Optimization of energy acquisition and environmental implication in Aquifer thermal energy storage

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Abstract. Aquifer thermal energy storage (ATES) plays an important role in energy supply, which is renewable energy storage. Based on the data related to geological information of aquifer in Amsterdam, this paper proposes a characteristic analysis of the ATES. Results indicate that the ATES will produce less carbon dioxide than traditional heating and cooling systems, and it will reduce more system cost. Meanwhile, different architectural design will affect the efficiency of ATES and environment problem and so on. Generally, a more comprehensive design of ATES is necessary, which provided more valuable ideas for the process design of the ATES. Then the best condition of the distance design in the ATES can be chosen.

1. Introduction
Energy and environmental problems, have caused serious ecological environment problems and have become the focus of government and public attention. In terms of these problems, energy conservation and new energy development have become the development themes, it is significantly important to find new energy saving and environmental protection energy instead of traditional energy. New and renewable sources of energy, especially geothermal resources, do not produce pollution to the environment, which has become an urgent need in recent years to supplement energy and gradually become an alternative energy source for the future. The earth itself is a huge reservoir of natural heat, which is the heat inside the earth. Geothermal energy is a clean, renewable energy source that has been widely used in many countries or regions. Currently, there are 21 countries in the world use geothermal energy to generate electricity, and 58 countries or regions make direct use of geothermal resources. Using the earth's internal heat is the use of aquifer thermal energy storage system [1]. The ATES uses the special structure of underground rock stratum in underground aquifers as heat or cool storage medium, to hoard the cold in winter for summer cooling, and the heat in summer for winter heating. The usual seasonal ATES is a way to recycle cold water or hot water into a reservoir. This method can not only effectively alleviate the shortage of energy utilization during peak energy utilization, but also improve energy efficiency, prevent thermal pollution and prevent land subsidence. This kind of utilization of seasonal temperature difference and underground aquifer energy storage can regulate the energy of nature itself and achieve the purpose of serving human beings, and the ATES can make less GHG than the conventional system, which produce heat for burning fuels, so that it has also a profound
impact on environmental protection [2]. How to make to ATES run more efficiently for satisfying both the users and the builders is a very important thing. Therefore, it is desired to develop optimal strategies for sustainable development of the ATES. Previously, a number of experiments and calculations have been conducted to analysis and optimize the ATES [3, 4].

1. This study discusses the influence of the distance with wells in building to ATES, calculate deterministic operation parameters of the system. The optimal design scheme is obtained through calculation and analysis, which provides more valuable ideas for the process design of ATES. Then choose the best condition of the distance design in ATES.

2. Study area and method

2.1. Study area and heating (cooling) load
The proposed method is applied into a real-world case study in Netherland. Netherland is the country which uses the most ATES in the world. the number of the ATES has increase rapidly over the past 30 years (from 0 in 1990 to about 3000 in 2017), because its quality of aquifers is good for keeping temperature of water well, and the aquifer depth can attend 200m, which is worth of building the ATES. In general, seasonal ATES systems are in heating mode in the winter and in cooling mode in the summer. However, due to variability in energy demand, a specific system may switch on and off several times per day and vary the pumping rate. Furthermore, in spring and autumn, systems may switch between heating and cooling mode. Heating and cooling loads in our simulations are simplified to four months heating period in winter and four months cooling period in summer, similar to the seasonal variation observed in an existing ATES system in the Netherlands. Flow rate and injection temperature are constant during each period and chosen to represent a typical system as applied in the utility sector. The robustness of this approximation was tested by running our model also using shorter and longer reduction periods, while preserving the total seasonal flow rate. The maximum pumping rate is determined from guidelines on maximum velocity on the borehole wall and the length of the well screen and set to 200 m³/h. For a system that has an average use of 1500 full load hours/season, with an injection temperature of 7°C and an extraction temperature of 17°C. The natural aquifer temperature is 10°C. The model was run for 30 years, which is the expected lifetime of the ATES.

2.2. Method

2.2.1. Efficiency analysis. Use this study uses simplify model of the ATES to choose appropriate distance between the wells (neglecting the influence of geological condition, like the condition of the aquifer, groundwater flow velocity and thermal diffusion) to meet the need of both builders and users. The distance of the well is determined by the thermal radius, which is defined as the maximum distance of the thermal front from the injection well in a homogeneous medium, neglecting vertical flow, advection by regional flow, thermal conduction and dispersion. The thermal radius can be calculated by setting the injected energy \( (C_w \cdot V \cdot \Delta T) \) equal to the energy stored in a cylinder, centered around the injecting well \( (C_a \cdot H \cdot \pi \cdot R_{th}) \), resulting in Eqs. (1):

\[
R_{th} = \frac{\sqrt{C_w V \Delta T}}{C_a \pi H} \tag{1}
\]

Where, \( C_a \) denotes the volumetric heat capacity of the aquifer (MJ); \( C_w \) denotes the volumetric heat capacity of the water. \( V \) denotes the storage capacity of aquifer water, \( H \) denotes the depth of the aquifer. \( \Delta T \) is temperature which can be extracted without loss. Many parameters for operation are calculated as follow:

From the modelled extraction temperature, the extracted energy for the operation time is determined as follow:
\[ E_x = C_u \cdot V \cdot \theta_i \cdot \Delta T \quad , \quad (V = q_{\text{max}} \cdot u_{\text{eq}} \cdot H) \] (2)

Where, \( q_{\text{max}} \) is the maximum flow rate per meter well screen and \( u_{\text{eq}} \) is the full load hours per season, when the distance is designed, the temperature loss can be calculated. According to the data of temperature change in one operating range with the different distance between the injection and the extraction wells, this study fits out a formula with the relationship between distance and temperature distance with the Eqs. (3).

\[ T_{\text{loss}} = 13.47925e^{-(-R/72.25353)} - 3.26801 \] (3)

Where, \( R \) denotes the distance between the well.

Because of the thermal interference, the wells with different temperature (cooling and heating) can decrease the quantity of the cold (or heat), while the wells with same temperature can keep the temperature well. The total temperature loss can be expressed by following

\[ T_{\text{loss}} = \lambda_2 \cdot (13.47925e^{-(-R_2/72.2535)} - 3.26801) - \lambda_1(13.47925e^{-(-R_1/72.2535)} - 3.26801) \] (4)

Where, \( \lambda_1 \) and \( \lambda_2 \) denotes the influence coefficient, which represent the impacts on temperature of the ATES under different \( R_1 \) and \( R_2 \) values. Then the thermal efficiency can be expressed by

\[ \theta_i = \frac{\Delta T - T_{\text{loss}}}{\Delta T} \] (5)

Where, \( \Delta T \) denotes temperature which can be extracted without loss.

Then the volume and the estimate volume can also be gotten by calculation.

**Economic and environment performance.** Two important reasons for applying the ATES: one is to reduce the cost for cooling and heating, the other is to reduce the \( \text{CO}_2 \) emission. The ATES system is operated to supply the heat by the heat pump and can directly provide the cooling, while the conventional system consists of the boiler system (efficiency 85\%) and the electrical compression cooling (coefficient of performance (COP) is 3.5). The economic and environment performance are shown by following calculations.

Total electricity uses by the ATES consist of the use of pumping of the groundwater, the use of driving heat pump. The total electricity uses of the ATES are calculated with following:

\[ E_{\text{elec,ATES}} = 2 \cdot q \cdot u_{\text{eq}} \cdot H \cdot E_p + E_s/(\text{COP}_H) \] (6)

Where, \( q \) denotes the pump rate (m\(^3\)/m/h), \( E_p \) is the electrical energy needed to pump 1 m\(^3\) of groundwater (kwh/m\(^3\)), \( \text{COP}_H \) denotes COP for heat.

In addition, the \( \text{CO}_2 \) emission is calculated based on the electricity use and the gas use. The \( \text{CO}_2 \) emission of the ATES and the conventional system are expressed with following.

\[ C_{\text{ATES}} = E_{\text{elec,ATES}} \cdot C_{\text{elec}} \] (7)

Where \( C_{\text{ATES}} \) denotes \( \text{CO}_2 \) emission of the ATES, \( C_{\text{elec}} \) denotes the emission factor gas

\[ E_{\text{elec,ATES}} = 2 \cdot q \cdot u_{\text{eq}} \cdot H \cdot E_p + E_s/(\text{COP}_H) \] (8)

Where, \( q \) denotes the pump rate (m\(^3\)/m/h), \( E_p \) is the electrical energy needed to pump 1 m\(^3\) of groundwater (kwh/m\(^3\)), \( \text{COP}_H \) denotes COP for heat.
In addition, the CO₂ emission is calculated based on the electricity use and the gas use. The CO₂ emission of the ATES and the conventional system are expressed with following.

\[ C_{ATES} = E_{elec,ATES} \cdot C_{elec} \]  

(9)

Where \( C_{ATES} \) denotes CO₂ emission of the ATES, \( C_{elec} \) denotes the emission factor gas.

3. Results of Comparison between the ATES and the conventional system

As a new energy storage, the ATES has a better advantage over the conventional system. In terms of the thermal performance, the total cost and CO₂ emissions of the system are calculated like the ATES. The ATES and the conventional system can be compared in the CO₂ emission and the total cost of use with the same energy production. A random set of distance can be set, which includes some representative combinations (the highest efficiency condition 11 (0.3, 1.5) \( R_{th} \), the lowest area of structure condition 1 (0.3, 0.3) \( R_{th} \), the highest energy extraction condition 10 (1.5,1.5) \( R_{th} \)), then calculate CO₂ emissions and the cost shown in Figure 1. The condition 10 gets the most CO₂ emissions being \( 10.19 \times 10^6 \) kg/year, the condition 1 can only have \( 0.39 \times 10^6 \) kg/year. (Here condition \( x (r_1, r_2) \) denotes the condition \( x \) in figure, \( r_1 \) denotes distance between the same wall, \( r_2 \) denotes distance of the different walls).

In terms of the total cost. Figure 2. Shows the cost between the ATES and the convention system. The cost of the ATES is \( 1.025 \times 10^8 \) €/year while the conventional system is \( 1.43 \times 10^9 \) €/year at most. In conclusion, the conventional system will cost more than the ATES with applying the same energy to use (cooling and heating).

![Figure 1. The CO₂ emissions of the ATES and the conventional system](image1)

![Figure 2. The cost of the ATES and the conventional system](image2)
4. Conclusion
In this paper, carbon dioxide and investment cost are calculated according to parameters of aquifer in Amsterdam. Generally, the main conclusions of comparison between the ATES and the conventional system are summarized as follows:

1. The ATES will produce less carbon dioxide than traditional heating and cooling systems. The ATES can only produce the CO₂ from electricity use. It can be concluded that the area of land determines CO₂ emission. However, the conventional system applies heat by fuel combustion and cold by air condition refrigeration. It produces large amount of CO₂ emissions by burning and by consumption of electric energy in air condition. When θv>80%, the CO₂ emissions reduction can be 2.68×10⁶ kg/year at least by using the ATES. It shows that the ATES will play a more important role on reducing the greenhouse gas emission and in environmental protection than the conventional system. The average reduction of CO₂ emissions is 22.8%.

2. The ATES can cost less than the conventional one. The result shows that no matter how much energy the system gets, the conventional cost may be approximately 14.1 times as much as the ATES cost. The cost of consumption has been reduced by about 10 times.

3. Getting more energy produces more CO₂, because more energy can cause more electricity to use, which produces more CO₂. There is a trade-off between energy acquisition and environmental protection. If the energy extraction is the only demand for building the ATES, the condition 15 is a best choice, which can produce the most amount of energy. If both the energy performance and the environment protection should be considered. The condition 11 is a suitable choice, which produces enough energy and make less CO₂ emissions.

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