hydraulic conditions [10], lack of knowledge regarding applicability, competition against fossil fuels, and poor commissioning.

1.3 History and development

Using the ground as a cooling and heating source began in the early age of humankind, when people started using the rock and soil in natural or artificial caverns. Caverns have been used as heating in winter and cooling in summer. Even though ground source heating-cooling systems were first introduced in 1945 in
Indianapolis, USA, using the ground as a source of thermal energy became more prevalent after the oil crisis at the beginning of the 1970s [11].

The first ground-sourced applications were installed during the end of 70s and 80s in China, the US, Switzerland and Denmark. These applications were realized as forms of low-temperature (12-30°C) and medium-to-high-temperature (60-204°C) heat storage [13][14]. Hausezz and Meyer [13] pioneered the applications of high-temperature ground-sourced applications [15][16][13]. Rabbimov et al. have reported that one of the first projects for solar-coupled ATES is in New York [17]. Solar thermal has been coupled with rock cavern storage and installed in Lyckebo, Sweden; these systems were installed in 1983 with maximum temperature of 53°C and 75°C respectively [18]. These types of systems account for 15% of ATES applications in Sweden, whereas the rest of them have been installed for both heating and cooling purposes [19]. In these applications, the ATES had a maximum depth of 400m.

However, as is mentioned in Annex 12 titled “High temperature underground thermal energy storage” [15], high temperature underground storage was not as successful as its design intended due to technical problems. The primary problems were the corrosion of material and well clogging due to the change in chemical property of water under high temperature. Additionally, high-temperature ATES systems require special permission and regular water treatment because high temperature influences the chemistry of the water and thereby the biological environment [15]. Technical and biological problems undermined the commercial use of high-temperature ATES (storage > 50°C). During 1985-1995, there were attempts to address problems concerning high-temperature storage. However, the International Energy Agency (IEA) advised that water conditions were more suitable for low temperature storage, or the system would require regular monitoring systems and water treatment to ensure the proper operation of the system.

The first steps of ATES in the Netherlands were taken in the late 1980s to store excess solar energy during the summer for utilization in the winter. In 1985, a first
project combined ATES with solar thermal energy (30°C) to provide space heating for an office building [22]. In 1988, ATES was used to provide space cooling (minimum 6°C) to office buildings. In 1983, solar collectors were combined with collective ATES to provide heating for approximately 100 households [20]. By 2000, there were already over 100 ATES in the Netherlands. In total, 40% of ATES projects were implemented in the Netherlands to provide cooling and heating services to the building. Low-temperature heat storage was used as a 12-20°C heating system. The temperature of ATES for cooling was realized at 6-12 °C and below. In the Netherlands in 2012, the number of ATES reached 1,500 and is expected to reach 18,000 by 2020 [12][21], see Fig. 1.1 Because low-temperature (6-20°C) ATES systems have been popularly used, this thesis focuses on the optimization of low-temperature systems that have been implemented for both heating and cooling.

Figure 1.1: Prospects of ATES systems in the Netherlands by 2020 [12]

1.4 The working principle of ATES

Aquifer thermal energy storage systems use the readily available underground water in the sandy layers of the ground to exchange heat with the building and its environment. The ATES system is an open-loop system and consists of two separate well groups: cold and warm wells. The building is connected to those wells with a piping system through which the water is pumped to a heat exchanger to transfer
heat to and from the building on a seasonal scale. This type of ATES is known as a low-temperature ATES system. During the cooling period, the cold well pump is employed to pump the available cold water to the building for the supply of cooling, and the extracted heat from the building is stored in the warm well. During the heating period, the extracted water from the warm well used to heat the building and is thus cooled by the process; the cooler water is stored in the cold well during the heating season. The storage wells can be situated horizontally or vertically (Fig. 1.2). A vertically spaced system is called a mono-well, and the horizontal spaced system is called a doublet system. The mono-well system has relatively lower heat capacity. However, the installation cost is lower than the doublet system due to the lower drilling costs.

![Doublet and mono-well ATES](image)

**Figure 1.2:** Doublet and mono-well ATES

Typically, a cold well and a warm well are designed to operate under 6-10°C and 16-25°C respectively, depending on the geological and climatic conditions [22]. Due to the suitable temperature for cooling, it is possible to directly supply the cooling without the use of any additional components, which is also known as free cooling or direct cooling. On the other hand, the warm well temperature must be amplified by employing a HP (heat pump). As a result, ATES systems are very energy efficient for cooling supply specifically and are therefore frequently applied for buildings with high cooling demand.
The thermal energy is normally well-preserved in the underground water. However, the underground water is not confined from the sides and is therefore vulnerable to heat losses to the surroundings. The ground conditions are a limiting factor for the feasibility of the system. The expected thermal energy recovery from ATES should range between 50-90%. Since the operation works based on seasonal heat transfer to and from the building, the stored thermal energy is influenced by the seasonal thermal balance between the cooling and the heating demand. The system should be in a near-yearly thermal balance to maintain the optimal sustainable use of ATES systems, avoid future mutual thermal interaction, and maintain certain temperature levels [21].

1.5 Ground-sourced applications

1.5.1 Open-loop systems
Open loop systems utilize underground water for heating and cooling supply. There are three forms of systems that are popularly available. The first system, low-temperature ATES, is explained in the previous section (1.4) and is the focus of this thesis. The other two applications are high-temperature ATES and geothermal mining. The estimated temperature range for high temperature ATES is 40-90°C for warm wells and 20-40°C for cold wells [22]. High-temperature ATES systems are used to store residual waste heat from the industrial processes and renewables such as solar thermal energy. Geo-thermal energy utilizes the deep geo heat that is available in the core of the earth. The geo heat can be available close to the surface depending on the location; however, the system is usually much deeper (1-3 km) than other ground-sourced applications. The main advantage of high temperature systems is that they can be utilized directly for heating supply, which eliminates need for a heat pump or boiler.

1.5.2 Closed-loop systems
In closed-loop systems, the water circulates in a closed loop heat exchanger that is located in the shallow surface (< 200m). Therefore, the heat carrier is separated from the ground and groundwater with a borehole in a closed-loop. The heat is transferred
to the ground through conduction as long as it is not surrounded by the flowing water regime. Therefore, a closed-loop system requires relatively less specification to accommodate to the ground than an open-loop system. Heating and cooling sources are injected into the same field, while the sources are separated in an open loop system such as ATES system. Most popularly, borehole thermal heat exchangers are used in this concept.

1.6 Goal of the research

Aquifer thermal energy storage systems are frequently applied based on simplifications during the design phase. Heating and cooling systems are designed to be based on a constant energy supply from an ATES. However, in practical applications, it is observed that the amount of energy is not as well-maintained in the well groups as expected due to the heat losses to the surroundings and especially due to thermal imbalance, which refers to the imbalance between heating and cooling demand. Besides, regulations are in place to maintain a thermal balance within the ATES over a period of 5 years for the sustainable use of sub-surfaces, which incurs extra operational cost for the system. Therefore, the system performance decreases due to the neglected disturbances posed by the building load, different external conditions such as warm winters, and the underground.

Aquifer thermal energy storage systems are usually applied in connection with supplementary equipment such as AHUs, cooling towers, and heat pumps to meet the cooling demand. It is possible to use those supplementary units to achieve a thermal balance through cold injection to the ground under the cooling-dominated load. Air handling unit and cooling tower are used to expel the excess heat from warm well by utilizing the ambient air and injecting the deficient cold into the cold well.

Past studies concerning ATES systems neglected the influence of building load and focused mainly on the heat losses to the surroundings through thermal modelling of the aquifer. However, thermal imbalance is an important parameter that potentially
influences the system performance. Thus, thermal imbalance should be considered in the existing installations and for future applications. Therefore, this research aims to assess the influence of thermal imbalance of ATES systems and to determine the possible solutions for maintaining the thermal balance in an energy-efficient manner. Since there is a direct relationship between the building load and the amount of energy stored in an ATES, this paper uses the following hypothesis:

*Integrated modelling approach of ATES, HVAC components, and buildings can pave the way for improved control of ATES system and lead to its energy-efficient operation under an unbalanced building load.*

1.7 Thesis objectives and research questions

Several objectives must be completed to test the hypothesis. As a first step, the thermal movement of heat stored in ATES was investigated through thermal modelling. Second, the developed model was integrated into an entire HVAC system to determine the influence of thermal imbalance. Last, possible control strategies were determined for energy-efficient operation of the system under the cooling-dominated building load.

- **What is the necessary aquifer model for ATES system analysis?**

  *This question was addressed in Chapter 2: “Heat transport in an aquifer connected to the building load” through a detailed literature review and methodology. The strengths and limitations of the existing models were outlined, and the method that was used to develop the ATES model was explained extensively.*

- **How to analyse ATES that is connected to the building and HVAC system?**

- **What is the influence of thermal imbalance on the ATES performance?**

  *These questions were addressed in Chapter 3: “Simulating ATES performance and thermal imbalance investigation” through an extensive methodology and case study.*
The method that was developed to analyse ATES system was explained in detail and applied to a case study to analyse the thermal imbalance effect.

- What is the alternative solution for reaching a thermal balance using an air handling unit with heat pump?
- How to achieve thermal balance in an energy-efficient manner?

Those were the ultimate questions that needed to be addressed in Chapters 4-5 “The control of HVAC units to achieve thermal balance.” These questions were answered through a simulation study carried out for ATES in connection with a heat pump and AHU.

1.7.1 Thesis Outline

The outline of the thesis is represented in Fig. 1.3 and contains the following five chapters.

Chapter 2: Development and evaluation of a building integrated aquifer thermal storage model

Aquifer thermal energy storage system is influenced from the ground, the operation of the HVAC systems and the building load. To be able to integrate ATES into a building and its HVAC systems, it is necessary to develop a thermal model that can both handle dynamics of the ground, the HVAC system and the building. Therefore, a 2D axisymmetric thermal model of an ATES was developed in this chapter. The developed model is validated with the data from an operational ATES

Chapter 3: A dynamic building and aquifer co-simulation method for thermal imbalance investigation

In this chapter, the developed co-simulation method is presented to simulate building, HVAC and ATES. A co-simulation is the best might also be the only way to consider the physics of HVAC system, building thermal characteristics and the
aquifer layers thoroughly. The software used are well-known and broadly used in HVAC and building modelling (TRNSYS) and computational fluid dynamics (CFD) modelling (COMSOL). The developed ATES model that is introduced in Chapter 1 was integrated into HVAC system. The developed method was used to investigate the effect of thermally unbalanced building load on the system performance.
Chapter 4: The Effectiveness of Night Ventilation for the Thermal Balance of an Aquifer Thermal Energy Storage System

Following the chapter 3, this chapter investigates the cold compensation methods using an air handling unit for a cooling dominated load. A heat pump can be used as cold compensation unit to support air handling unit, which is a traditional method in practice. Night ventilation is proposed as an alternative solution to replace the heat pump. Correspondingly, the energy performance of night ventilation to achieve a thermal balance is determined and compared with the traditional method.

Chapter 5: The Optimal Use of an Air Handling Unit to Achieve a Thermal Balance in an Aquifer Thermal Energy Storage

It is possible to use an air handling unit in two different modes: direct compensation (DC) and night ventilation (NV). Direct compensation is frequently applied method in the buildings; however, it has never been compared with night ventilation in terms of energy performance. Therefore, this chapter explores the effectiveness of NV over DC. Ultimately, the optimal use of an air handling unit, that is combining NV with DC, is determined in the thermal imbalance concept.

Chapter 6 – Discussion and Conclusion

In this final chapter, the results of the previous chapters were discussed and conclusions have been made. Based on the findings, the limitation of this study and an outlook on future research is determined.

1.8 References


Introduction


Chapter 2

DEVELOPMENT OF A BUILDING INTEGRATED ATES MODEL

ATES systems are complex systems to analyse as a number of ground conditions influence heat losses within the aquifer. However, the amount of heat available in ATES also influenced by the dynamic heat transfer from the building. Taking into account the variations in the building and below ground conditions, there is the need for the development of an integrated ATES model that can potentially handle the dynamics on both sides. Based on that, a model was developed and validated with experimental data.

2.1 Introduction

In an attempt to decrease CO$_2$ emissions in heating and cooling applications, the ground has been introduced as an efficient cooling/heating option for buildings. One of those applications: the ‘aquifer thermal energy storage system (ATES)’ uses energy stored in readily available underground water to exchange heat or cold with a building. ATES is also widely recognized as one of the most energy efficient heat/cool options [1]. Compared to traditional cooling/heating systems, ATESs can achieve 90-95% energy saving on heating/cooling when used directly, and 60-85% energy saving when coupled to a heat pump [2].

When used in buildings, the temperature of ATES varies throughout the year due to the influence of heat losses to the surroundings and the amount of injection/extraction of heat/cold to/from the ground. Since buildings have varying
heating and cooling demand patterns all year round, it influences the amount of heat/cold injection to the ground. Given that the rate and amount of heat and cold water injection and extraction to the well also influence heat loss and gain in the well, it is, therefore, imperative that this variation is considered in the evaluation of ATES connected with buildings.

A few studies [3-5] have been conducted to investigate the performance of ATES in connection with a building load. The authors in [3] for example investigated the performance of ATES connected to solar thermal and heat pump, while the authors in [4] analysed the influence of various operational settings in a building on ATES performance. On the other hand, the authors in [5] performed a simulation for high-temperature ATES connected to combined heat and power (CHP) system and heat pumps to assess the energy performance on the district level. These studies have shown the relationship between the building load with ATES. In these studies, the ATES model was developed using TRANSAT (ATES model in TRNSYS) [3], [5], [6] and C code [4] which is based on the finite difference method (FDM) that has limited capability to deal with the complex and dynamic interactions between the various parameters that influence ATES performance, in an attempt to have lightweight computational load.

Most other studies using more advanced simulation technique based on the finite element method (FEM) and finite volume method (FVM) [7-17] have mainly evaluated the performance of ATES independent of the connected load in the buildings. Thermal models of ATES have been discussed and analysed under various subtopics including buoyancy[7-9], preferential pathways [10], dispersion [11-13], thermal interaction [14-16] and natural groundwater flow [17]. These subtopics can be discussed extensively depending on the potential influence on heat recovery and the temperature distribution around the well. In general, most authors [6-17] argue that the ground is a complex medium to model since it is influenced by various parameters. For instance, buoyancy is an important factor that influences the temperature distribution for high-temperature ATES [7-9]. Dispersion is not
negligible in heterogeneous ground layers and high-velocity water regions [18]. Thermal interaction is a concern for the places where the ATESs are densely installed and heavily affected by the operational parameters as well as certain ground conditions such as hydraulic conductivity [15]. In most of the developed FEM/FVM ATES models, the injected/extracted heat introduced is often considered constant for a certain period of time (usually days of the year), which do not dynamically change depending on building load, to analyse the influence of certain ground parameters. This results in discrepancies between the reality and the simulation since in reality operational parameters are sensitive to (half-hourly/ hourly) changes in the building load or other dynamics within whole HVAC system. In addition, these models are mostly developed using strong computational fluid dynamics software such as SHEMAT, FEFLOW, MT3DMS, MODFLOW[19-21], which have limited capability to integrate building simulation tools (such as Energy-plus, TRNSYS, MATLAB, Modelica).

Taking into account the variations in the ground conditions and their influence on the heat recovery [7-17], there is a need for the use of advanced simulation techniques such as FEM and FVM, which are common methods for solving fluid dynamics as well as complex geometries and boundaries. Whilst it is proven that advanced tools such as FEM/FVM are able to provide improved ATES models [7-17], models that integrate buildings with ATES have however been limited to those based on FDM [3-6]. Those based on the FEM/FVM [7-17] are limited with non-dynamic operational conditions, which further buttresses the need for a model that is potentially capable of dealing with various ground conditions, while at the same time dealing with dynamics imposed by the building load.

Therefore, giving the advantages of FEM in solving complex geometries and boundaries [7-20], in this paper a dynamic ATES model based on FEM was developed. Unlike most simulation models used in for the evaluation of ATES [7-20], the model was developed using a combination of COMSOL and MATLAB. The combination of COMSOL and MATLAB facilitates interconnectivity with building
simulation tools (such as Energy-plus, TRNSYS, Modelica) through MATLAB. The developed model was subsequently validated using the data from an operational ATES from which an absolute mean deviation between the real data and simulation results was determined as 0.17°C and 0.12°C for the cold and warm well respectively.

The subsequent sections of this paper are outlined as follows: section 2.0 provides a literature survey on the previous models of ATES using FEM and FVM method, section 3.0 provides a description of the simulation tools and the ATES model. Section 4.0 provides a discussion of the results and validation of the ATES model, while section 5.0 provides the conclusions.

2.2 Previous modelling studies

As noted in the preceding section, models that integrate into building with ATES have been limited to those based on FDM. Most studies on ATES have often focused on below ground conditions [7-17] and the very few studies [3-6] that combine both above and below ground conditions are often based on the inadequate FDM. Therefore, in this section, previous modelings of ATES were collected to determine what the FEM and FVM based modelings could potentially solve in the past studies in order to address the possible challenges that a user can face with FDM method. Most of the studies presented in Table 2.1 dealt with various heat transfer phenomena such as dispersion, thermal interference, buoyancy and natural ground water flow to have a better prediction of the expansion of the thermal front and the temperature distribution around the well. Although the expansion of thermal front differs depending on the capabilities of the ground, the rapid increase in the utilization of the ground is expected to contribute to the scarcity of ground space so that the potential use of aquifers in the area of interest can be maximized. The proper definition of heat transfer function enables the optimal layout as well as a well-defined model for the integration into building load [22].
Development of a building integrated ATES model

Previous studies shown in Table 2.1, depending on the applied location, the mentioned heat transfer functions were significant. Dispersion effect was often studied with heterogeneity (layering) in the ground, where the water was not uniformly distributed due to the differences in hydraulic conductivity of the layers. Dispersion results in a decrease in heat recovery as well as significant uncertainty in the thermal plume expansion [23], [24]. [25] has predicted a maximum of 80% plume extent in comparison to homogenous porous media, which has increased the risk for thermal interaction between well groups. In the absence of natural groundwater flow, the effect of dispersion on the heat recovery is considerably low (around 0 and 3%). The presence of groundwater flow of 100 ($m/\text{year}$) has intensified the effect of dispersion to 0-12% since heat losses increase through advection [17].

Thermal interaction between well groups has potentially decreased the heat recovery by 20% or improve by 25% depending on the layout of the well position [14]. The risk for thermal interaction changes depending on the parameters such as the distance between well groups, injection/extraction rates, hydraulic conductivity and natural ground water flow [15], [16]. In case the ATES is bounded by the sides with a concrete wall, concrete can act as good insulator and improves the heat recovery [8]. Natural ground water speed is a very significant parameter that can affect the heat recovery [10],[3]. High natural velocity can make the high-temperature ATES impracticable due to the migration of high amount of heat, [10] has predicted around 37% and a 78% decrease in heat recovery for the natural ground water velocity of $5 \times 10^{-7}(m/s)$ and $10^{-6}(m/s)$ respectively. The heat recovery is influenced not only by the intensity but also the direction of the natural ground water flow [17]. [12] has shown the layout of the well arrangement poses different risk levels for thermal interaction.

Buoyancy has been a significant parameter for the high-temperature ATESs. [7] defined the critical limit temperature to take into account buoyancy effect. [28] has shown that buoyancy has less influence on temperature distribution under high-velocity regions. High-temperature ATES also influences the hydraulic conductivity
of the aquifer. An increase in water temperature from 16.2°C to 50°C led an increase of hydraulic conductivity from $1.97 \times 10^{-6}$ to $2.82 \times 10^{-6}$ (m/s) [28].

**Table 2.1: Previous modelings of ATES**

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Low Temp</th>
<th>High Temp</th>
<th>Natural water flow</th>
<th>Buoyancy</th>
<th>Dispersion</th>
<th>Thermal interaction</th>
<th>Building Integration</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10] [11] [27]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
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</tr>
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<td>[7][8][28]</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>[9]</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FVM</td>
</tr>
<tr>
<td>[14] [29]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FVM</td>
</tr>
<tr>
<td>[15]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>FVM</td>
</tr>
<tr>
<td>[16]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FVM</td>
</tr>
<tr>
<td>[12] [13] [22] [30] [31]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FEM, FVM</td>
</tr>
<tr>
<td>[32]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FVM</td>
</tr>
<tr>
<td>[3]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FDM</td>
</tr>
<tr>
<td>[4]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>FDM</td>
</tr>
<tr>
<td>[5]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FDM</td>
</tr>
<tr>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>FDM</td>
</tr>
</tbody>
</table>

As summarized from the literature, the temperature in ATES is influenced by various transfer functions (Table2.1), domain [23], [24], boundary [8], [15], [16] and transient [28] conditions, which pose challenges for the use of FDM method. It has been shown that FEM and FVM methods were popularly used deal with the complexity in the past studies (Table2.1). However, the ATES models integrated into building was limited with inadequate FDM [3-6], where certain conditions such as dispersion, buoyancy, thermal interaction and natural ground water flow, which influence ATES performances are often ignored.
2.3 Methodology

2.3.1 COMSOL for ATES modelling

The ATES was modeled using COMSOL subsurface and heat transfer module [33]. Heat losses are influenced by two operational entities: temperature and flow in the same medium; which results in mass and heat transfer in the porous media. Convective heat transfer occurs through transportation of particles via advection due to the hydraulic head difference during the charging/discharging period. In addition to the operational parameters, there are several physical ground parameters that affect the heat transfer such as porosity, hydraulic conductivity, the thickness of aquifer and some other known parameters such as heat capacity, density and thermal conductivity.

Porosity determines the thermal capacity of a volume of the aquifer. As the porosity increases, the thermal capacity of the aquifer increases since water is able to hold more heat in comparison to the ground. It allows the ATES to keep the thermal energy close to the injection/extraction point [3]. Porosity determines the specific heat capacity from:

\[ C_{p_{aq}} = C_{p_{water}} \phi + C_{p_{sand}}(1 - \phi) \]  

(1)

Where, \( C_{p_{aq}} \) is the specific heat capacity of the aquifer, \( \phi \) is the porosity, \( C_{p_{water}} \) is the specific heat capacity of water, \( C_{p_{sand}} \) is the specific heat capacity of sand.

Hydraulic conductivity is used to determine the resistance of porous media to the movement of water. Hydraulic conductivity should be high enough to yield a certain amount of water flow to neutralize the net head increase, whereas it should be low enough to ensure low thermal migration from the injection point. High hydraulic conductivity increase the risk for thermal interaction between well groups [34].

The thickness of aquifer determines the thermal capacity of a confined ATES. Thermal energy injection should be high enough to satisfy the capacity since the well is going to experience slow changes in temperature. The authors in [3] have shown
Development of a building integrated ATES model

that increase in the thickness lowers the losses through conduction to the surroundings by means of low area/volume ratio.

2.3.1.1 Governing equations

Mass transfer in an aquifer is represented by forced and natural convection. Forced convection is the transport of mass in the presence of external forces (injection/extraction). Natural convection is the transport of solute through dynamic nature of fluid which can be driven by the buoyancy, diffusion or advection. Following equation satisfies the flow of water in porous media. The flow flux of water is written as a function of head gradient and coefficient of hydraulic conductivity.

\[ \bar{q} = -K \bar{\nabla} h \]  

(2)

Where \( \bar{q} \) is darcy flow, \( K \) is hydraulic conductivity \((m/s)\), \( h \) is hydraulic head \((m)\). Transient drawdown of the injection/extraction is presented with the following equation.

\[ \rho S_s \frac{dp}{dt} = Q_s \bar{\nabla} (\rho q) \]  

(3)

Where \( S_s \) is the storage coefficient, \( \rho \) is the specific heat capacity, \( Q_s \) is the source/sink term. The average extraction flow rate of cold well and warm well is calculated as 40 and 18 \((m^3/h)\), respectively. System does not cause significant drawdown (less than a meter)(see in Fig. 2.1) to take into account for low temperature ATES [35], [3]. The drawdown is calculated based on the parameters in Table 2.2 and using analytical solution (Eq. 4).

As a result, storage coefficient is considered as zero, which means that there is no transient drawdown of water by time; thus, the pressure distribution around the well is considered steady. Analytic translation of injection/extraction rate into hydraulic head change is shown as follows [3]:

24
\[
\frac{dh}{dL} = \frac{Q}{2\pi KA} \ln \left( \frac{r_a}{r_f} \right)
\]  
(4)

where \( A \) is the thickness, \( r_a \) is actual point, \( r_f \) is reference point. As it is seen from the equation increase in the thickness lower the hydraulic change and therefore, the mixing rate within the aquifer. Mass transfer in a porous media is defined by darcy law. For homogeneously distributed ground properties, hydraulic conductivity is distributed uniformly so-called isotropic. The groundwater mass conservation equations are described with the following equation (Eq.5).

\[
[\nabla.(K\rho \nabla h)]dV = Q_s
\]  
(5)

Figure 2. 1: Steady state drawdown for injection and extraction

Full heat transfer equation (Eq.6) including conduction and convection are derived from Fourier and Darcy laws as shown with the following [3];

\[
(\rho c)_s \frac{\partial T}{\partial t} = \nabla \left( (\rho c)_{aq} (\lambda_{aq}) \nabla T(r) \right) - (\rho c)_f \nabla \left( q(r) T(r) \right) + Q_s
\]  
(6)

Where \( \lambda_{aq} \) is the thermal conductivity of aquifer, \( (\rho c)_f \) specific heat capacity of fluid, \( (\rho c)_{aq} \) specific heat capacity of the aquifer.

Table 2. 2: Input parameters for the model
Development of a building integrated ATES model

<table>
<thead>
<tr>
<th>Physical Conditions</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity</td>
<td>m/s</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Thermal conductivity of aquifer</td>
<td>W/(m°C)</td>
<td>2.5</td>
</tr>
<tr>
<td>Initial ground temperature cold well</td>
<td>°C</td>
<td>11.5</td>
</tr>
<tr>
<td>Initial ground temperature warm well</td>
<td>°C</td>
<td>12.5</td>
</tr>
<tr>
<td>Effective Porosity</td>
<td>%</td>
<td>35</td>
</tr>
<tr>
<td>Thickness of the cold aquifer</td>
<td>m</td>
<td>20</td>
</tr>
<tr>
<td>Thickness of the warm aquifer</td>
<td>m</td>
<td>50</td>
</tr>
<tr>
<td>Volumetric heat capacity of aquifer</td>
<td>MJ/m$^3$K</td>
<td>2.45</td>
</tr>
<tr>
<td>Volumetric heat capacity of clay</td>
<td>MJ/m$^3$K</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operational Conditions</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection/extraction flow rate warm well (6 steps)</td>
<td>m$^3$/h</td>
<td>6/12/20/30/40/45</td>
</tr>
<tr>
<td>Injection/extraction flow rate cold well (6 steps)</td>
<td>m$^3$/h</td>
<td>20/35/50/80/100/110</td>
</tr>
<tr>
<td>Injection temperature heating season</td>
<td>°C</td>
<td>6-11</td>
</tr>
<tr>
<td>Injection temperature cooling season</td>
<td>°C</td>
<td>13-17</td>
</tr>
</tbody>
</table>

2.3.1.2 **Meshing**

The model consists of a total of 16 boundaries and 5 domains that are numerically solved by the finite element method (Fig.2.2). The computational domain was quadratically meshed, and the complete mesh consists of 84933 elements domain elements and 666 boundary elements. The minimum element quality was 0.512. The
simulation time was set to 1 hour. The aquifer is confined by two 5 meter wide impermeable layers of clay.

![Diagram of 2D Axis-symmetric domain of confined ATES](image)

**Figure 2.2**: 2D Axis-symmetric domain of confined ATES

### Boundary conditions

Source and sink terms were introduced on the same boundary and vary time dependently. Two wells were simulated in two different domains with the same conditions. The active boundary was defined as source term on charging period, and sink term on extraction period. Pressure set for the lateral, upper and lower sides were set to zero. The following equation was used to convert the flow rate into the hydraulic head difference, on the active boundary [36]:

\[
H_{in} = \frac{Q}{2\pi B} \log \frac{r}{r_0}, \quad H_{out} = -\frac{Q}{2\pi B} \log \frac{r}{r_0}
\]  

(7)

Where Q is the extraction/injection from/to aquifer (m³/s), B is the transmissivity (m²/s), r is the radius of domain (m), r₀ is radius of borehole (m). Temperature boundaries were chosen as symmetry boundary condition which means
that there is no heat transfer beyond the domain. The mathematical representation of boundary conditions are shown as follows:

\[ T_{in(r_0,t)} = T_{in}, \quad T_{in(\infty,t)} = -n(-k\nabla T) = 0, \quad H_{in} = f(Q), \quad H_{(\infty,t)} = 0 \]

2.3.1.4 Assumptions

The factors that have less effect on heat recovery on ATES can be neglected for the integration into the HVAC system model. Besides, Dutch ground conditions for the case study are quite suitable to simplify the model. By referring the previous models [3], [17], the factors that have less effect on heat recovery can be eliminated. The following assumptions were implemented in the model:

1. The computational domain is homogenous and isotropic. Therefore, the flow of water in each dimension was considered same.
2. ATES is confined by two impermeable layers; therefore, the vertical infiltration of water is neglected.
3. There is an only radial movement of water. (Dupuis approach)
4. Since there is no vertical infiltration, thermal interaction is neglected due to the separation of wells with a clay layer. The conduction is not neglected.
5. Although natural ground water flow has a considerable effect on the temperature, natural ground water flow is neglected in this study since it is very low (few meters in a year) in the Netherlands. Thus, the ATES model could be simplified into 2D Axisymmetric model [3].
6. Dispersion and buoyancy effects are neglected, dispersion effect is very limited in cases with no natural ground water flow (0-5% decrease in heat recovery) [17].

2.3.2 Sizing the ATES

Sommer et. al [21] defined the maximum distance that thermal front can be away from the injection well in a homogenous ground conditions and neglecting the vertical infiltration, natural ground water flow, dispersion and thermal conduction (Eq.8).
\[ R_{th} = \frac{c_w V_{storage}}{c_{aq} \pi b} \]  \hspace{1cm} (8)

Where, \( V \) is the volumetric injection rate, \( c_w \) is the heat capacity of water, \( c_{aq} \) is the heat capacity of the aquifer, \( b \) is the thickness of the aquifer. The Dutch society reported that the triple of the defined \( R_{th} \) is enough to avoid thermal interaction, which can be translated into no more heat transfer beyond that radius. Since no heat flux boundary condition is defined at the end of the domain, the domain size based on the triple of \( (R_{th}) \). Therefore, First, the total injected volume of water was calculated for the projected 4 year data to determined \( V_{storage} \), and Eq.8 was applied to size the thermal radius \(|AB|\) of the domain.

![Graph of total water injection and hourly extraction flow rate from the wells](image)

**Figure 2. 3:** Hourly extraction flow rate from the wells

Taking into account the maximum total injected volume in one season which is 176000 \((m^3)\) for warm well and 57000 \((m^3)\) for cold well (Fig.2.3), the total calculated radius is 120 \((m)\) for both of the wells. In order to confirm the size of domain, the maximum amount of volume in one season applied for both wells and it was observed that the size of the domain was sufficient to apply no heat transfer boundary at the end of the domain. The water is injected with a fixed temperature of 16 °C for warm well and 8 °C for cold well (Figs.2.4, 2.5).
2.3.3 MATLAB link COMSOL

There is a developed tool for the communication between MATLAB and COMSOL. Using MATLAB Live-Link tool, COMSOL models can be controlled through MATLAB and COMSOL performs in the batch mode. All globally predefined variables, parameter, geometries, meshes and boundaries on COMSOL can be controlled on MATLAB (Fig. 2.6). For the time-dependent solutions, it is also
possible to control the time-steps for each iteration, which allows the user to adapt various time steps depending on the level of changes in the particular period of time. Adapting time-steps is important since calculation time is heavily influenced by the amount cycles during the simulation, maybe, even more than the complexity of the model. To give an example, the simulation can solve 100 time steps of simulation in 7 seconds, while, it takes approximately 500 seconds to solve 100 steps in the 100 cycle. For instance, for this study, there are 3 different modes of operation for warm and cold well. While the cycles are applied for each time step during injection and extraction period, the cycles can be decreased for the resting mode, where there is only the heat is conducted to the surroundings. There is no difference between calculating the conduction equation, for instance, in 1 iteration for the period of 10 hours or 1 hourly 10 iterations; however, the calculation time can be improved significantly.

Figure 2. 6: Co-simulation scheme between MATLAB and COMSOL
The boundary connected to the building is activated based on the mode of operation, where the hydraulic head is defined as negative during extraction, positive during injection and zero during the resting period. There are two physics coupled in the domain which is heat transfer in porous media module and subsurface flow module. While subsurface flow module is solving pressure distribution within the domain, heat transfer module is calculating temperature distribution depending on the pressure distribution. Heat transfer boundary is defined as heat flux depending on the pressure information.

2.4 Results

2.4.1 ATES model validation

The validation study was conducted using the hourly data from an office building located in Amsterdam, the Netherlands using 4 years of data. The simulation was conducted using MATLAB in connection with COMSOL. The system is a doublet, using two wells of approximately 50 and 100 meters depth for cold and warm well respectively. The ground layer information as the ground is drilled are stored on an online database [37]. From the stored information, the aquifer containing layer can be determined to be sand with a thickness of 20m and 60m, which are seperated by the clay layer [37]. The parameter estimations for the ground layers is obtained from [33] and [14] (Table 2.2). The temperature sensors are located on the extraction/injection point of the ATES which was filtered based on the signal coming from the active pump. In addition, as mentioned earlier (see Fig.2.3), the minimal flow rate of cold extraction and warm extraction are 20 and 6 \(m^3/h\), respectively; therefore, the temperature values are not taken into account for the lower values of minimal flow rate. There are moments where the extraction temperature experiences sudden peaks. These are the moments when the data is received right after the pump is activated. The sensor basically measures the temperature of the conducted heat during the resting mode, not the temperature of the ground water, which is quite visible by looking at the cold well temperature. There are many points where the
water temperature exceeds natural ground temperature of 11.5 °C, which is supposed to be maximum temperature for cold well (Fig.2.7). In addition, the trend of the extraction temperature for cold and warm well is stable during the extraction period. The temperature data logger is Testo 176H2, which has an accuracy of ±0.2 °K (between -20 and 70°C). The measurements are executed with a calibrated ‘TA-Hydronics Scope’ using pressure differential measurements over balancing valves. TA-Hydronics Scope has an accuracy of 0.1°K and the flow accuracy of ±0.1 (l/s). The sensitivity of the temperature sensor is 0.1°C. The temperature of the top layer soil has the yearly average ambient temperature, which is 10.4°C in Amsterdam. The ground temperature increases by 2°C for every 100 meters [32]. Therefore, ground temperature was taken as 11.5 °C and 12.5 °C as an initial condition for cold well and warm well domain respectively. The variable speed pump connected to the ATES was working in 6 steps (Table 2.2) depending on the temperature output of the heat exchanger.

![Figure 2.7: Filtered extraction temperature](image-url)
Figure 2.8: Validation study of the warm well

Figure 2.9: Validation study of the cold well

In Figs. 2.8, 2.9, the black line shows the temperature change on the injection/extraction point. The extraction temperature is significant to predict for the building integration; therefore, the intention was to match the extraction temperature (red and blue line) with simulated temperature (black line). During the injection period, time-dependent values of flow rates and temperatures were defined on the
boundary and, extraction temperature was predicted based on the extracted amount during the extraction period. The yearly mean absolute temperature deviation is as high as 0.8°C and 0.5°C for warm and cold well respectively on the first extraction temperature (Fig.2.10) in the first season, the deviation for both cold and warm wells is higher due to uncertainties in the previous years. The fact is that ATES has been operational 4 years prior to that year. Therefore, the left over heat in the well is uncertain prior to the simulated dates. The measured temperature was available after the 4th year of operation which means that the measured temperature was expected to have a low-temperature gradient in comparison to the simulated temperature in the first couple of years due to the change in heat recovery by years. It is known that the heat recovery increases year by year [11], [14] and becomes relatively steady in the 4th year, as a result, simulation results experience higher temperature gradient in comparison to the experimental data. The trend of temperature matches closely in the 3rd and 4th year of simulation. Specifically, looking at the final year, where the heat recovery rates close to each other and the initial discharge temperature is close to each other, The yearly mean temperature deviation in the final year is as low as 0.17°C and 0.12°C for cold well and warm well (Fig.2.11), respectively. In the second year, the warm well temperature sensor on the discharge pump malfunctions at the beginning of the discharge, therefore; it deviates more at the beginning of the 2nd extraction period (Fig. 2.10).

2.5 Discussion

The integration of ATES into building applications has been found limited based on the review of previously studied ATES systems. On the one hand, there are various conditions of the ground, on the other hand, there are dynamics of the building that can influence the temperature distribution in ATES. Frequently, ATES models were decoupled from the building, the effect of ground parameters on the heat recovery was investigated based on the fixed boundary conditions of heat flux into the domain. Therefore, there was no model validated with the experimental data.
As it is proven in the review of the models [3-6], the heat recovery of ATES can be very site-specific. None of them [3-6] defined any different physics or domain conditions, in an attempt to make the model as simple as possible. TRNATES model
which is frequently used is limited with solving the dynamics of the underground. For instance, [6] applied the TRNATES for high-temperature ATES, where the buoyancy effect was neglected. The changes in thermal properties such as density, hydraulic conductivity were not considered. The authors in [3], [4] have taken into account the natural ground water flow; however, have not considered or evaluated the possible dispersion effect. All ATES systems were considered as individuals and completely isolated from the other ATES systems. However, in reality, ATESs can be situated in an area surrounded by a group of ATESs, where the system performance can be significantly influenced by thermal interaction. In that case, adding dispersion and thermal interaction effect to the physics of numerical solution can be necessary due to the increase of thermal plume bigger than expected. This is where a finite element method become functional to define new dynamics, domains and boundary conditions to the model. The drawback of this model is the computational load. Although the presented model is relatively simple in terms of a number of elements, the calculation period takes more time in cycles. For instance, the simulation can solve 100-time step of simulation in 7 seconds at once, while, it takes approximately 500 seconds in the cycle mode (1 cycle for each time-step). A validation study has proven that the developed model using MATLAB-COMSOL can predict the behavior of ATES accurately and capable of handling hourly changes in the injection/extraction heat rates. More importantly, since the model is controlled from MATLAB, it can be easily introduced to the models developed in MATLAB or coupled to the co-simulation with building energy software (such as TRNSYS, Modelica, Energy plus) [38-40]. The studied softwares (such as SHEMAT, FEFLOW, MT3DMS, MODFLOW) [19-21] in previous models (presented in Table 2.1) have a limitation in integrating into dynamic building simulation tools.

2.6 Conclusion

This paper introduced the existing models based on the ground characteristics for low and high-temperature ATES to summarize the influence of various heat transfer
function on the heat recovery. The results with these models confirmed the need for a model that is adaptable into various ground conditions and dynamics of the buildings. The co-simulation between MATLAB and COMSOL was introduced to simulate FEM model based on the varying flow rate and temperature information from the building side. In order to prove adaptability and reliability of the FEM model, a validation study performed using MATLAB in connection with COMSOL. Performed validation study has shown its potential for handling the dynamics of the building. The yearly absolute mean deviation between the simulated and the measured values for the well extraction temperature was as low as 0.17°C and 0.12°C for cold well and warm well, respectively.

2.7 References


combined heat and power, heat pumps and high temperature aquifer thermal energy storage,” *Energy Build.*, vol. 84, pp. 142–151, Dec. 2014.


Chapter 3

A CO-SIMULATION METHOD TO INVESTIGATE THERMAL IMBALANCE IN AN ATES SYSTEM

ATES systems are designed to operate with a temperature difference of at least 8 °C between wells, whereas the existing installations operate in practice with an average temperature difference of 4 °C. The ATES supply temperature is influenced by heat losses to the surroundings and the yearly balance of total heat exchange of heating and cooling between a building and the groundwater. Due to the lack of tools capable of simulating the system that connects ATES with the buildings, in this chapter, we developed a co-simulation method that combines COMSOL, MATLAB and TRNSYS. The developed method was applied to three buildings representing different thermal load profiles. The performance analysis were made correspondingly.

A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Hydraulic Conductivity (m/s)</td>
</tr>
<tr>
<td>Q_b</td>
<td>Heat transfer to the building (kJ)</td>
</tr>
<tr>
<td>h</td>
<td>Hydraulic head (m)</td>
</tr>
<tr>
<td>Q_{b}</td>
<td>COP_{HP} COP cooling supply in heat pump mode</td>
</tr>
<tr>
<td>q</td>
<td>flow flux (m^2/s)</td>
</tr>
<tr>
<td>Q_{direct}</td>
<td>COP of direct cooling supply</td>
</tr>
<tr>
<td>\rho</td>
<td>density (kg/m^3)</td>
</tr>
<tr>
<td>COP_{cooling}</td>
<td>Cooling COP</td>
</tr>
<tr>
<td>S_s</td>
<td>Storage term</td>
</tr>
<tr>
<td>COP_{heating}</td>
<td>Heating COP</td>
</tr>
<tr>
<td>Q_s</td>
<td>Source term (m^3/s)</td>
</tr>
<tr>
<td>COP_{sys}</td>
<td>System COP</td>
</tr>
<tr>
<td>Q_{HP}</td>
<td>Cooling supply to the building (HP mode)</td>
</tr>
<tr>
<td>(pc)_f</td>
<td>Specific heat capacity of fluid (kJ/kgK)</td>
</tr>
<tr>
<td>Q_{DC}</td>
<td>Cooling supply to the building (DC mode) (kJ)</td>
</tr>
<tr>
<td>(pc)_{aq}</td>
<td>Specific heat capacity of aquifer(kJ/kgK)</td>
</tr>
<tr>
<td>Q_{cool}</td>
<td>Total cooling supply to the building (kJ)</td>
</tr>
<tr>
<td>\lambda_{aq}</td>
<td>Thermal conductivity of aquifer (Km/kJ)</td>
</tr>
<tr>
<td>W_{pump,cw}</td>
<td>Electricity consumption of cold well pump (kJ)</td>
</tr>
<tr>
<td>Q_{inj}</td>
<td>Injected heat to the ground (kJ)</td>
</tr>
<tr>
<td>W_{pump,ww}</td>
<td>Electricity consumption of warm well pump (kJ)</td>
</tr>
<tr>
<td>Q_{ext}</td>
<td>Extracted heat from the ground(kJ)</td>
</tr>
<tr>
<td>T_{cw}</td>
<td>Extraction temperature from the cold well (°C)</td>
</tr>
<tr>
<td>T_{ww}</td>
<td>Extraction temperature from the warm well of cold well( °C)</td>
</tr>
</tbody>
</table>
3.1 Introduction

Energy consumption in buildings has been inevitably increasing for the last several decades. Heating and cooling systems are responsible for the majority of the energy use within a building. As a result, numerous underground thermal storage systems have been introduced as energy-efficient sources for heating and cooling applications in combination with a heat pump, due to the suitable and stable supply temperature.

Commonly, there are two underground thermal storage systems that have inter-seasonal operation. One is borehole thermal energy storage (BTES), and the other is aquifer thermal energy storage (ATES). In the BTES system, heat is exchanged with the ground through closed-loop pipes by means of conduction. ATES utilizes readily available groundwater to transport heat to a building using an open-loop pipe system. The exchanged heat is stored in the same storage field throughout the season in a BTES system, while it is stored separately using doublet wells in an ATES system: in a cold well in the winter and a warm well in the summer. Therefore, there is no direct thermal interaction between sources, as in BTES systems (Fig. 3.1). ATES systems are designed to operate with a temperature difference of 8 °C or higher depending on the operation settings. The system is usually designed to operate with an injection temperature of between 6 and 8 °C in the cold well and 16 to 18 °C in the warm well for a ground temperature of 12 °C in the Netherlands. However, current installations operate with an average temperature difference of 4 °C [1], [2], thus the expected operating temperature level is practically not achieved. This influences the overall system energy performance negatively. Well temperature varies throughout the year, which is influenced by heat losses to the surroundings and, more importantly, by the amount of injected/extracted heat to/from the ground, due to the fact that buildings have different thermal load patterns (cooling/heating domination) over the year. The amount of heat and cold in the wells is directly influenced by the building load, which eventually influences the temperature level in the warm and cold wells.
Following the implementation of recent building energy regulations, buildings are now constructed with much improved insulation techniques and air tightness, which has resulted in increased cooling demand. Depending on the building’s structure and internal heat gain, cooling demand can exceed heating demand in buildings in central and northern Europe, especially in non-residential buildings. Specifically, the ATES concept with heat pumps is able to provide highly efficient cooling performance [3], [4], [5], [6] and is thus frequently applied in the Netherlands, where there is a cooling domination in the office building load. In the future, ATES systems are therefore expected to be increasingly applied in buildings with a higher need for cooling than...
A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

for heating [1]; thus, cooling domination in a building load is inevitable for ATES systems.

Thermal imbalance is a problem for both ATES and BTES systems for ground-sourced applications that have inter-seasonal operation. This problem has been intensively studied for BTES systems in several studies [7], [8], [9], [10], [11], [12], [13] and studies [7], [8], [9], [10], [11], [12], [13] conclude that system performance decreases over time and even results in system failures in heating/cooling supply as a result of the thermal imbalance due to the change in overall supply temperature from the ground.

However, the thermal imbalance problem has not been studied in an ATES context. Studies of ATES systems [14], [15], [16], [17] have mainly focused on the thermal modelling of ATES to determine the effect of ground conditions on heat recovery and temperature distribution in the well. Thermal models are significant for correctly characterizing the thermal response of the ground; however, it is not possible to accurately determine temperature levels disconnected from the building load due to the differences in the amount heat extraction. The studies concerning ATES connected to a building are limited to mostly to the experimental data analysis [5], [6], [18], [19] due to the lack of commercial or non-commercial simulation tools.

Taking into account the thermal imbalance problem and the lack of available simulation tools for ATES, in this study, we explored the influence of thermal imbalance on the supply temperature from ATES and the performance of ATES connected to the building load. Therefore, we first develop a co-simulation platform that is able to simulate ATES connected to a building load. Later, the developed model is applied to a building for three different U-values that represent three different thermal imbalance ratios. Correspondingly, the influence of each thermal imbalance ratio on temperature levels and performance of the system is determined.

The subsequent sections of this paper are as follows. Section 2 is a literature survey on previous studies of ATES and BTES; section 3 provides the methodology and a
description of the case study and the co-simulation platform; section 4 provides the results; section 5 discusses the results; and section 6 provides the conclusions.

3.1. Literature review

Studies concerning the performance analysis of an ATES system have been found to be limited. Existing studies concerning ATES connected to a building load have been conducted to determine the overall performance of the ATES system using experimental data [5], [6], [18], [19] and some simulations [6], [20], [21], [22]. D. Vanhoudt et al. [5] extensively compare an existing HVAC system with an ATES system in terms of operational cost and COP using the experimental data from the building. They determine that by applying ATES, 71% of the primary energy use can be reduced. Paksoy et al. [18] show that ATES can maintain a 60% higher COP than a conventional cooling system in a supermarket in Turkey. Turgut et al. [19] determine energy cost savings of 70% when ATES is used for heating a greenhouse in comparison to fuel oil. Kranz et al. [6] conduct an experimental analysis and a parametric study to determine the optimal operational parameters for an ATES system. The COP of the system is considerably influenced by the temperature level of the cooling network and the threshold temperature for regeneration of ATES using an air-water heat exchanger [21]. Ghaebi evaluates the performance of ATES’s various operation modes: ATES for only cooling, ATES for heating connected to solar thermal and ATES for both heating and cooling. The analysis shows that the COP for a cooling operation is as high as 17.2 when ATES is used for heating and cooling, while the COP for cooling is 10.36 due to the additional storage of cold using the wasted heat from the heat pump. The thermal imbalance problem has not yet been studied for the ATES system.

Although the ATES and BTES systems show some differences in their operation, BTES and ATES are both ground heat storage systems with inter-season operation, which makes it possible to compare the two systems. Therefore, this literature survey focuses not only on ATES systems but also on BTES systems in order to point out
the thermal imbalance effect on the system. Previous studies concerning the thermal imbalance problem in BTES conclude that the imbalance ratio has a considerable influence on the overall ground temperature. Because the heat is extracted and injected from the same field, the ground temperature decreases/increases steadily year by year. Studies ([7], [8], [9], [10], [11]) have shown that the ground temperature can change in the range of ±10 °C after 10 years of operation (Fig. 3.2). The influence of thermal imbalance on the source temperature differs in ATES systems due to the separation of the heating and cooling source, which needs to be investigated.

![Graph showing thermal imbalance influence of BTES](image)

**Figure 3.2:** Thermal imbalance influence of BTES [7], [8], [9], [10], [11], [12]

The existing studies [6], [20], [21], [22] that conduct simulation studies for the ATES system have been mostly implemented in TRNSYS. The authors in [6], [20], [22] use TRANSAT for an ATES model that is developed for TRNSYS. However, TRANSAT is not commercially or non-commercially available anymore. The authors in [21] develop a C code for the ATES model, which has no public access. The authors in [16] have already given detailed information on the need for a
A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

dynamic ATES model based on the finite element method (FEM) and develop an ATES model that is able to address the time dynamics imposed by a building load.

Co-simulation is a known approach for building energy management systems in buildings. Popular co-simulation approaches can be found in previous studies, such as Energy Plus with Java [23], Energy Plus with MATLAB and Energy Plus with computational fluid dynamics (CFD) [24], [25]. However, a co-simulation approach toward CFD in connection with TRNSYS is a relatively new concept. The effectiveness of this method has been proven by Ferroukhi et al. [26]. TRNSYS has been frequently used to form complex energy flow diagrams within ATES systems in previous studies [6], [20], [22]. COMSOL has also been proven as an effective tool to solve a FEM-based numerical model of an ATES system [16]. Since, a new simulation platform is needed to enable the analysis of ATES within a system under the thermal imbalance concept, we first develop and present a new co-simulation method consisting of the tools namely COMSOL, MATLAB and TRNSYS that simulates ATES connected to a building load.

3.2 Methodology

3.2.1 Co-simulation platform
In this study, we combined TRNSYS, used for HVAC system modelling, and COMSOL, used for the ATES model. More detailed information on how the co-simulation works is given in section 3.5. The system was simulated based on the coupling of three simulation softwares: TRNSYS 17, MATLAB and COMSOL. TRNSYS 17 was used to form the whole energy flow diagram, including the components of the building and heating/cooling systems (see Fig. 3.3), and COMSOL was used to model ATES. Information was exchanged between COMSOL and TRNSYS through MATLAB (acting as a master). Depending on the building load information, MATLAB activates one well group in charging mode and the rest of the wells in discharging mode.
The developed model was based on a case study of an office building in the Netherlands. The building has a total area of 3,520 m². Due to the fact that ATES systems only started to be applied after the 1980s [27], an energy flow diagram (Fig. 3.4) was applied and adapted for buildings of the same size built in 1980–1990, 1990–2000 and 2000–2010. U values (Table 3.1) were selected and applied based on the statistical average values applied to Dutch buildings in compliance with the build year [28]. This is intended to show the influence of the different building load profiles on the ATES ground source well temperatures.

There are two horizontally positioned wells integrated into the system and working in cyclic conditions. The operation is switched depending on the season. In this study, the ATES system was designed to work in 16 °C heating and 8 °C cooling well operation temperatures at a ground temperature of 12 °C, presenting a typical application in the Netherlands [29], [30]. Since ATES was hydraulically decoupled by a heat exchanger from the building side, the flow rate was adjustable in order to inject heat at the desired temperature into the wells. Depending on the inlet temperature to the wells, the proportional controller modulated the flow rate.
The system has three operational modes (Fig. 3.4): heating with heat pump (HP), direct cooling with ATES, and cooling with HP.

**Figure 3.4:** Workflow of the aquifer and HVAC integrated system

**Table 3.1:** U values for the cases

<table>
<thead>
<tr>
<th>Case/U values</th>
<th>Wall</th>
<th>Window</th>
<th>Floor</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980-1990 building</td>
<td>0.8</td>
<td>2.6</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>1990-2000 building</td>
<td>0.6</td>
<td>2.3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>post-2000 building</td>
<td>0.6</td>
<td>2.1</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Heating with HP: The heat pump in connection with an air handling unit (AHU) and an ATES system is used to meet the entire heating/cooling demand of the building. During the heating season, the warm well provides heat for the evaporator of the heat pump, and chilled water is injected back into the cold well. Simultaneously, the building is heated up, and the cold well is being charged.
Direct cooling with ATES: In the cooling period, when the ambient air usually exceeds 13 °C, ATES directly extracts heat from incoming air through the cooling coil and injects the heat into the warm well.

Cooling with HP: If the cooling demand is not met, the outlet water from the cold well is pumped into the evaporator to further cool down the temperature supply to the cooling coil when the heat pump operates in chiller mode. The returned water from the cooling coil further extracts the heat at the condenser and finally re-injects all the heat into the warm well.

The office building operates during normal working hours from 7 a.m. to 6 p.m. on weekdays. ASHRAE Standard [31] was used to determine the occupancy rate for each hour, whereas no occupancy was considered during the weekend. The AHU was responsible for the distribution of heating and cooling. The heating temperature for the building was set at 21 °C with a ± 2 °C temperature dead band for the HP. Practically, for ATES system, the set point for direct cooling supply operation is set to lower cooling set point than the set point for HP operation. By doing so, ATES operates before HP to satisfy the cooling demand. In this study, the cooling control was set to 22 °C with ± 2 °C for the ATES and 24 °C ± 2 °C for the HP; therefore, the inside temperature was floating around 21.5 in the heating season and 24 °C in the cooling season. By setting the set point lower for the direct cooling supply, it was guaranteed that HP would operate when ATES was not sufficient, which was significant to assess the effect of the thermal quality of water on the performance of the system. The damper embedded in the AHU was controlled to limit the fresh air supply to a rate of 13.5 (L/s) per occupant, which is the needed amount for an office environment according to standards. In order to make a fair comparison between seasons, the starting simulation time was set to the first day of the cooling period; therefore, the warm well was primarily being charged in all simulations.

In this study, the return water temperature from the building side was designed in the range of 4–8 °C, while the cooling network was designed as 18–30 °C (Table
3.2), as it is practically applied [6]; therefore, the system could inject a temperature of 8 and 16 °C into the wells by adjusting the flow rate on the ATES side. The reason for the high return temperature in the chiller mode is due to the heat exchange on both the ATES and the condenser sides of the heat pump.

Table 3.2: Design results for the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature to AHU on direct cooling</td>
<td>°C</td>
<td>13 – 15</td>
</tr>
<tr>
<td>Inlet temperature to AHU in HP mode</td>
<td>°C</td>
<td>8 – 10</td>
</tr>
<tr>
<td>Inlet temperature to heating network</td>
<td>°C</td>
<td>35 – 40</td>
</tr>
<tr>
<td>Return temperature from cooling network on direct cooling</td>
<td>°C</td>
<td>18 – 20</td>
</tr>
<tr>
<td>Return temperature from cooling network in GSHP mode</td>
<td>°C</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Return temperature from cooling network on heating</td>
<td>°C</td>
<td>4 – 8</td>
</tr>
</tbody>
</table>

3.2.1.2 *TRNSYS for building and HVAC modeling*

The building was simulated using type 56, a multi-zone building model implementing actual building specifications. The AHU was modelled using type 600, which represents the central heating/cooling and air supply of a building with constant flow rate and power. The heat pump was modelled using TRNSYS type 927, which is applicable for groundwater source heat pumps. The HP model was calibrated using a manufacturer’s datasheet with flow rate, heating/cooling power, and capacity. Components were controlled using differential controllers (type 4). Differential controllers were used to control the set-point temperature of the indoor air, the percentage of fresh air supply and the flow rates of the circulated water. A proportional controller (type 1669) was used to modulate the pump operation on the aquifer side.

Due to the different modes of operation in the system, there were many flow diverters and flow mixers in the hydraulic scheme. Control signals were assigned to the pumps
and flow diverters (type 647) to activate the necessary pipelines. The colored lines show the water pipeline network and the rest of the lines in Fig. 3.5.

![Energy flow diagram in TRNSYS](image)

Figure 3.5: Energy flow diagram in TRNSYS

### 3.2.1.3 COMSOL for aquifer modelling

The ATES model was numerically solved using the FEM. The model used in [32] was used for this paper as well. The flow of water in porous media was solved according to the Darcy law and coupled to heat transfer functions to determine the temperature distribution throughout the meshed domain.

The flow flux of water is written as a function of head gradient and coefficient of hydraulic conductivity:

\[
\vec{q} = -K\vec{\nabla}h
\]  

(1)

Transient drawdown on the injection/extraction is presented with the following equation:
Mass transfer in a porous medium is defined by the Darcy law. For homogenously distributed ground properties, hydraulic conductivity is distributed uniformly, or isotropically. The groundwater mass conservation equation is described by the following equation. \( Q_s \) was defined as a source term for infiltration or as sink term for the discharge of water.

\[
\n\[ \nabla \cdot (K \rho \nabla h) \right] dV = Q_s \tag{3} 
\n\]

The full heat transfer equation including conduction and convection is derived from the Fourier and Darcy law, as shown in the following:

\[
(pc)_s \frac{\partial T}{\partial t} = \nabla \cdot \left( (pc)_{aq} \left( \lambda_{aq} \nabla T(r) \right) - (pc)_f \nabla (q(r) T(r)) \right) + Q_s \tag{4} 
\]

where \( \lambda_{aq} \) is the thermal conductivity of the aquifer, \( p \) is the density, \( (pc)_f \) the specific heat capacity of fluid and \( (pc)_{aq} \) the specific heat capacity of the aquifer.

The following conditions (Table 3.3) were applied.

**Table 3.3: 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 x 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 aquifer</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Volumetric heat capacity of aquifer</td>
<td>2.45</td>
<td>MJ/m^3K</td>
</tr>
</tbody>
</table>

**Operational Conditions**

<table>
<thead>
<tr>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
</table>
### Injection/extraction flow rate of warm well (adjustable)
- 0-200 m$^3$/h

### Injection/extraction flow rate of cold well (adjustable)
- 0-200 m$^3$/h

### Injection temperature in heating season
- 8 °C

### Injection temperature in cooling season
- 16 °C

#### 3.2.1.4 TRNSYS-MATLAB-COMSOL co-simulation

In this study, co-simulation with three softwares, MATLAB, COMSOL, and TRNSYS, was conducted. Using the MATLAB component (type 155) of TRNSYS, it was possible to call external functions written in a MATLAB script. MATLAB has a toolbox that enables a connection with COMSOL. With this toolbox, MATLAB commands were able to run on a COMSOL server. Thus, MATLAB was responsible for the information exchange between the software, playing a mediating role. However, type 155 was not capable of identifying COMSOL scripts in MATLAB. Therefore, the connection between TRNSYS and COMSOL was decoupled, synchronized, and solved separately. Information was exchanged through a common database provided in text files.

The co-simulation framework is shown in Fig. 3.6. The co-simulation was controlled by MATLAB and transferred input information from TRNSYS depending on the last updated status information in the file. By doing so, TRNSYS did not take a step before COMSOL found a solution for the domain and printed it to the file. The information was exchanged through text files. TRNSYS solves input variables based on the formed energy flow network and provides output variables for COMSOL through text files. COMSOL implemented the output from TRNSYS and sent the calculated output back to TRNSYS, thereby forming the whole cycle.
A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

**Figure 3.6:** Schematic diagram of the co-simulation framework

Warm and cold well models were described in COMSOL in connection with MATLAB. As shown in Fig. 3.7, COMSOL needed the information from TRNSYS, including inlet water temperature, inlet flow rate and the percentage of discharge pump, to calculate the heat transfer in the aquifer. Warm well and cold well signals were used to decide which well was in charging or discharging mode.
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Thus, warm and cold well models simultaneously implemented the input variables and sent outputs, including the outlet water temperature and flow rate, back to TRNSYS through component type 155. The inlet temperature and flow rate to ATES were dependent on the cooling/heating load required for the building. COMSOL solved the models simultaneously based on the temperature and flow rate defined by the dynamic boundaries. In turn, warm well and cold well temperatures were provided as outputs, and TRNSYS returned the system with the temperature from either the cold well or the warm well, depending on the mode of operation.

The order of information exchange was important for the convergence and communication between COMSOL and TRNSYS. Adding a MATLAB component into such a complex system may cause false information exchange and synchronization problems between COMSOL and MATLAB. To avoid this problem, the order of information exchange between components was arranged in the order of heat transfer between components in TRNSYS. In this system, first the building load was calculated along with the required heat or cold transfer based on

Figure 3.7: Information exchange between COMSOL and TRNSYS
the control signal. The HVAC components’ order was arranged depending on the circulation system. Lastly, MATLAB was responsible for the information exchange.

### 3.2.2 Performance indicators

The imbalance ratio of the building load differs from the ground side and depends on the components in the system. Therefore, in this study, the degree of imbalance was expressed using the imbalance ratio (IR), which is determined from the amount of energy extracted from the ground [5].

\[
IR = \frac{Q_{inj} - Q_{ext}}{\max(Q_{inj}, Q_{ext})} \times 100\% \tag{5}
\]

where \(Q_{inj}\) is heat injected into the ground based on the temperature difference between the inlet of the warm well and the outlet of the cold well, and \(Q_{ext}\) is the heat extracted from the ground. By using this equation, the thermal imbalance was calculated based on the temperature difference between the outlet of the warm well and the inlet of the cold well.

The percentage of the well pump varies depending on the temperature difference between the warm and cold well and the amount of heat transfer with the building.

\[
W_{pump,ww} = \frac{Q_b}{C_{p,water} (T_{ww} - 8)} \tag{6}
\]

\[
W_{pump,cw} = \frac{Q_b}{C_{p,water} (16 - T_{cw})} \tag{7}
\]

where \(Q_b\) is the heat transfer with the building, \(C_{p,water}\) is the specific heat capacity of the water, \(T_{ww}\) is the extraction temperature from the warm well, and \(T_{cw}\) is the extraction temperature from the cold well. The simulation starting time was set to the first cooling operation time in order to make a fair comparison between the temperature changes of the warm and cold wells. Thus the system COP for heating and cooling, \(COP_{sys}\), is calculated based on the ratio between the energy extracted from the fan coil and the total electricity consumption in one heating/cooling season.
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\[ COP_{HPC} = \frac{Q_{hpc}}{W_{fans} + W_{pump, cw} + W_{hp}} \]  

\[ COP_{direct} = \frac{Q_{dc}}{W_{fans} + W_{pump, cw}} \]  

\[ COP_{cooling} = \frac{Q_{cool}}{W_{fans} + W_{pump, cw} + W_{hp}} \]  

\[ COP_{heating} = \frac{Q_{heat}}{W_{fans} + W_{pump, ww} + W_{hp}} \]  

\[ COP_{sys} = \frac{Q_{cool} + Q_{heat}}{W_{fans} + W_{pump, cw} + W_{pump, ww} + W_{hp}} \]

where \( Q_{hpc} \) is the rejected heat from the building in the heat pump in chiller mode, \( Q_{dc} \) is the rejected heat from the building in direct cooling supply mode, \( Q_{cool} \) is the total rejected heat from the building, and \( Q_{heat} \) is the total heat transfer to the building. \( W_{fans}, W_{pumps} \) and \( W_{hp} \) are the electricity consumption of ventilation fans, pumps and HP, respectively. In addition, HP cooling, HP heating and direct cooling hours were calculated and changes were projected for a 10-year period.

### 3.3 Results

#### 3.3.1 Thermal imbalance

Heat transfer rates to the ground were presented for each case, as shown in Fig. 3.8. The case buildings, 1980-1990, 1990-2000 and post-2000 building presented the annual absolute heat transfer of 774, 558 and 442MWh to the ground, respectively, which were named as balanced case, case 1 and case 2, respectively. As can be observed, as the insulation within the building increases, the amount of heat exchange with the ground decreases due to the lower building demand. During the heating period, heat is directly exchanged with the evaporator. Since the heat pump is working with a fixed load, the amount of the extracted heat from the ground is in the rated heating capacity of the heat pump, which slightly varies depending on
the COP. On the other hand, the heat injection rates vary greatly due to the direct heat exchange between the supply water and the indoor air temperature.

![Hourly heat transfer in three cases](image)

**Figure 3. 8:** Hourly heat transfer in three cases

For the balanced case, the cooling capacity of ATES along with heat pump can reach a capacity of 250 $W/m^2$, which can be two to three times higher than the capacity of the heat pump [5]. The heat pump was sized based on the peak cooling/heating demand, which resulted in the rated capacities of 95, 70 and 60 $W/m^2$ of HP, which in turn resulted in a relatively higher cooling capacity for the balanced case and case 1 in relation to the size of HP. Eventually, the thermal imbalances in the amount of heat transfer to the ground were determined to be 79%, 51% and -5.3% for case 2, case 1 and the balanced case, respectively.

### 3.3.2 Temperature

The dynamic yearly averaged and hourly groundwater temperature trends are presented in Figs. 3.9 and 3.10. The cases (Fig. 3.8) presented 180, 200 and 230 days of the cooling season for the balanced case, case 1 and case 2, respectively. While the average extraction temperature is directly influenced by the thermal imbalance ratio, the yearly trend is influenced by the accumulation of heat/cold. The increases
in temperature in case 1 and case 2 for the cold well were quite small, since there was a very small amount of surplus cold from year to year. Specifically, there was a higher gradient in the first four years of operation due to the higher increase in the temperature for all cases [33]. The average extraction temperatures (Fig. 3.10) were improved at the end of the 10th year for the cold well by 0.50, 0.14 and 0.01 °C and for the warm well by 0.47, 0.28 and 0.06 °C for the balanced case, case 1 and case 2, respectively. The average extracted cold well temperatures were determined to be 8.4, 9.9 and 10.9 °C, respectively, at the end of the 10th year.

Figure 3.9: Hourly temperature changes in wells

Fig. 3.11 presents the temperature distribution in the 2D axisymmetric domain at the end of the 10th charging period. It can be seen that the domain size was sufficient to simulate total heat/cold injection. The thermal imbalance was visible for each case. The thermal front reaches as far as 300 m, 175 m and 90 m for case 2, case 1 and the balanced case, respectively. The thermal front for the cold well was as low as 50 m.
A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

Figure 3. 10: Yearly averaged extraction temperature; cw stands for cold well and ww stands for warm well.

Figure 3. 11: Temperature distribution for cold well (left) and warm well (right)

It can be clearly observed that as the thermal imbalance ratio increased for the cooling-dominated loads, the cold-well temperature was significantly influenced (Figs. 3.9, 3.10). The balanced thermal load maintained the highest overall thermal
potential for both wells, where the system achieved a temperature difference of 7.6 °C. Case 1 and case 2 saw a temperature difference of 6.1 and 5.1 °C, respectively, at the end of the 10 years of operation.

### 3.3.3 System performance

The system performance was analyzed based on the supply temperature from ATES. In order to eliminate the influence of the system design parameters, the supply temperature of ATES for case 1 and the balanced case were also applied to the building in case 2 in order to make a fair comparison. As shown in Eqs. 6 and 7, the power consumption of the well pump varies. Since the well pump is modulated to be able to inject 16 °C and 8 °C water for the wells, the energy consumption of the pump varies depending on the temperature levels of the wells and the heat transfer rate. It is possible to see (Table 3.4) that $W_{\text{pump,ww}}$ varied very slightly, since the warm well temperature did not change significantly. However, there is an obvious difference for $W_{\text{pump,cw}}$ due to the change in cold well temperature. Since the supply temperature from the cold well is the highest (lowest temperature difference), $W_{\text{pump,cw}}$ is the highest and decreases as the cold well temperature decreases.

#### Table 3.4: Power consumption of the well pump

<table>
<thead>
<tr>
<th>Case</th>
<th>Average power consumption (kWh)</th>
<th>$W_{\text{pump,ww}}$</th>
<th>$W_{\text{pump,cw}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>balanced case</td>
<td>4.7</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>case 1</td>
<td>4.4</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>case 2</td>
<td>4.4</td>
<td>12.2</td>
<td></td>
</tr>
</tbody>
</table>

Since the chiller operation hours decreased, there was a noticeable improvement in $COP_{\text{cooling}}$ as well. Fig. 3.12 presents the COP values of direct supply of cooling ($COP_{\text{direct}}$) and of the heat pump in chiller mode ($COP_{HPC}$). Since the direct supply of cooling was in the cost-of-pump operation, direct supply achieved a higher COP.
than the heat pump in chiller mode. It is also seen in Fig. 3.12 that the heat pump was working more frequently during the middle of the cooling period as the cooling demand rates of the building increased. $COP_{HPC}$ varies slightly due to the small variations in cooling capacity of the heat pump, while $COP_{direct}$ varies widely depending on the supply temperature and the indoor temperature of the building.

Fig. 3.13 presents the change in the number of heat pump operations in chiller mode. In relation to the temperature levels (Fig. 3.8), the system COPs for cooling ($COP_{cooling}$) and heating ($COP_{heating}$) were influenced. $COP_{cooling}$ was mainly influenced by the reduction of the chiller operation (Figs. 3.13, 3.14). As expected, there is a noticeable difference between case 2 and the balanced case, due to the temperature difference in the cold supply temperature, where the $COP_{cooling}$ for the balanced case was 13.2 and 9.8 for case 2. On the other hand, $COP_{heating}$ was negligibly influenced, due to the small difference between the warm-well temperature and the power consumption of the pump. Eventually, $COP_{sys}$ was 8.3
for the balanced case, whereas it was 7.3 for case 2 at the end of the 10th year of operation.

**Figure 3.13:** Comparison of the chiller operation

**Figure 3.14:** Performance of the system
3.4 Discussion

Thermal imbalances in the amount of heat transfer to the ground remain a subject that needs to be investigated for ground-sourced applications including BTES and ATES systems. Previous studies [22], [8], [9], [10], [11], [12] mainly focus on BTES systems due to the broad application of the system. Since the heat is transferred to the same field in a BTES system, there is a direct interaction between cold and heat sources, and the source temperature from the ground is severely influenced, with the ground temperature changing in the range of ±10 °C depending on the thermal imbalance ratio. In BTES systems, the accumulation of heat/cold results in steady decrease/increase in the temperature year by year. For ATES, however, it was observed that yearly temperature change is limited to the accumulation of heat and cold sources, which is also known as the change in heat recovery for each individual well. It was observed that there is a direct influence on the availability of heat and cold stored in the wells. For instance, a thermal imbalance ratio of 79% resulted in an average extraction temperature of 10.9 °C from the cold well. Considering the 16 °C of the injection temperature, the system operates under a 5.1 °C, 6.1 °C and 7.6 °C temperature difference for case 2, case 1 and the balanced case in the cold supply, respectively, while the expected temperature difference of the heat exchanger is at least 8 °C [2] in the Netherlands. This may result in a decrease in the direct cooling supply hours and even in a cooling problem during peak demand if the heat pump is sized based on the capacity of ATES in cooling supply. Similarly, Kranz et al. [16] determine a lower extraction temperature for a warm well and a higher extraction for a cold well than the designed temperature due to underestimated building demand.

As mentioned in previous studies [21], [16], [6], cold wells are an important natural source for cooling due to the suitable ground temperature, which also makes the system very sensitive to changes in the cold-well temperature. The decrease in the supply temperature from 10.9 °C to 8.4 °C increases the $COP_{\text{cooling}}$ from 9.6 to 12.3 due to the increase in the direct cooling share.
A co-simulation platform was developed in this study. The co-simulation method can be used for further investigation for other applications. The main limitation of this method in comparison to the one in previous studies [6], [20], [21] is the calculation period. Since COMSOL applies the FEM, this method can be more time-consuming in comparison with the finite difference model (TRANSAT) in TRNSYS and eventually requires more time and sources to be implemented. Besides, there are additional time losses due to the information exchange between the software. The advantage of this method is the reliability and the adaptability of both ATES and the TRNSYS model to the various ground and building conditions, which is also mentioned in [32]. In this paper, the thermal interaction between the well groups was neglected due to the fact that the current installations were installed with enough spacing. The thermal interaction may occur in the very long term and in a very high domination of a group of wells in the region [1]. The selected temperature settings for ATES are usually applied in the range of 16-18 °C for a warm well and 6-8 °C for a cold well in the Netherlands. The design parameters for operating conditions, such as the injection temperatures for well groups and indoor temperature settings, may vary depending on where the system is applied. Various ground conditions and operational parameters can be further investigated; however, that is out of the scope of this paper.

3.5 Conclusion

A co-simulation method using TRNSYS-MATLAB-COMSOL for integrating ATES modelling into building HVAC system modelling has been presented. The co-simulation method was applied to three cases. The thermal imbalance effect on temperature changes of ATES and the performance of the system was investigated. The following conclusions can be drawn from this study:

1. The co-simulation method is capable of integrating ATES into a building-dynamic simulation, allowing the user to analyze system dynamics.
Thermal imbalances have a direct influence on the temperature levels of the wells, which also affects the thermal potential of the cold and warm wells. Although the warm well is hardly influenced by cooling-dominated loads, the cold well temperature is significantly influenced by a 79% thermal imbalance ratio, where the average supply temperature from the cold well deviates by 2.5 °C from the balanced case.

The cooling performance is highly sensitive to the cold supply temperature. A decrease of the cold well temperature by 2.5 °C decreases the $COP_{cooling}$ from 13.2 to 9.8 due to a decrease in the direct cooling supply share. Eventually, the $COP_{sys}$ is 13.7% higher in the balanced case than in the case with a 79% thermal imbalance ratio and 6% higher than the case with 51%.

Overall, these results indicate that the thermal potential of ATES is influenced by thermal imbalance. While the current practices are designed with at least 8 °C between the cold and warm well, the temperature difference is as low as 5.1 °C for a building with a 79% thermal imbalance ratio in cooling supply, which leads to problems for the optimal design of the system and a decrease in overall performance of 13.7%. Therefore, the ATES integrated systems should be properly sized in accordance with building load and possible extraction temperature from the wells in order to maintain a reliable and energy-efficient system design.

### 3.6 References

A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system


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[31] “ASHRAE 90.1 Appendix G. Building Performance Rating Method.”


Chapter 4

THE USE OF NIGHT VENTILATION FOR ACHIEVING A THERMAL BALANCE IN AN ATES SYSTEM

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 the thermal balance for cooling dominated loads. This approach increases the operational cost and energy consumption of ATES heating/cooling systems. In this chapter, an alternative approach, night ventilation (NV) is used to replace the operation with an heat pump for achieving a thermal balance. The potential effectiveness of night ventilation is determined.

A Co-Simulation Method to Investigate Thermal Imbalance in an ATES system

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP_{HPC}$</td>
<td>COP cooling supply in heat pump mode</td>
</tr>
<tr>
<td>$COP_{direct}$</td>
<td>COP of direct cooling supply</td>
</tr>
<tr>
<td>$COP_{cooling}$</td>
<td>Cooling COP</td>
</tr>
<tr>
<td>$COP_{heating}$</td>
<td>Heating COP</td>
</tr>
<tr>
<td>$Q_b$</td>
<td>heat transfer to the building (kJ)</td>
</tr>
<tr>
<td>$T_{ww}$</td>
<td>extraction temperature from the warm well pump</td>
</tr>
<tr>
<td>$Q_{sup,a}$</td>
<td>extracted heat from ATES (kJ)</td>
</tr>
<tr>
<td>$W_{pump,ww}$</td>
<td>supplied power for the warm well pump (kJ)</td>
</tr>
<tr>
<td>$Q_{sup,b}$</td>
<td>supplied heat to the building (kJ)</td>
</tr>
<tr>
<td>$W_{pump,cw}$</td>
<td>supplied power for the cold well (kJ/s)</td>
</tr>
<tr>
<td>$P_{HP}$</td>
<td>power consumption of the HP (kJ)</td>
</tr>
</tbody>
</table>

4.1 Introduction

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 16-18°C in the warm well and between 6-8°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 efficien-
The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system

cy. 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].

Figure 4.1: An ATES system in cooling and regeneration mode, modified from [9]

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. 4.1 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
The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system

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], [12], [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] [15], [16], [17], [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
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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 analysed. 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.

4.2 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], [24], [25], Asia [26], [27], [28] and Europe [26], [27], [28], [29], [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 4.1 shows a list of
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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 20MWh 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 rejecter [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]. Ghaebi 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.
### Table 4.1: Some hybrid ATES applications worldwide

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Location</th>
<th>Cooling Dominated</th>
<th>Heating Dominated</th>
<th>Cold-Warm Well Injection</th>
<th>System Components</th>
<th>Building Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>[31]</td>
<td>Eindhoven, Netherlands</td>
<td>✓</td>
<td></td>
<td>6/16</td>
<td>ATES + HP + CT</td>
<td>University</td>
</tr>
<tr>
<td>[7]</td>
<td>Utrecht, Netherlands</td>
<td>✓</td>
<td></td>
<td>8/14</td>
<td>ATES + HP + AHU</td>
<td>Office building</td>
</tr>
<tr>
<td>[10]</td>
<td>Tehran, Iran</td>
<td>✓</td>
<td></td>
<td>3/14, 43/65</td>
<td>ATES + HP + CT + solar thermal</td>
<td>Residentia l building</td>
</tr>
<tr>
<td>[32]</td>
<td>Bucharest, Romania</td>
<td>✓</td>
<td></td>
<td>5/15, 35/50</td>
<td>ATES + HP + CHP</td>
<td>Community building</td>
</tr>
<tr>
<td>[13]</td>
<td>Rostock, Germany</td>
<td>✓</td>
<td></td>
<td>10/50</td>
<td>ATES + HP + solar thermal + boiler</td>
<td>Collective system</td>
</tr>
<tr>
<td>[33]</td>
<td>Oslo, Norway</td>
<td>✓</td>
<td></td>
<td>-</td>
<td>ATES + HP + boiler</td>
<td>Airport</td>
</tr>
<tr>
<td>[34]</td>
<td>Mersin, Turkey</td>
<td>✓</td>
<td></td>
<td>18</td>
<td>ATES + AHU</td>
<td>Commercial building</td>
</tr>
<tr>
<td>[4]</td>
<td>Antwerp, Belgium</td>
<td>✓</td>
<td></td>
<td>8/18</td>
<td>ATES + HP</td>
<td>Hospital</td>
</tr>
</tbody>
</table>
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.
4.3 Methodology

4.3.1 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 3.520 m$^2$ and volume of 9.370 m$^3$. 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 426MWh and heat extraction of 86MWh. The ATES system works in a cyclical mode. The injection temperature was designed at 16$^\circ$C for the warm well and 8$^\circ$C for the cold well. The maximum heating or cooling capacity varies throughout the year depending on the extraction temperature. The injected heat varies depending on the indoor air temperature since the heat is directly exchanged with the indoor air. The extracted heat varies slightly based on the heating capacity of the HP, since the heat is exchanged with the evaporator of the HP. The heat capacity also changes depending on operation. While heat is supplied solely from the HP, the HP assists the ATES system in the cooling supply, which influences the heating and cooling capacities of the ATES. The cooling capacity can be as high as 3 times the heating capacity [4].

Air is distributed to each floor using chilled beam units in the small offices and ventilation vents throughout the open-plan offices. The AHU has two bypass options: recirculation and regeneration. The recirculation option can be used to recirculate air within the building to preserve heat in the structure. Regeneration bypass is used to reject additional heat from the ATES system in the regeneration mode. The heat recovery wheel is inactive in the regeneration mode. The regeneration valve bypasses the connection between the building and air supply in order to reject heat directly using the ambient air. The coil of the AHU can be used for both heating and cooling (Fig. 4.2).
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Figure 4.2: The AHU schema

4.3.2 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 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.

4.3.3 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 Figs. 4.3A, 4.3B, 4.3C (dashed line represents inactive line, normal line represents active lines):
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**Base case:** The building utilizes no regeneration strategy.

**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. (Figs. 4.3B, 4.3C)

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 \((T_{in})\) 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 (Figs. 4.3A, 4.3B).

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. 4.4). In this way, it is possible to create a reliable comparison between HPC and NV.
4.3.4 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 catalogue 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.

4.3.4.1 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 4.2 was applied for the model.

<table>
<thead>
<tr>
<th>Table 4.2: Physical parameters of ATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Conditions</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
</tr>
<tr>
<td>Thermal conductivity of aquifer</td>
</tr>
<tr>
<td>Initial ground temperature cold well</td>
</tr>
</tbody>
</table>
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Mean ambient temperature 10.4 °C
Effective porosity 35 %
Thickness of the aquifer 10 m
Volumetric heat capacity of aquifer 2.45 MJ/(m³K)

4.3.4.2 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 4.3). Two external files (for cooling and heating) were incorporated into the HP model in which the model reads the catalogue data 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.

Table 4.3: Physical parameters of heat pump

<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>m³/hr</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>

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.

\[ W_{\text{pump,ww}} = \left( \frac{Q_b}{C_{\text{water}}(T_{\text{ww}} - 8)} \right) / V_{\text{max}} \cdot W_{\text{max}} \]  (1)
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\[ W_{pump,cw} = \left( \frac{Q_b}{C_{p,water}(16-T_{cw})} \right) / V_{max} \]

Where, \( Q_b \) is the heat transfer to the building, \( C_{p,water} \) 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, \( W_{pump,ww} \) is the supplied power for the warm well pump, and \( W_{pump,cw} \) is the supplied power for the cold well pump.

4.3.5 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 behaviour 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.

### 4.3.6 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. $COP_{HP, reg}$ is calculated to determine the performance of an HP in HPC mode, while $COP_{DC, reg}$ is the performance indicator of an AHU in DC mode.

\[
COP_{DC, reg} = \frac{Q_{sup,a}}{P_{fan} + W_{pump,ww}} \quad (3)
\]

\[
COP_{HPC} = \frac{Q_{sup,a}}{P_{fan} + P_{HP} + W_{pump,ww}} \quad (4)
\]

\[
COP_{direct\_cooling} = \frac{Q_{sup,a}}{P_{fan} + W_{pump,cw}} \quad (5)
\]

\[
COP_{HP\_c} = \frac{Q_{sup,a}}{P_{fan} + P_{HP} + W_{pump,cw}} \quad (6)
\]

\[
COP_{HP\_h} = \frac{Q_{sup,b}}{P_{fan} + P_{HP} + W_{pump,ww}} \quad (7)
\]

\[
COP_{sys} = \frac{Q_{cool} + Q_{heat}}{W_{fans} + W_{pump,cw} + W_{pump,ww} + W_{hp}} \quad (8)
\]

Where, $Q_{sup,a}$ is the extracted heat from the ATES system, $Q_{sup,b}$ is the supplied heat to the building, $P_{fan}$ is the power consumption of the fan of the AHU, $P_{HP}$ is the power consumption of the HP, and $COP_{sys}$ is the system COP.

### 4.4 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].

4.4.1 Temperature
As shown in Fig. 4.5, 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.

Figure 4.5: Temperature variation in the wells (cold well (cw), warm well (ww))

4.4.2 Operation Time
As can be seen in Fig. 4.6, 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.

![Figure 4.6: Operation time for cases](image)

### 4.4.3 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. 4.6), it can be seen that rates of heat transfer to the ground vary (Figs. 4.8, 4.9). 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 extraction rate of DC and base heat extraction totaled 61 and 26 MWh/month, respectively. 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. 4.8), 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. 4.7), which ultimately lowers the heat rejection into the ground (Fig. 4.9) 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.
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Figure 4.7: The effect of NV on the indoor temperature

Figure 4.8: Hourly heat extraction from regeneration modes
Figure 4.9: Monthly heat transfer rates to the ground

4.4.4 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, 2). Therefore it was possible to see similarities in the trends of heat transfer to the ground and the electricity consumption of the pump (Figs. 4.10). In all cases, power consumption is the highest during the cooling mode (Fig. 4.10) 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. 4.5). 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.

![Hourly electricity consumption of the pump for all cases](image)

**Figure 4. 10:** Hourly electricity consumption of the pump for all cases

### 4.4.5 Coefficient of Performance

Coefficient of performance differs depending on the mode of operation. Fig. 4.11 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).
4.4.6 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. 4.12 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.

![Bar chart showing operation hours of HP cooling](image)

**Figure 4.12:** The number of chiller operation hours

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. 4.13). Eventually, \( \text{COP}_{\text{sys}} \) 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 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. 4.12) 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.

![Graph showing electricity consumption for different modes and cases](image)

**Figure 4.13:** Electricity consumption for different modes and cases

### 4.5 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], [45], [46]. In those studies [38], [37], [44], [45], [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
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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], [49], [50] concerning NV, which have shown that cooling load reduction vary between 18-50%. 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 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 regions and with various control strategies.

4.6 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.
The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system

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.

4.7 References


The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system


The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system

[25] “Marseille, T.J. & Wilke, D.A. Review of the aquifer seasonal thermal energy storage building HVAC system at the Melville, New York, Mid-Island Mail Facility, article, August 1, 1992; United States. (digital.library.unt.edu/ark:/67531/metadc1185917/: accessed August 4, 2018),


The Use of Night Ventilation for Achieving a Thermal Balance in an ATES system


Chapter 5

THE EFFECTIVE UTILIZATION OF AN AIR HANDLING UNIT FOR BALANCING AN AQUIFER THERMAL ENERGY STORAGE SYSTEM

ATES’s operation is limited by strict regulations, one of which is the requirement for balance in the amount of heat transfer to the ground. Commonly, an air handling unit (AHU) is utilized to expel heat from the ATES system for cooling dominated loads. This is known as the direct compensation (DC) method. In this chapter, an alternative approach that uses night ventilation (NV) was presented as a promising solution in combination with DC. The optimal operation of an AHU was determined for balancing an ATES.

This chapter was submitted as: Bozkaya, B. & Zeiler, W. (2019), The effective utilization of an air handling unit for balancing an aquifer thermal energy storage system.
The Effective Utilization of an Air Handling Unit for Balancing an ATES system

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_b$</td>
<td>heat transfer to the building (kJ)</td>
</tr>
<tr>
<td>$T_{ww}$</td>
<td>extraction temperature from the warm well ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{cw}$</td>
<td>extraction temperature from the cold ($^\circ$C)</td>
</tr>
<tr>
<td>$W_{max}$</td>
<td>maximum power supply (kJ)</td>
</tr>
<tr>
<td>$W_{pump,ww}$</td>
<td>supplied power for the warm well pump (kJ)</td>
</tr>
<tr>
<td>$W_{pump,cw}$</td>
<td>supplied power for the cold well pump (kJ)</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>maximum flow rate capacity ($m^3/hr$)</td>
</tr>
</tbody>
</table>

5.1 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 meters. Therefore, ATES systems are increasingly applied to buildings with high cooling requirements.

Groundwater is stored in water-containing layers of soil, sand and rock, called aquifers. The heat is stored in the water available in an aquifer is stored in two separated wells, namely a cold well and a warm well. The building can be cooled in summer with the water from the cold well and the returning warm water from the building can be stored in the warm well. This water can then be used to heat the building can be stored in the cold well and used in summer again [2]. Unlike other
types of thermal storage systems, ATES systems are not confined by certain geometrical boundaries and are characterized as having high storage capacity and operating according to a seasonal timeframe. Due to their ability to store high volumes of water, the system is usually installed for large applications such as commercial building on individual [3] [4] or district levels [5], [6]. Since ATES systems are usually applied for buildings with high cooling needs systems are eventually under a cooling dominated load, which results in surplus heat and deficient cold injection into the ground. Thermally unbalanced cold injection into the ground results in dominance of warm well groups and results in thermal interaction with the cold well groups. In order to preserve the efficiency and sustainability of the system, governmental regulations are in place to prevent thermal imbalances between the well groups. 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 [7]. 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], [4], [8], [9], [10]. Cooling towers (CTs) [3], [8], air handling units (AHUs) [4], [9], [10] and heat pumps (HPs) [9], [10] 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 20MWh of energy [8]. 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 also utilized when the
ambient temperature is lower than 2°C. The authors in [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 [10] studied an ATES system that utilizes an AHU when the ambient temperature is below 4°C. Vanhoudt et al. [9] 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], [4], [8], [9], [10], cold compensation methods are popularly applied to compensate for deficient cold in the cold well. The operation temperature for CTs and AHUs ranges between 2-6°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 [11], [12], [13], [14]. 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 [15]. 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% [15].

The use of CTs and AHUs in DC mode and HPs is very common [3], [4], [8], [9], [10], [15]. 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, we first investigated the thermal imbalance ratio of a cooling dominated building. Next, we determined the potential of NV together with DC mode at various operational temperatures. 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.

5.2 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], [4], [8], [9], [10], there have been few studies concerned with ATES system performance connected to building load. Past studies mainly focused on thermal modelling of ATES systems [16], [17], [18], [19], [20] 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.

Optimizing operational settings for charging a thermal energy storage system connected to building load is an approach used in existing studies [21] to achieve high energy performance. This approach has been considered for ATES systems as well. Studies considering this approach [4], [22] have mainly focused on the sensitivity of the system performance to operational settings such as injection temperature [22], injection flow rate [22], 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 4-8°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 [22] adapted various operational settings for ATES systems where the same amount of cooling energy was stored at various injection 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 5.1, AHUs and CTs have been popularly used for BTES and ATES systems for cooling dominant loads. In ATES systems in the Netherlands and Belgium [9], 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 [9]. 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.

Bozkaya et al initiated the thermal imbalance investigation and analyzed the effect under various thermal imbalance rates [41]. The findings showed that thermal imbalance could decrease the system performance up to 13.7% depending on thermal imbalance rate.
The Effective Utilization of an Air Handling Unit for Balancing an ATES system

Table 5.1: ATES and BTES Studies Under the Thermal Balancing Concept

<table>
<thead>
<tr>
<th>Ref.</th>
<th>System</th>
<th>Heating Dominant</th>
<th>Cooling Dominant</th>
<th>Thermal Balancing Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>[23]</td>
<td></td>
<td>✓</td>
<td></td>
<td>Thermosphyon</td>
</tr>
<tr>
<td>[24]</td>
<td></td>
<td>✓</td>
<td></td>
<td>Air source heat exchanger fan</td>
</tr>
<tr>
<td>[25]</td>
<td></td>
<td></td>
<td>✓</td>
<td>AHU</td>
</tr>
<tr>
<td>[26]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[27]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[28]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[29]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Phase change material</td>
</tr>
<tr>
<td>[30]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[31]</td>
<td></td>
<td></td>
<td>✓</td>
<td>AHU</td>
</tr>
<tr>
<td>[32]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Solar thermal</td>
</tr>
<tr>
<td>[33]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Thermal storage bath</td>
</tr>
<tr>
<td>[34]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Borehole free cooling</td>
</tr>
<tr>
<td>[35]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[36]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[37]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Solar thermal</td>
</tr>
<tr>
<td>[38]</td>
<td></td>
<td></td>
<td>✓</td>
<td>Thermosyphon</td>
</tr>
<tr>
<td>[4]</td>
<td></td>
<td></td>
<td>✓</td>
<td>AHU</td>
</tr>
<tr>
<td>[9]</td>
<td></td>
<td></td>
<td>✓</td>
<td>AHU + HP</td>
</tr>
<tr>
<td>[39]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
<tr>
<td>[40]</td>
<td></td>
<td></td>
<td>✓</td>
<td>CT</td>
</tr>
</tbody>
</table>
As an alternative option, NV can be used for balancing purposes by lowering the cooling demand for the cooling dominated load [15], [41]. The effectiveness of NV in decreasing cooling and peak cooling loads has been proven in many studies [11], [12], [13], [14]. Depending on physical and operational parameters, NV can decrease the cooling demand by 18-50% [11], [12], [13], [14]. In addition, NV lowers the average annual indoor temperature between 3-6°C for heavy-weight buildings [42], [43], 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 [9].

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 2-10°C [44] [45] [46] 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. Consequently, the share of NV for cold compensation is needed to be determined in collaboration with DC mode.

5.3 Case Study Building and System Description

This case study analyzed a commercial building with a total area of 3,520 m² located in the Netherlands. According to results from the TRNSYS multi-zone building model (Type 56), the heating and cooling demands are 105MWh and 295MWh, respectively. The building required cooling from March 10 to November 1, which totalled 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 [47], [48]. 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 [9]. The cooling network feed temperature was designed to be between 13-14°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 [9]. 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. 5.1). 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.
5.3.1 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
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energy for heating, see Fig. 5.2. 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 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.

**Figure 5.2:** Schematic Diagram of the Air Flow Network in AHU

5.3.2 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 (∆T)°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 [49]:

- 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 $\Delta T$°C (Table 5.2) between the indoor and outdoor temperatures.

For each different temperature difference ($\Delta T$)°C values between indoor and outdoor temperatures, case scenarios were generated. As the temperature difference increases between indoor and outdoor temperature, which ranges between 2-10°C [44] [45] [46], NV works more energy efficiently. However, at the same time, the number of operation hours decreases as the temperature difference ($\Delta T$)°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.
The Effective Utilization of an Air Handling Unit for Balancing an ATES system

Table 5.2: Description of Cases

<table>
<thead>
<tr>
<th>Cases</th>
<th>Base Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆T</td>
<td>No control</td>
<td>Only DC</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

5.4 Methodology

5.4.1 Simulation Models

5.4.1.1 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 [50], 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 [50], which took place in the Netherlands.

5.4.1.2 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],[51], [52], [53], [54]. Based on existing studies [52], [55] and the validation study [56], 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 catalogue data (Table 5.3), 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) [52], [57] 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, 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.

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

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

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.

**Table 5.3: Physical Parameters of the 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>m³/hr</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>

Weather data for Amsterdam, the Netherlands was used in the simulation.
5.4.1.3 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.

5.5 Results

5.5.1 Operation Time
The operation time of AHU in NV mode is illustrated in Fig. 5.3 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 1,012 h for Case 7 and a minimum of 83 h for Case 2 (Fig. 5.4). It was observed that NV operated more frequently during the hot period (Fig. 5.3), specifically, between June and July, when the internal heat gains increased significantly due to relatively high 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.
5.5.2 Temperature

5.5.2.1 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.

![Graph showing temperature changes](image)

**Figure 5.5:** The Temperature Change of the Warm Well (ww) and Cold Well (cw)

5.5.2.2 *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. 5.6, 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.

**Figure 5.6:** The Temperature Change of Indoor Temperature

**Figure 5.7:** The Average Indoor Temperature for Each Cases
5.5.3 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. 5.8). 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.

![Comparison of heat transfer to the ground for each case](image)

**Figure 5.8:** Heat Transfer to the Ground for Each Case

5.5.4 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. 5.9), 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. 5.6, 5.7). 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. 5.10). 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. 5.4). Eventually, the optimal balance between the NV and DC modes was determined for Case 4. In comparison to Case 1, the system COP was improved by 16%, from 5.6 to 6.5 (Fig. 5.11). For each case, the system benefited from any amount of substitution between NV and DC.

Figure 5. 9: The Amount of HP Operation in Cooling Mode
5.6 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], [9] 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], [22], [58] 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 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, we evaluated an ATES system operating under a 70% thermal imbalance rate. 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 [15], 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
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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% [10], [12], [13], [14], and the average indoor temperature was reduced by 3-6°C [42], [43]. 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.

5.7 Conclusions

We explored the effectiveness of NV operation compared to DC operation. 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.

5.8 References


The Effective Utilization of an Air Handling Unit for Balancing an ATES system


The Effective Utilization of an Air Handling Unit for Balancing an ATES system


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Chapter 6

DISCUSSION AND LIMITATION

Existing studies concerning ATES have been limited to detailed thermal modelling and few focused on the performance analysis of ATES in the HVAC system. Therefore, a new simulation technique was developed to pave the way for reliable, user friendly ATES system analysis, which was later used to analyse thermal imbalance problem. Achieving thermal balance is costly; therefore, it is not possible to ignore accurate performance analysis of the existing and correct sizing for the future applications. This chapter, discusses the results and the previous studies to explore the innovations and limitations within the study.
To improve the performance of the ATES systems under thermal imbalance, several sub questions were answered with the obtained results. In this chapter, those results were discussed and compared with other studies under each sub question.

6.1 Discussion

What is the needed aquifer model for ATES system analysis?

This question was addressed through extensive literature review. The available ATES models were explored and compared with each other. Existing studies [1], [2], [3], [4], [5] showed that an aquifer is a complex media as a number of conditions influences the heat transfer. Assessing an ATES initially needs understanding of hydrology and geology to be able to predict the behaviour of water in that environment. Numerous numerical modelling studies [1], [2], [3], [4], [5] were conducted under various subtopics such as thermal interaction between the well groups [6], preferential pathways [2], natural groundwater flow [3], dispersion [7], [8] and buoyancy [9] to determine the influence of various ground parameters and surroundings on the thermal performance of storage decoupled from the building. Due to the complexity of ground conditions, modelling studies were popularly developed based on FEM and FVM, which are adequate to solve complex physical conditions. Thermal modelling is sufficient for accurately predicting the temperature output of storage systems for the given ground conditions. However, it is not possible to consider the storage system disconnected from the building load. Considering the dynamics on both ground and building side, it is necessary to develop a model that can handle both. There were few studies [10], [11], [12] that have focused on ATES system connected to the building load, in those studies, the ATES model was based on the finite difference method and was not validated with real measurements. In the developed ATES models, the authors used fixed boundary conditions to make parametric and sensitivity analysis in order to assess the efficiency of storage itself. However, in reality ATES is exposed to time-varying boundary conditions such as flow rate and injection temperature as a function of the building load. On the other
hand, the model should have the potential to be used in a complex environment. By developing a model based on the finite element method and validation study, the new model proved to be both reliable and capable of handling time-dynamic boundary conditions.

**How to analyse ATES connected to the building and HVAC system?**

Due to the limited number of simulation studies and the simulation tools for ATES system, a co-simulation platform was developed to investigate the system as a whole. The co-simulation method was based on three different software; TRNSYS for HVAC simulation which was popularly used for ATES systems [12], [10], MATLAB for information exchange and COMSOL for ATES model [1]. This method allowed the integration of a Finite Element Modelling model into the simulation environment where the information was exchanged between ATES and the building in a time dynamic manner. The advantage of this method over the past ATES simulation studies is the adaptability of the ATES model into various ground conditions, which is difficult to apply with the studied TRANSAT [10],[12] model that is based on Finite Difference Modelling (FDM). Besides, the integrated ATES model was validated to maintain the reliability [13]. In addition, TRNSYS was applied which is commonly used for energy analysis and containing already validated HVAC models. All in all, the developed co-simulation platform assisted user with the enhanced reliability on the performance analysis.

**What is the influence of thermal imbalance on the performance?**

The developed co-simulation platform was used to investigate the influence of thermally unbalanced building load on system performance. It was observed that previous studies mainly focused on the analysis of experimental data and sensitivity [14], [15] analysis for various operational settings [11], [10]. However, seasonal thermal storages that have an inter-seasonal operation are influenced by the yearly balance in the amount of heat transfer between heating period and cooling period. Due to widespread use and operational differences, BTES systems have been
Discussion and Limitation

intensively studied under the thermal imbalance concept. Those studies indicated that thermal imbalance is an important factor that undermines the performance of the system by changing the source temperature. It was shown that the system experiences significant change (±10°C) in the source temperature for a thermal imbalance ratio of ±80%. Since the heat is transferred to the same field in BTES system, the source temperature changed gradually year by year. However, the thermal imbalance for ATES system showed that the change in the average ground temperature was 2.5°C for the imbalance ratio of 80%. Similarly, based on the experimental analysis of Kranz et. al [10], the system could not reach the designed temperature level due to the thermal imbalance. Vanhoudt et. al [14] determined significant difference in the cooling performance due to high cooling domination in the load. Unlike BTES system, the average temperature of cold and warm well of ATES are not influenced by the yearly change due to the separation of the sources. In addition, system performance is likely to be affected more from the cooling dominated load than a heating dominated load for low temperature ATES. Because, the cooling Coefficient Of Performance can be as high as 17.2 [11], 16 [10] and 12.3 [16]. It was also found to be quite sensitive to temperature change of the cold well. A temperature change of 2.5 °C resulted in 13.7% decrease in system performance.

**How to achieve thermal balance in an energy efficient way?**

Most studies [11], [10],[14],[15] mentioned ATES as a very efficient energy storage system neglecting the influence of dynamic thermal building load. In those studies, sensitivity analysis were conducted to determine the influence of operational settings such as the injection temperature to warm and cold well [11], [10] inlet temperature to the cooling and heating network in the building [10] and so on. No study evaluated thermal imbalance problem. However, taking into account the past BTES studies in this thermal imbalance concept, it was possible to observe that there were many methods developed for heat/cold compensation to achieve thermal balance. In those methods, there was a frequently used technique in which the cooling/heating load was dispatched between the units; thereby reaching thermal balance. In reality, it is
Discussion and Limitation

mostly inevitable to have an unbalanced building load. Thermal balance within the system was maintained by the heat compensation methods, which incurred additional operational cost as mentioned in [17]. It was determined that thermally unbalanced load is less efficient than the balanced load [16]. The efficiency was further deteriorated when the thermal balance was reached using compensation methods [18]. Taking into account thermal imbalance including the cost of compensation method, the system performance could decrease considerably in comparison to the balanced case [16], [18]. Traditionally, an air handling unit was only used in Direct Compensation (DC) mode and a heat pump as a supplementary component. It was possible to reduce the cost of compensation methods for cooling dominated load significantly using night ventilation as substitute for heat pump. Present study showed that night ventilation was a promising technique to decrease the cooling demand from ATES. However, it should be noted that night ventilation was quite sensitive to the ambient conditions and the physical properties of the building, which might differ significantly from case to case.

6.2 Limitation

Several limitations were identified in the present study. The main limitation in this study in comparison to other ATES studies was the simulation time as the developed co-simulation takes longer due to a number of reasons.

There are operational settings that are specifically set for the system. The designed injection temperature setting for this study was 16°C for a warm well and 8°C for cold well. However, in reality, the temperature setting varies in the range of 16-25 and 4-8 for warm and cold well, respectively, depending on the climate and ground conditions. Therefore, the system performance may also change depending on the operational setting.

The influence of thermal imbalance can be intensified by the thermal interaction between the sources. As discussed earlier, the performance of BTES system is severely influenced for that reason. In the present study, the thermal interaction of
ATES system is neglected due to the fact that the existing applications are designed with enough spacing. However, it can be a concern in places where ATES systems are densely installed under high thermal imbalance ratio.

The effectiveness of night ventilation (NV) was proven in some studies. Night ventilation was effective in decreasing the cooling demand from ATES [19],[20],[21]. However, the performance of NV varies depending on the building specification and weather conditions. For this specific case, NV decreased the cooling demand by 20%. However, in reality the cooling demand can be reduced by up to 50% [10], [22], [23], [24]. Therefore, the study should be repeated for different buildings in different climate regions. Some parametric analysis can be useful to determine the boundaries of this technique.

As described in this study, thermal imbalance and its compensation highly depends on the ambient conditions which change from season to season, leading to different imbalance ratio every year. Besides, the performance of the compensation methods also depends on the ambient condition. Therefore, it is imperative to develop a control system that can adapt into this dynamic ambient conditions and respond it in an optimal way. In the current study, the system was controlled using fixed set-point since the ambient condition was considered the same for each year.

6.3 References


Discussion and Limitation


Chapter 7

CONCLUSION AND FUTURE WORK

Throughout the thesis, ATES thermal modelling, a co-simulation method for an integrated ATES system, HVAC system and building simulation, the influence of thermal imbalance and the control of thermal imbalance were explored. Thermal imbalance is a problem for seasonal thermal energy storage systems such as ATES, since unbalanced building load is almost inevitable. It is necessary to wisely control the system components to achieve desired energy efficiency within the system. For this study, night ventilation was used as an alternative method using an air handling unit. Night ventilation found to be promising method; however, the number of studies should be increased for various climate regions, various system components and various smart control strategies. In this chapter, the thesis was concluded and the important findings were listed. In addition, some recommendations were explored as future work.
7.1 Conclusion

It is proven that ATES systems are energy efficient heating/cooling suppliers, which makes them increasingly popular. The use of ATES is expected to increase rapidly in the near future; therefore, it is important to optimally integrate its operation to the building in order to sustainably and energy efficiently utilize the system. There are several challenges associated with the ATES system, one of which is thermally unbalanced building thermal load. Considering the dense installation, reaching thermal balance is crucial to avoid future thermal interaction between the well groups. In this dissertation, it was aimed to find solutions to energy efficiently achieve thermal balance within the whole system: ATES, HVAC and building. Several conclusions can be drawn from the project.

- In the first step, a 2D axisymmetric thermal model was developed using COMSOL based on the finite element method. It was shown that the model could simulate the dynamic thermal load imposed by the building, which was transferred via MATLAB to COMSOL. The model was tested with an experimental data from an operational ATES in Amsterdam, the Netherlands. The output of the model closely matched with the real measurements. That also confirmed that COMSOL in connection to MATLAB can be used to simulate ATES under the dynamic building load.

- Aquifer thermal energy storage system is a complex system which is influenced by ground conditions and the building load. The performance of the system highly depends on the dynamic building load. Therefore, a co-simulation method was adapted to simulate ATES connected to the HVAC system and the building load. The co-simulation method was tested to determine the influence of thermal imbalance on the energy performance. TRNSYS where the building and its HVAC system simulated could communicate COMSOL via MATLAB. It was explored that a thermally balanced ATES system maintain higher thermal quality in the wells, which results in improved energy efficiency. Numerically, the results indicated
that a thermally balanced load assisted the system to save up to 13.7% of annual energy consumption.

- Thermally unbalanced building load is inevitable hence it is necessary to find an energy efficient solution to reach a thermal balance within the system. Using co-simulation method, an ATES system connected to an air handling unit and a heat pump was analysed. Traditionally, an air handling unit and a heat pump are used to inject the deficient cold for cooling dominated loads. As an alternative solution, air handling was also utilized in a night ventilation method. It was determined that night ventilation was a prominent technique to substitute for costly heat pump operation. It was possible to energy efficiently eliminate the number of heat pump operation hours. Consequently, the overall system COP was improved by 26%.

- In chapter 4, it was proven that an air handling unit could provide energy efficient solution for cold compensation using two modes of operation; one of which is the direct compensation and the other one is night ventilation. In chapter 5, optimal operation of an air handling unit was determined by modulating the set point temperature for both night ventilation and direct compensation mode. It was intended to determine the optimal combination between these modes. It was explored that participation of night ventilation in substitute for direct compensation mode could save some energy. The optimal operational parameters for air handling unit was determined. Numerical results indicated an energy saving of 16% in optimal combination of Direct Compensation and night ventilation.

This thesis determined a new approach that paved the way for analysing ATES dynamic operation coupled to the building and its HVAC system. Secondly, the importance of a thermally unbalanced load was shown as a parameter that needs to be taken into account for existing and the future applications.
Conclusion and Future work

7.2 Future Works

Considering the limited amount of studies focused on the performance analysis of ATES system, there are a lot of works needed to be investigated for future and existing applications.

- It is possible to investigate a wide range of ATES applications based on various temperature levels. Thermal imbalance concept can be applied to high temperature ATES system where the temperature for warm well can increase up to more than 50°C. Depending on the temperature level, the system operation also changes in comparison to the present system. High temperature ATES systems under thermal imbalance can be a research direction to be explored.

- Frequently, ATES systems are equipped with various supplementary units such as cooling tower, solar thermal, short term storage etc. Thermal balancing strategies can be replicated with various supplementary units, which are popularly studied for other ground source applications.

- As the new smart control methods emerge, it is possible to control ATES system in an adaptive and intelligent way under thermal imbalance concept. Since the operation of ATES highly depends on the amount of heat transfer with the building, the control system should adapt to the varying climate conditions. Recently developed smart control methods such as model predictive control are in place to use in such storage systems, especially in the smart grid concept. The weather conditions can be predicted and the operation of ATES can be planned in advance in the seasonal scale.

- As a result of global warming, it is expected that cooling domination in building loads increases. In addition, it will limit the operation of AHU in DC and NV mode. Eventually, global warming is expected to undermine the operation of ATES by contributing the thermal imbalance and limiting the operation of heat compensation. An ATES system can be projected based on the predicted weather data to determine the possible scenarios.
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