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Numerically predicting surface displacement patterns to inform monitoring well strategies in underground H2 storage for a reservoir at Ketzin site in Germany

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The transition to a sustainable energy landscape has intensified interest in geological storage of hydrogen (H2) as an energy carrier and buffer. Repeated injection and withdrawal of H2 induce complex thermo-poroelastic responses in the subsurface, making it essential to predict these changes accurately to ensure reservoir integrity and informed reservoir management. This study employs a coupled thermo-poroelastic finite element model built within COMSOL Multiphysics to simulate the geomechanical and thermal evolution of a reservoir at the Ketzin site in the North German Basin, Germany, during H2 injection and extraction phases. The model incorporates fluid flow, heat transport, and mechanical deformation in a fully coupled manner. By doing so, it provides realistic estimates of pore pressure variations, temperature gradients, and resulting stress field alterations.
A key focus of the simulations is quantifying the spatial and temporal distribution of surface displacement near the operational wellbore for a given injection scenario. Near the injection wellbore, pressure-driven flow maintains higher gas saturations, whereas further away from the wellbore, plume spreading leads to lower saturation levels. These reservoir dynamics translate into subtle yet detectable deformation patterns at the surface. Thermo-hydro-mechanical coupling significantly influences porosity and permeability changes during cyclic operation, while thermoelastic effects remain relatively small due to limited temperature contrasts between injection fluids and the reservoir. The fully coupled thermo-poroelastic changes can lead to vertical displacement on the order of millimeters, potentially accumulating over multiple cycles and affecting the near-surface stability and infrastructure, however it remain very small.
One key finding is that localized uplift signals evolving over the injection-withdrawal cycle serve as diagnostic indicators of subsurface stress distribution and fluid fronts. Leveraging these insights, we investigate optimal placement strategies for a dedicated monitoring well. By positioning this well at a strategically chosen offset from the operational wellbore, it becomes possible to directly measure critical parameters such as pressure, temperature, and deformation, while minimizing operational risks and maximizing the value of collected data. Such monitoring can capture early signs of fluid migration and mechanical response, thereby supporting proactive reservoir management and early warning detection systems.
Beyond the exemplary Ketzin case, the modeling framework and insights presented here can be extended to other subsurface hydrogen storage sites worldwide in sedimentary basins. By linking geomechanical simulations to practical monitoring strategies, this research advances the reliable, safe, and efficient long-term storage of hydrogen in the pursuit of a more sustainable global energy future.

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References

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