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Integrated Geophysical and Thermo-Mechanical Assessment of Subsurface Thermal Energy Storage Systems in Coastal Sedimentary Basins

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ABSTRACT

Subsurface Thermal Energy Storage (STES) systems are increasingly being considered as sustainable solutions for seasonal energy storage in heating and cooling applications. However, their performance and long-term stability depend on complex coupled thermo-hydro-mechanical (THM) processes occurring within geological formations. This study presents an integrated geophysical and thermo-mechanical framework for evaluating the feasibility of STES systems in coastal sedimentary environments. The approach combines subsurface characterization using geophysical methods with coupled thermal, hydraulic, and mechanical modelling to assess reservoir suitability and system stability. The study further evaluates heat transport, fluid flow, stress distribution, and energy efficiency within porous geological media. Key risks such as thermal breakthrough, pore pressure variation, subsidence, and borehole instability are also examined. The proposed framework provides a unified methodology for improving STES design, optimizing performance, and ensuring safe long-term operation in complex geological settings.

Keywords: energy storage, geological formations, Subsurface Thermal Energy Storage

1. INTRODUCTION

The global transition toward sustainable and low-carbon energy systems has intensified research into efficient thermal energy storage technologies. Subsurface Thermal Energy Storage (STES) systems, including Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES), are increasingly recognized as viable technologies for seasonal energy storage in heating and cooling applications (Bloemendal & Hartog, 2018; Lund & Toth, 2021).

These systems utilize underground geological formations as natural reservoirs for storing excess thermal energy, which can later be retrieved when demand increases. Compared to surface-based storage systems, STES offers advantages such as high storage capacity, low surface footprint, and long-term thermal stability.

However, the efficiency and safety of STES systems depend strongly on coupled physical processes within porous geological media. During injection and extraction of thermal energy, subsurface formations experience simultaneous changes in temperature, pore pressure, and mechanical stress. These interactions are described as thermo-hydro-mechanical (THM) processes, which significantly influence heat transport, fluid flow, and deformation behavior.

The theoretical foundation of these coupled processes is rooted in poroelasticity theory, which describes the interaction between fluid pressure and mechanical deformation in saturated porous media (Biot, 1941). Modern numerical implementations of these coupled systems are commonly solved using finite element and finite volume methods to capture complex interactions in geological formations (Zienkiewicz et al., 1999).

In coastal sedimentary basins such as the Niger Delta, the application of STES systems presents additional challenges. These environments are characterized by weakly consolidated sediments, high groundwater levels, and complex stratigraphic variations, all of which influence both thermal and mechanical responses of the subsurface.

Despite increasing global interest, many existing studies treat thermal, hydraulic, and mechanical aspects of STES systems separately. This fragmented approach limits accurate prediction of system performance and long-term stability. Therefore, there is a need for an integrated framework that combines geophysical characterization with coupled thermo-mechanical modelling to assess STES feasibility more realistically.

2. Study Area / Geological Setting

The study is situated within a representative coastal sedimentary environment of the Niger Delta Basin, Southern Nigeria. The Niger Delta is one of the world's largest regressive delta systems, formed through long-term sediment deposition from the Niger–Benue river system (Short & Stauble, 1967; Reijers, 2011).

The basin is composed of three major lithostratigraphic units: the Benin Formation, Agbada Formation, and Akata Formation. The Benin Formation consists predominantly of unconsolidated sands and gravels with minor clay interbeds and represents the main freshwater aquifer system in the region (Doust & Omatsola, 1990). The Agbada Formation is composed of alternating sandstone and shale sequences and serves as both hydrocarbon reservoirs and sealing units. The underlying Akata Formation consists mainly of overpressured marine shales with very low permeability (Avbovbo, 1978).

Hydrogeologically, the Niger Delta is characterized by shallow unconfined to semi-confined aquifer systems with high groundwater tables influenced by rainfall intensity, tidal fluctuations, and seasonal recharge variability (Ehirim & Nwankwo, 2010). These conditions strongly influence subsurface fluid flow and heat transport processes relevant to STES systems.

From a geomechanical perspective, the sediments of the Niger Delta are weakly consolidated, highly compressible, and prone to subsidence under changes in pore pressure and thermal loading (Onu & Ogbonnaya, 2015). These mechanical properties are critical when evaluating the stability of subsurface energy storage systems.

The combination of high groundwater saturation, variable lithology, and weak mechanical strength makes the Niger Delta both a challenging and informative environment for evaluating the feasibility of Subsurface Thermal Energy Storage systems.

3. METHODOLOGY

This study adopts an integrated geophysical and thermo-mechanical modelling framework to evaluate the feasibility of Subsurface Thermal Energy Storage (STES) systems in coastal sedimentary environments. The methodology combines subsurface characterization, coupled thermo-hydro-mechanical (THM) conceptual modelling, numerical simulation, and performance evaluation.

3.1 Geophysical Site Characterization

Subsurface characterization is carried out using geophysical methods to determine lithological, structural, and hydrogeological properties of the study area. Electrical Resistivity Tomography (ERT) is used to delineate subsurface layers based on variations in resistivity, where low resistivity zones typically correspond to water-saturated formations and higher resistivity values indicate clay-rich or compacted layers (Kearey et al., 2013).

Seismic refraction methods are applied to estimate subsurface velocity structures and determine layer boundaries and depth to competent bedrock. These methods are useful for identifying structural discontinuities such as faults and fractures that may influence fluid flow and thermal transport (Telford et al., 1990).

Hydrogeological parameters such as permeability, porosity, and transmissivity are inferred from geophysical interpretation and existing regional hydrogeological studies.

3.2 Thermo-Hydro-Mechanical (THM) Framework

The subsurface is modeled as a saturated porous medium where heat transfer, fluid flow, and mechanical deformation occur simultaneously. The coupling between these processes is essential for accurately describing STES behaviour under thermal loading conditions.

The theoretical basis of this coupled system is founded on poroelasticity theory, which describes the interaction between pore pressure and mechanical deformation in saturated media (Biot, 1941). Numerical implementation of such coupled systems is commonly achieved using finite element and finite volume methods (Zienkiewicz et al., 1999).

Changes in temperature affect fluid density and viscosity, while pore pressure variations influence effective stress and mechanical stability of the formation.

3.3 Numerical Modelling Approach

A numerical model is developed to simulate cyclic injection and extraction of thermal energy in the subsurface. The governing THM equations are solved using discretized numerical methods to capture spatial and temporal variations in temperature, pore pressure, and stress fields.

The model domain is constructed based on geophysical interpretation of the study area stratigraphy. Material properties such as thermal conductivity, permeability, Young's modulus, and specific heat capacity are assigned according to lithological units.

Boundary conditions simulate seasonal injection and extraction cycles typical of STES operation. Sensitivity analysis is conducted to evaluate the influence of key parameters such as permeability and thermal conductivity on system performance.

3.4 Exergy Analysis

Exergy analysis is applied to evaluate the thermodynamic performance of the STES system. Unlike energy analysis, exergy analysis accounts for both the quantity and quality of energy.

Exergy efficiency is used to quantify irreversible losses due to heat dispersion, conduction into surrounding formations, and mixing of fluids at different temperatures (Bejan, 2016).

This approach provides a more realistic assessment of system performance compared to conventional energy-based methods.

3.5 Geomechanical Stability Assessment

The geomechanical response of the subsurface is evaluated by analyzing stress redistribution and deformation induced by thermal and hydraulic loading. Thermal expansion and contraction of geological materials result in changes in effective stress, which may lead to subsidence or uplift.

Borehole stability is assessed by evaluating stress concentration around injection and extraction wells, which may lead to casing deformation or failure under extreme conditions (Onu & Ogbonnaya, 2015).

4. Governing Equations and Theoretical Formulation

Subsurface Thermal Energy Storage (STES) systems are governed by coupled thermo-hydro-mechanical (THM) processes in porous media. These processes describe the interaction between fluid flow, heat transfer, and mechanical deformation under thermal loading conditions.

The governing equations are based on poroelasticity theory, which describes fluid–solid interaction in saturated porous media (Biot, 1941). Numerical solutions of these coupled systems are commonly implemented using finite element and finite volume methods (Zienkiewicz et al., 1999).

4.1 Mass Conservation Equation

Fluid flow in porous media is described by the continuity equation:

$$\frac{\partial(\phi\rho_w)}{\partial t} + \nabla \cdot (\rho_w \mathbf{q}_w) = Q_w$$

Darcy’s law defines fluid velocity as:

$$\mathbf{q}_w = -\frac{\kappa}{\mu} \nabla p$$

where κ is permeability, μ is fluid viscosity, and p is pore pressure.

4.2 Heat Transport Equation

Heat transfer in porous media is governed by:

$$\frac{\partial}{\partial t} \left[(\phi\rho_w c_w + (1 - \phi)\rho_s c_s) T \right] + \nabla \cdot (\rho_w c_w \mathbf{q}_w T) - \nabla \cdot (k_{eff} \nabla T) = Q_T$$

Effective thermal conductivity is expressed as:

$$k_{eff} = \phi k_w + (1 - \phi) k_s$$

4.3 Mechanical Equilibrium Equation

The stress equilibrium equation is given as:

$$\nabla \cdot \sigma - \nabla p + \rho \mathbf{b} - \alpha_T K \nabla T = 0$$

This describes the coupling between mechanical deformation, pore pressure, and thermal loading.

5. RESULTS AND DISCUSSION

The coupled THM analysis of STES systems shows that subsurface response is highly dependent on geological properties and operational conditions.

5.1 Thermal Behaviour

Thermal injection creates a plume around the injection well, which expands radially with time. Heat transport is influenced by groundwater movement and formation permeability. This behaviour is consistent with aquifer thermal energy storage systems reported in previous studies (Bloemendal & Hartog, 2018; Lund & Toth, 2021).

Thermal breakthrough occurs when the heated zone reaches the extraction well, reducing system efficiency.

5.2 Hydraulic Response

Injection and extraction cycles cause periodic pore pressure fluctuations. These variations influence effective stress and can affect formation stability. This behaviour is consistent with coupled poroelastic systems described in classical THM theory (Biot, 1941).

5.3 Geomechanical Response

Thermal expansion and contraction of the porous medium induce small deformation in the subsurface. Uplift occurs during heating while subsidence occurs during cooling. Stress concentration near wellbores may affect long-term stability, particularly in weak sedimentary formations (Onu & Ogbonnaya, 2015).

5.4 Exergy Performance

Exergy analysis indicates that irreversible losses occur due to:

- heat dispersion
- conduction into surrounding formations
- mixing of fluids at different temperatures

This reduces overall system efficiency compared to ideal energy storage systems (Bejan, 2016).

5.5 Integrated Interpretation

The results confirm that STES performance is governed by coupled thermal, hydraulic, and mechanical interactions. Key controlling parameters include permeability, thermal conductivity, groundwater flow, and mechanical stiffness of the formation.

In coastal sedimentary basins such as the Niger Delta, weak soil strength and high groundwater saturation increase both thermal losses and geomechanical risks.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study developed an integrated geophysical and thermo-mechanical framework for evaluating Subsurface Thermal Energy Storage systems in coastal sedimentary environments.

The results demonstrate that STES systems are controlled by coupled thermo-hydro-mechanical processes that govern heat transfer, fluid flow, and deformation in porous media (Biot, 1941; Zienkiewicz et al., 1999).

Geophysical methods are essential for identifying suitable aquifer formations, while geomechanical analysis ensures structural stability during long-term operation. Exergy analysis further highlights thermodynamic inefficiencies in real systems (Bejan, 2016).

6.2 RECOMMENDATIONS

1. STES systems should be sited in confined aquifers with moderate permeability and stable mechanical properties.
2. Detailed geophysical surveys should be conducted prior to installation (Kearey et al., 2013).

3. Continuous monitoring of pressure, temperature, and deformation is required for safe operation.
4. Future studies should incorporate field validation of THM models.
5. Advanced THMC (thermo-hydro-mechanical-chemical) modelling should be developed for improved accuracy.

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