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ATES systems performance in practice: analysis of operational data from ATES systems in the province of Utrecht, The Netherlands

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ABSTRACT

Energy consumption for space heating and cooling of buildings can be decreased by 40-80% by use of Aquifer Thermal Energy Storage (ATES). ATES is a proven technique, however, it is not known how efficient currently operating systems are recovering stored energy from the subsurface and how this can be determined with available data. Recent research suggests that storage conditions have a large influence on the recovery (e.g. shape and size of stored volume). In addition, literature and previous research show that other aspects of ATES system are often unfavorable (e.g. subsurface energy imbalance, small ΔT). Therefore, the main goal of this research is to define a framework to determine overall performance of ATES systems by analysis of monitoring data from operational ATES systems. The province of Utrecht was selected for this. Monthly operational data of 57 ATES systems (40% of the ATES systems in the province) was provided by the authorities and pre-processed accordingly. Results showed that recovery efficiency is positively correlated to system size (stored volume) and that ambient groundwater temperature is site-specific and should be determined for each ATES system individually. Ambient groundwater temperature can vary more than 4 °C and are spatially correlated. Next to this, a large part of the analyzed systems are not equally storing heat and cold in the subsurface. More than 80% of the studied ATES systems have an subsurface heat imbalance larger than 10%. Altogether, results indicate that a big part of the ATES systems in the province of Utrecht can substantially improve their ATES system (management) to increase long-term energy savings. This research provides an useful assessment framework to determine if an ATES system is performing correctly and what aspect of the specific ATES system needs most improvement.

1. INTRODUCTION

More than 10 % of total worldwide energy consumption is used for space heating and cooling of buildings (Ürge-Vorsatz et al., 2015). Energy consumption for conventional heating and cooling of buildings can be decreased by 40-80% by use of Aquifer Thermal Energy Storage (ATES) (Fig. 1). ATES use groundwater to store energy in temperature ranges of ca. 7-18 degrees Celsius. Excess heat collected in summer is stored in aquifers and used in periods of heating demand (winter) to heat the building(s). This subsequently generates cold water which is stored in the subsurface to be used to cool buildings during warm periods (Dickinson et al., 2009). Currently there are about 3000 operational ATES systems in The Netherlands (Fleuchaus et al., 2018). Although ATES is a proven technique, uncertainties exist on their performance. It is not known how efficient these systems are recovering stored energy from the subsurface and if this can be determined with the standard data that is being collected. Recent research suggests that storage conditions are of large influence on the recovery of stored energy from the subsurface (e.g. shape and size of stored volume) (Bloemendal & Hartog, 2018). In addition to the recovery efficiency (η_{th}), other factors (e.g. subsurface energy imbalance, small ΔT) can be used to evaluate ATES system operation. Together, these factors could determine whether ATES systems are operating properly.

The main objectives of this research were therefore to define a framework to determine overall performance of ATES systems and to use this framework to analyze data of operational ATES systems. This can subsequently contribute to better designs of new ATES systems and provide an usable framework to have better insight in ATES system performance.

- Identify a framework to determine overall performance of ATES systems

- Analyze monitoring data of operational ATES systems to determine the overall performance of ATES system
- Find key factors impacting the overall performance of ATES systems (e.g. storage conditions)

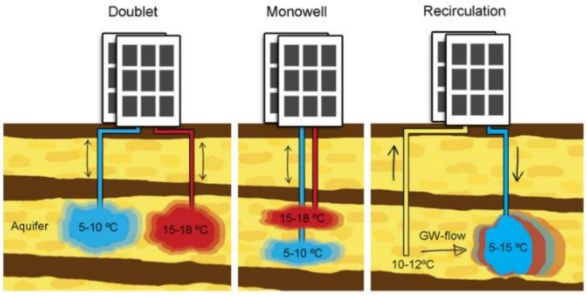

Figure 1 Basic working principle of a doublet system, mono-well system and a recirculation system. From: (Bloemendal & Olsthoorn, 2018)

2. METHODS

For this research, data was used provided by the province of Utrecht. The data consists of year reports, which are provided annually to the provinces by ATES permit holders, which is a mandatory task. This chapter describes the characteristics of the data, how they were processed and which methods were used to analyze the operational data.

2.1 characteristics and Pre-processing

Available data was checked on quality and completeness according to:

- extraction volumes
- extracted cold and warm energy
- minimum 4 years of data

2.2 Assessment framework

ATES systems can be characterized using different methods (Bloemendal & Hartog, 2018; Sommer et al., 2013). This framework could improve operational performance of ATES systems and allow for fair comparison between different ATES systems. The ΔT and the r_{SHB} are already used as parameters for the controlling authority (provinces) to check if ATES systems are operating as designed and permitted. Next to this, the recovery efficiency is added to this framework, to also get insight in the subsurface energy losses. This results in the following assessment parameters.

- High recovery efficiency = high performance
- SHB close to zero = balance in used energy = high performance
- Large ΔT = high performance

Based on the used data and previous studies the following classification table is determined (Table 1). The Overall Performance (OP) of each ATES system is subsequently calculated as the average of the [ΔT] score, the mean (cold & warm) efficiency [ηth] score and the mean (cold & warm) [r_{SHB}] score.

$$OP = \frac{(\Delta T_{score} + \eta th_{score} + rSHB_{score})}{3} \quad [1]$$

Table 1 classification table of Overall Performance (OP)

Score	η_{th} (%)	r_{SHB} (-)	ΔT (°C)
High (3)	> 66	0-0.2	>5
Medium (2)	33-66	0.2-0.4	2.5-5
Low (1)	0-33	> 0.4	0-2.5

2.3. Assessment parameters

2.3.1 Recovery efficiency

The recovery efficiency is calculated to determine the long-term effectiveness of energy storage and subsequent recovery for both cold and warm wells. This method is mainly based on Sommer et al. (2013) & Bloemendal and Hartog (2018). The energy stored in an ATES well (warm or cold) is defined by the volume of the injected water and the temperature of the water compared to the site specific ambient groundwater temperature. For this research energy storage is calculated on a monthly basis, but depending on the data this can also be done more frequently. By summing the stored amounts of energy for the entire length of the dataset it is determined how much energy is stored and how much of this energy is extracted after storage. The recovery efficiency is calculated as the fraction of total extracted energy divided by the total injected energy. This is done for both the cold and warm well, resulting in a recovery efficiency per well. Density of water is dependent on temperature, and therefore density (and thereby the amount of energy per volume water) changes. However, for low temperature ATES, density has no significant influence (van Lopik et al., 2016). The recovery efficiency is therefore determined as:

$$\eta_{th} = \frac{sum(E_{out})}{sum(E_{in})} = \frac{sum(\, abs(T_{amb} - T_{ext}) * V_{ext})}{sum(\, abs(T_{amb} - T_{inj}) * V_{inj})} \quad [2]$$

T_{amb} is the ambient (background) groundwater temperature, which is site specific.

2.3.2 Building energy exchange

The energy that is extracted by an ATES system and used for cooling/heating of the building is also calculated with the same operational data. Both heating (warm water is extracted from the warm well, energy is extracted by the system by a heat exchanger and the same volume of water is subsequently injected into the cold well) and cooling (cold water is extracted from the cold well, energy is extracted by the system and the same volume of water is subsequently injected into the warm well) depends on the demand of the building which is dependent on the outside climate. Three parameter are used to perceive the building energy exchange, mainly based on Sommer et al. (2013).

ΔT

This variable is the average temperature change that is achieved by exchange of energy between the ATES and building system through the heat exchanger. The ΔT represents the amount of energy that is exchanged on average per volume extracted water. The ΔT can therefore be calculated for both cooling and heating.

$$\Delta T = \frac{E_{extracted(total)}}{V_{extracted(total)} * c} \quad [3]$$

With c being the volumetric heat capacity of water (0.0011625 Mwh/(kg*K)).

Subsurface Heating Volume Balance ratio

The Subsurface Heating Volume Balance ratio (r_{SHVB}) is a parameter that indicates the cumulative volume ratio of stored cold and warm water due to ATES operation (eq. 4). Positive SHVB indicates more storage of 'warm' water compared to 'cold' water. This determines that the ATES system used more volume for cooling compared to heating.

$$r_{SHVB} = \frac{V_{extracted(cooling)} - V_{extracted(heating)}}{V_{extracted(cooling)} + V_{extracted(heating)}} \quad [4]$$

Subsurface Heat Balance ratio

The Subsurface Heat Balance ratio (r_{SHB}) is similar to the SHVB, but instead of keeping track of stored volumes, the SHB determines the ratio between stored 'cold' and 'warm' energy. Positive SHB indicates heating of the subsurface (more energy extracted for cooling compared to heating).

$$SHB = \frac{E_{extracted(cooling)} - E_{extracted(heating)}}{E_{extracted(cooling)} + E_{extracted(heating)}} \quad [5]$$

The ΔT and the SHB are used as important parameters for the controlling authority (provinces) to check if ATES systems are operating as designed and permitted. ATES users should aim for high ΔT (more energy/m^3, a.k.a. productivity), because the more energy stored per m^3 the less subsurface space is used. They are also obligated to assure an energy balance (SHB). Both parameters are used to ensure no stored energy is wasted and that the subsurface is used to its full potential, thus making it possible for other stakeholders to also use ATES for their buildings.

2.4 Ambient groundwater temperature

Shallow groundwater temperatures (approximately upper 5m of subsurface) are influenced by daily temperature fluctuations. When going deeper, looking at depths that are being used for ATES systems (-50m to -250m), these fluctuations dampen out and the groundwater temperature reflects the yearly average surface temperature, which for the Netherlands is around 10-12 °C. Because recovery efficiency is dependent on the ambient groundwater temperature (T_{amb}), and data showed that the ambient groundwater temperature for different systems varied, a method was conceived to calculate ambient groundwater temperature for each individual ATES system.

$$T_{amb} = \frac{\overline{T_{extraction(cold)}} + \overline{T_{extraction(warm)}}}{2} \quad [6]$$

The mean temperature between the average extracted warm and cold wells (eq. 2) gave the best results, which was mainly based on a visual check of all available data (Fig. 2).

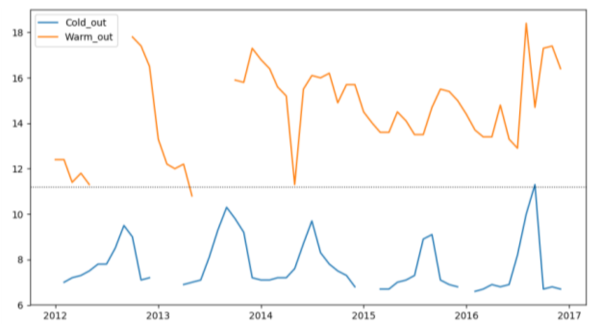

Figure 2 Calculation of ambient groundwater temperature using ATES operational data.

3. RESULTS AND DISCUSSION

3.1 Description of ATES systems

Most of the analyzed systems are found in or close to the larger cities Utrecht, Amersfoort, Nieuwegein and Veenendaal (Fig. 6). Pre-processing resulted in a subset of 57 ATES systems, which is about 35% of all ATES systems in Utrecht. The subset consists of 19 mono-wells, 35 doublet systems and 3 recirculation systems (Fig. 3), which is about the same distribution of system types compared to all ATES found in the province of Utrecht. About 15% of initially considered ATES systems was not in operation long enough to be used for this analysis. The other 50% of the systems was not used because good quality data was unavailable.

The monitored yearly pumped volume is lower than permitted for most ATES systems . Some systems reach the maximum permitted volume in certain years, but overall significantly lower amounts are being pumped (Fig. 4). The monitored volumes are calculated as the average yearly extracted volume during the entire period. This means individual years can have higher or lower pumping volumes Averaged over the entire dataset (4-7 years) of each system only 55.4% of the total permitted volume is being used. Three systems exceed the yearly maximum permitted volume on average for more than four years.

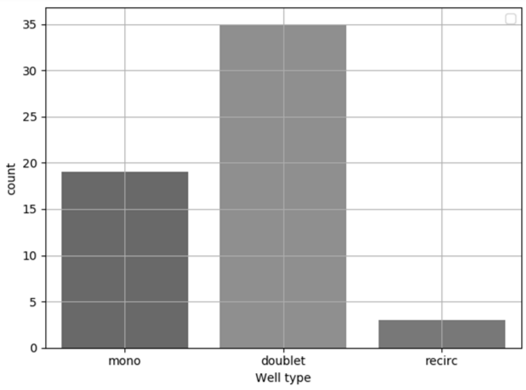

Figure 3 ATES type distribution of final dataset (Total 57 systems)

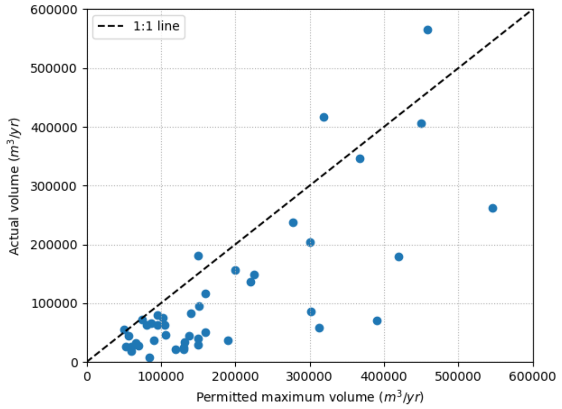

Figure 4 The permitted maximum volume versus the average actual extracted volume. Dotted line: 1:1 line.

3.2 Ambient groundwater temperature

The ambient groundwater temperature found In the province of Utrecht is on average ± 12 °C, varying from 10.5 to 15.9 (Fig. 5). Most systems (>80%) have ambient Temperatures between 11 and 13 °C. The two systems that are found with a very high ambient temperature (> 15 °C) are found close to the surface. This could possibly be because of the interaction with shallow heat sources near built-up area (e.g. influence of other ATES/BTES systems).

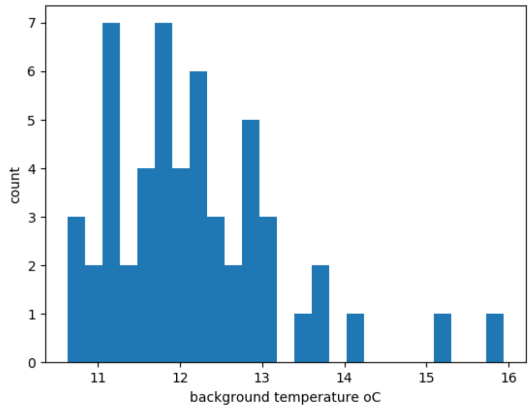

Figure 5 The ambient groundwater temperature (background temperature) found for all ATES sites.

To look at spatial differences in background temperature different subsets were made based on location (Figure 6). An extra subset of the north-west group was made to look more detailed at the crowded city center of Utrecht (1*). Distribution of ambient groundwater temperatures in each region shows that not only site specific differences are of influence, but also spatial differences can be observed (Fig 7). The background temperature determined of the subsurface of the city center of Utrecht is clearly higher than the other regions. This might show the influence of the urban heat island on the groundwater temperature (Ferguson & Woodbury, 2007). Recent groundwater measurements in the shallow subsurface of Utrecht city center support these results., temperatures up to 14.5 °C were observed (Deltares, 2017).

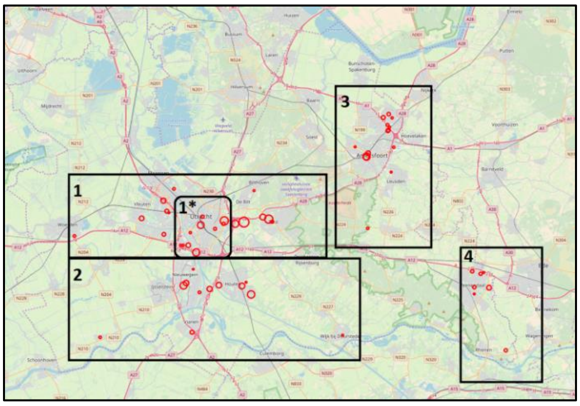

Figure 6 Overview of the ATES systems used for this research in the province of Utrecht.

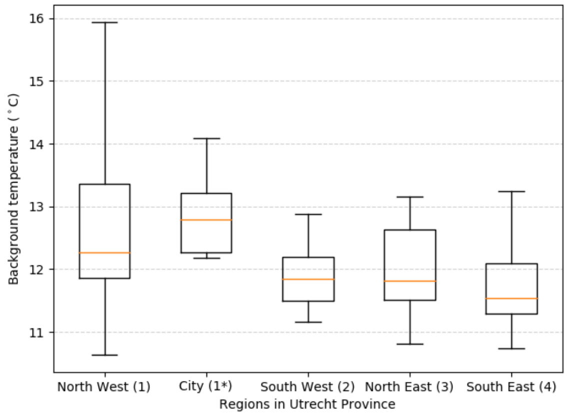

Figure 7 The ambient groundwater flow determined for each sub-area. Highest ambient groundwater temperature is found for the city Utrecht (1*).

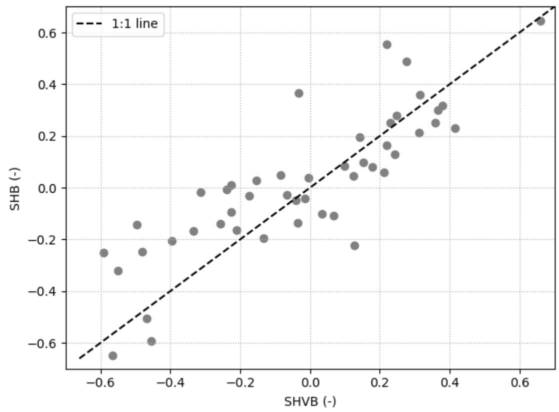

Figure 8 Relationship between the SHVB and the SHB

3.3 Energy exchange between building and ATES

The SHB distribution for all systems shows approximately a normal distribution with most systems between -50% and +50% (Fig. 8). Only 14% of all ATES systems has an SHB imbalance smaller than 10%, and therefore more than 80% of the studied ATES systems have an subsurface heat imbalance larger than 10%. Both the r_{SHVB} and the r_{SHB} can range from -60% to + 60% and are significantly correlated (Fig. 8). This indicates that the specific long-term balance between heating and cooling of a system can be obtained by only using extraction/injection data (r_{SHVB}), or, by combining volumetric and temperature data (r_{SHB}). This also shows that the ΔT for both cooling and heating is similar per specific ATES system.

The ΔT indicates how much energy is exchanged per unit extracted volume (Fig. 9). Overall there is a normal distribution both with cooling and heating demand. On average the ΔT for heating is 4.2 °C (e.g. 14.2 °C extraction from warm well, 10 °C injection in cold well) and ΔT for cooling is 4.4 (e.g. 10 °C extraction from cold well, 14.4 injection in warm well). Some systems have a very high ΔT when heating, which is probably due to high extra electrical energy input by a heat pump.

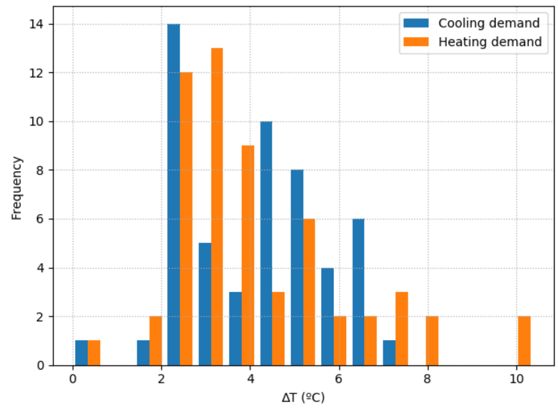

Figure 9 ΔT for all systems for both heating and cooling.

3.4 Recovery efficiency

The distribution of efficiencies is similar for the warm and cold wells (Fig. 10). Almost 20% of all calculated efficiencies are found between -25 and 0%. These calculated values are due to poor data quality and wrongly calculated T_{amb} and are therefore not a good representation of the η_{th} in practice for those systems. When excluding this part a normal distribution can be observed centered around 30 - 50% efficiency (Fig. 10).

Calculated efficiencies in the range of 80-150% are most likely not realistic for properly operating ATES systems and can possibly occur due to a combination of large imbalance and unvailability of data of previous years. In this way, energy that was stored in the past is extracted during the period that is taken into account. Another explanation could be that the ambient groundwater temperature has no been calculated accurately, which is probably caused by poor data quality. This could have a significant influence on the efficiency, but because actual ambient groundwater temperatures are unkown this can not be checked.

Analysis of storage conditions were done based on the framework provided by Bloemendal and Hartog

(2018). This showed that the storage conditions of the analyzed ATES systems were in most cases suboptimal (Fig. 11). Partly because of design (short screen lengths) and also because the systems aren't using the maximum permitted volume (50%). Results showed that large storage volumes have a significantly higher efficiency.

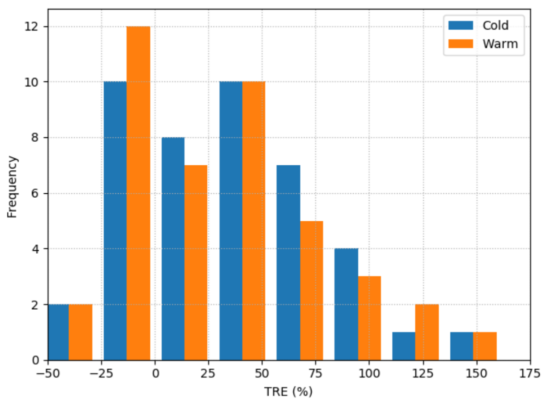

Figure 10 Recovery efficiencies (of cold and warm wells) of all ATES systems.

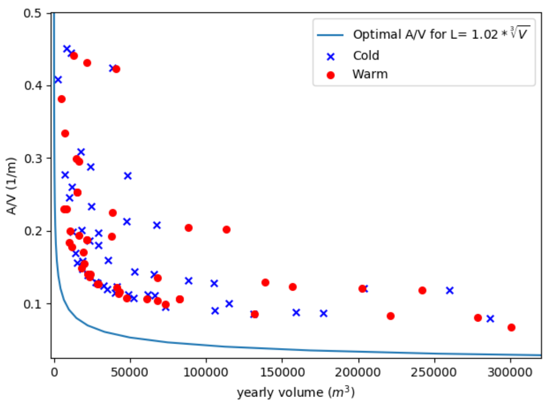

Figure 11 Relationship between yearly average extracted volumes and A/V.

3.5 Overall performance

Figure 12 gives the overall performance of the ATES systems. This overview can be helpful to quickly determine which ATES system is not performing as designed/permitted. The results of the assessment framework can subsequently give insight in the reason of this deviant performance. Subsequently a more detailed check-up can be done on the systems characterization to see if the causes of this deviant performance can be obtained from the data.

The results of this study altogether indicate that more energy (CO_2) could potentially be saved. Possible improvements for individual ATES systems could be to use a bigger portion of the permitted volume or to respond adequately when the system is not balanced (e.g. by storing extra cold/heat when possible). Better monitoring of ATES systems and improving operational data processing would give more and better insight in performance of ATES systems.

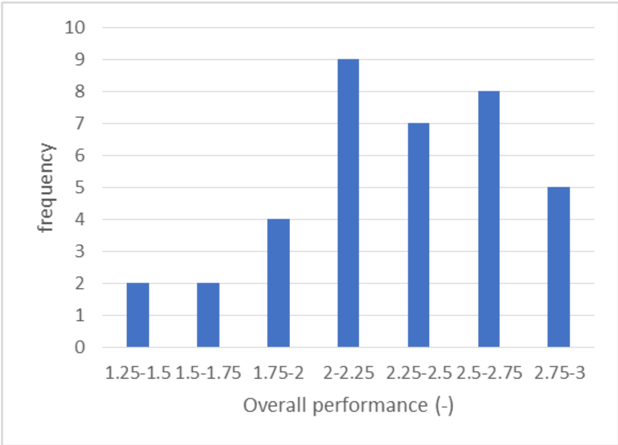

Figure 12 The overall performance of the ATES systems.

4. CONCLUSIONS

This research analyzed data of operational ATES systems in the province of Utrecht and determined assessment parameters that can be used to do an overall performance assessment. Pre-processing resulted in a subset of 57 ATES systems, which is about 35% of all ATES systems in Utrecht. This shows that data exchange between the authorities and ATES users can improve. The monitoring authority can assist in this by providing more and stricter supervision and thereby collecting more complete operational data. Results showed that recovery efficiency is positively correlated to system size (stored volume). Ambient groundwater temperature are site-specific (can vary more than 4 °C) and should therefore be determined for each ATES system individually. Next to this, a large part of the analyzed systems are not equally storing heat and cold in the subsurface. More than 80% of the studied ATES systems have an subsurface heat imbalance larger than 10%. It is recommended to make the overall performance analysis complete by including the use of non-thermal energy sources (heat-pump) and determine their share in the total energy use to see how much of the building energy use is actually from stored thermal energy. Altogether, results indicate that a big part of the ATES systems in the province of Utrecht can substantially improve their ATES system (management) to increase long-term energy savings. This research provides an useful assessment framework to determine if an ATES system is performing correctly, and what aspect of the overall ATES system performance needs most improvement.

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