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Numerical Simulation of ATES Systems Performance in the Permo-Triassic Sherwood Sandstone Group

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1 INTRODUCTION

Aquifer thermal energy storage (ATES) systems, a cost-effective heating and cooling technology, have been used in many European countries such as the Netherlands, Sweden, Belgium, Denmark and Germany for space heating and cooling in public buildings, including hospitals and airports (Fleuchaus et al., 2018). Since the first ATES systems experiment at the University of Neuchâtel, Switzerland, in 1974, over 2,500 systems have been deployed across Europe (Fleuchaus et al., 2018; Tsang and Hopkins, 1982). The Netherlands has the highest number of ATES system installations globally (Figure 1), and it has one of the world's largest systems at Eindhoven University of Technology, which saves over 1,200 tons of CO_2 annually (Behi et al., 2014). Another notable use of ATES systems in Europe is at Sweden's Arlanda Airport for air conditioning, pre-heating ventilation air, and snow melting at the airport gates. This saves 3 GWh and 15 GWh of the airport's annual electrical and district heating consumption, respectively (Stockholm Arlanda Airport, 2012).

In the United Kingdom (UK), ATES use is low despite the presence of suitable aquifers, such as the Chalk aquifer and Carboniferous and Permo-Triassic sandstones beneath major cities with considerable heating and cooling demands. There are only 11 operational ATES systems deployments in the UK, all located in England, and London accounts for more than 90 per cent of the total (Jackson et al., 2024). Limited technical knowledge of ATES systems, insufficient awareness and regulatory requirements are some of the reasons for this low usage (Jackson et al., 2024).

Although the UK was one of the Western countries that conducted research on geothermal energy as an alternative energy source during the 1970s oil crisis, it did not follow through on many of these efforts, and only a few demonstrator projects were completed (Downing and Gray, 1986). This is mainly because of a significant drop in oil prices and the UK's emergence as a major oil exporter. However, following the signing into law of the UK Climate Change Act in 2008, with a commitment to achieve net-zero emissions by 2050 and the need for energy security, geothermal energy, including ATES systems, has been at the centre of decarbonising heating and cooling (Abesser and Walke, 2022; Committee on Climate Change, 2019).

The Permo-Triassic Sherwood Sandstone Group (SSG) is an important geologic formation in the UK for groundwater and geothermal energy applications, and it occurs at varying depths across different basins. It has moderate to high permeability and porosity, which makes it suitable for ATES systems installations. The estimated geothermal energy potential of SSG in the Wessex, Cheshire, Worcester, Eastern England and Northern Ireland basins is more than 200 EJ (Busby, 2014; Rollin et al., 1995).

This study investigates the thermal recovery efficiency of the Sherwood Sandstone Group in Northern Ireland for ATES systems installation using numerical modelling. 2D and 3D numerical models were developed using FEFLOW to determine the amount of heat that can be stored/extracted over a ten-year period across boreholes. The outcome of this research is essential for improving the use of SSG for ATES systems in the UK, thus contributing to the country's decarbonisation targets by 2050.

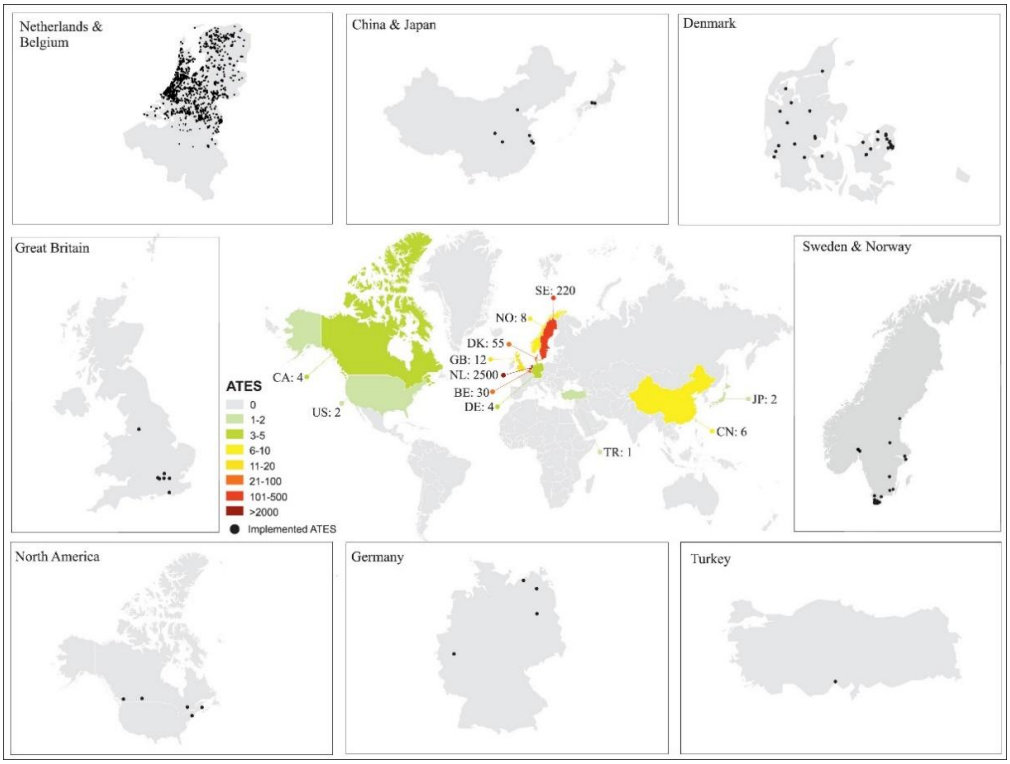


Figure 1. Global distribution of ATES Systems (Fleuchaus et al., 2018)

2 METHODS

2.1 Description of study area

The study area is located within the Lagan Valley in Northern Ireland (Figure 2) and consists of three 100m deep boreholes completed into the lower part of the Sherwood Sandstone Group. Each borehole is completed across ~30m of cased, less-permeable deposit (sands and glacial till) underlain by ~70 m of uncased SSG. Previous field exercises conducted in these boreholes, which involved borehole geophysical logging and pumping tests, have determined the heterogeneity and hydrogeological properties of Sherwood Sandstone, including porosity at this site (Oguntade et al., 2025).

2.2 Numerical Modelling

This study uses FEFLOW ®, a finite element computer modelling software, to simulate ATES systems' efficiency. The modelling work builds on previous field studies of SSG at this location, and both 2D and 3D models were constructed to represent borehole conditions.

The model construction involves a 200m x 200m domain and a doublet well system (separate injection and abstraction wells). A vertical discretisation of 5m, representing 20 layers over the entire borehole depth, was used. This layer thickness strikes a balance between computational efficiency and the need to accurately simulate thermal plume dynamics and vertical flow components, which are critical in ATES systems. Furthermore, based on the measured groundwater background temperatures in the boreholes, a reference temperature of 15 °C and an injected temperature of 35°C were applied in the model. The simulated ATES systems operate seasonally over 10 years (3,600 days), alternating between injection during warmer months and abstraction during cooler months (Table 1).

The model also compared scenarios with 2 extraction boreholes and 1 injection borehole ATES systems with 1 extraction borehole and 1 injection borehole ATES systems to determine the most efficient and cost-effective installation at this site.

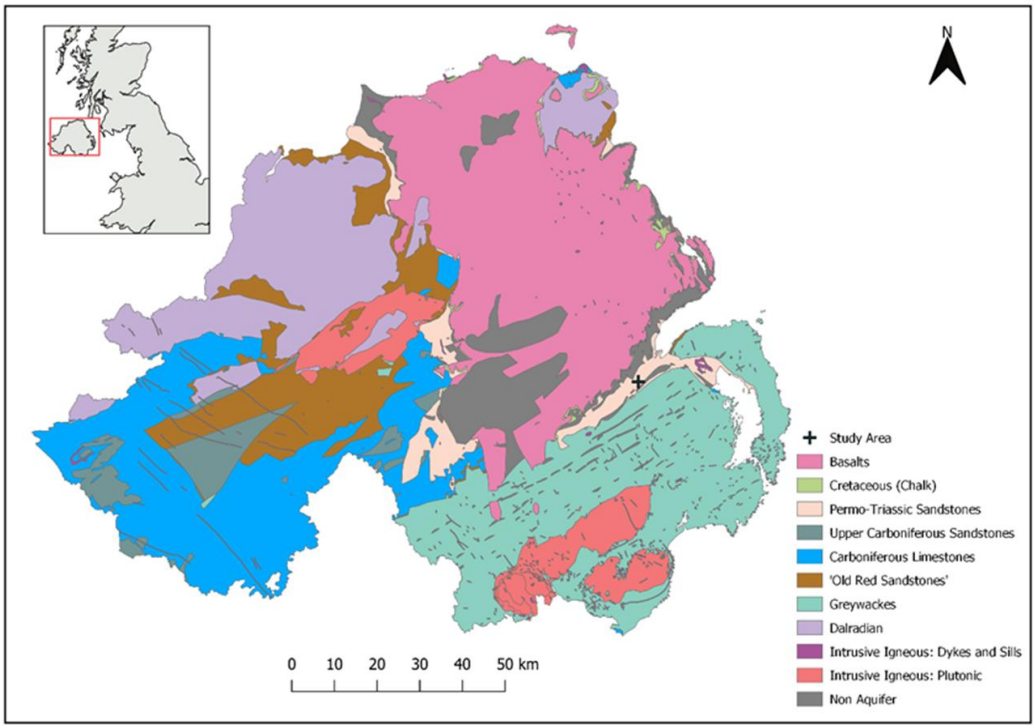


Figure 2. Groundwater formations in Northern Ireland (bedrock), the inset shows the United Kingdom

Table 1. Operational cycle of the ATES systems

Time (days)	Activity
0-90	Injection period
90-180	Storage period
180-270	Extraction period
270-360	Storage period

3 RESULTS

From the numerical models, the thermal recovery efficiency, defined as the ratio of thermal energy extracted from the system to that injected into the system for both abstraction and injection wells (Equation 1), was obtained. The thermal recovery efficiency varies and gradually increases each year.

$$\eta = \frac{\int_{extraction} c_{water}\,(T_e - T_o) Q.dt}{\int_{injection} c_{water}\,(T_i - T_o)\,Q.dt} \quad (1)$$

Where η is the thermal recovery efficiency, c_{water} is the volumetric heat capacity of water, T_e and T_i are the temperatures of the water that is extracted and injected, T_o is the natural temperature of the aquifer, and Q is the pumping rate.

4 DISCUSSION AND CONCLUSION

This study analyses the numerical modelling of ATES systems' performance over 10 years in the lower part of the Permo-Triassic Sherwood Sandstone Group of Northern Ireland. From the results, there is a progressive yearly increase in the thermal recovery efficiency. This could be due to improved thermal and hydraulic balance in the aquifer. In the first few years, the aquifer is relatively "cold," but with each cycle, residual heat from previous warm seasons remains, gradually increasing its baseline temperature. This thermal conditioning reduces the temperature gradient losses and improves efficiency. Furthermore, over repeated cycles, as the surrounding geology warms, the temperature difference between the stored heat and the formation decreases, thereby reducing heat losses and improving thermal recovery efficiency.

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