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Editorial

Engineered subsurface hydrogen generation: Insights for sustainable production system

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Abstract:
Subsurface hydrogen generation encompasses both natural and engineered processes. Natural subsurface hydrogen, often referred to as geological hydrogen, is produced by in-situ geochemical reactions without human intervention. The term engineered subsurface hydrogen generation is adopted here to describe controllable reservoir operations aimed at producing hydrogen, which can be further divided into three routes, namely stimulated geological hydrogen via serpentinization of ultramafic rocks by water-looping, subsurface chemical looping via steel-slag-mediated iron redox water splitting, and subsurface conversion of organic-rich formations via thermal, biological, or chemical pathways. Only stimulated geological hydrogen falls within the strict definition of geological hydrogen; the other two are engineered subsurface processes that do not qualify as geological hydrogen. Our experiments on serpentinization indicate that hydrogen generation and release can be physically decoupled, implying that engineered production strategies such as pressure drawdown and cyclic injection-production are required. Crucially, the field value of engineered subsurface hydrogen generation depends on whether these hydrogen-generating reactions can be engineered as controllable reservoir operations. These routes therefore require reaction-specific production systems rather than a universal well pattern. Drawing on geothermal doublets, multistage-fractured horizontal wells, radial jet laterals, shock fracturing and blasting fracturing, a completion-centered framework is outlined in which wellbores, fractures, catalysts or reactive solids, renewable heating, hydrogen separation and underground storage are designed as one production system. Key questions are further identified, including reaction kinetics coupled with heat and mass transfer, catalyst and injectivity maintenance, and pilot evaluation by H_2 recovery, energy output-input ratio and carbon balance.

1. Introduction

Low-carbon energy systems are increasingly organized around variable wind and solar power, which cannot by itself provide storable chemical fuels (Hassanpouryouzband et al., 2025), and wind, solar, geothermal and storage capacities are therefore operated as one multi-energy hub (Wang et al., 2024). Hydrogen can bridge the fuel gap only if its production moves away from fossil reforming and is linked to infrastructure that handles heat, fluids, gases and long-duration storage (Salahshoor and Afzal, 2022; Yang and He, 2026). Mature and depleted hydrocarbon basins already provide wells, fractures and surface facilities, and engineered subsurface hydrogen generation (ESHG) treats this inherited system as a controllable reactor (Yuan et al., 2026), the central question being how to compress geologic reactions into

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production timescales while controlling heat, mass transfer and product recovery (Liu et al., 2025a; Egert et al., 2026). In our experiments, approximately 84% of generated H_2 was retained in situ, with capillary and adsorption dominating over dissolution and free gas accumulation, so generation and release can be decoupled and passive recovery may underestimate reservoir potential. Retention was measured for serpentinization and remains to be tested for the other routes, so the requirement is treated here as a hypothesis: lowering pore pressure destabilizes the capillary seals that hold the gas phase and shifts adsorption equilibrium toward the free phase, while repeated injection-production sweeps desorbed H_2 to the producer instead of leaving it to re-adsorb. The well system must therefore allow large pressure differentials and periodic injection reversal, acting as a thermodynamic trigger rather than a passive conduit. These systems should be reaction-specific in wells, fractures and surface facilities while sharing one engineering chain, in which wellbores, fractures, catalysts or reactive solids, renewable heating, hydrogen separation and underground storage are engineered as one production system.

2. Three reaction routes for subsurface hydrogen

These three routes are distinguished by where the reductant comes from and which solid accepts the oxygen. The first is stimulated geological hydrogen (SGH) via serpentinization of ultramafic rocks by water-looping, in which the oxygen acceptor is the reservoir rock itself: Fe^{2+} in olivine and pyroxene is oxidized to magnetite while water is reduced to H_2, as in $3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$. SGH is the engineered form of this naturally occurring process, serpentinization being its representative mechanism, and it operates within a temperature, pH and fluid-chemistry window that is now being parameterized (Mayhew et al., 2013). The second is subsurface chemical looping via steel-slag-mediated iron redox water splitting, in which the oxygen carrier is placed in the reservoir rather than inherited from it. The iron in the slag is present mainly as Fe^{2+} in non-stoichiometric wustite and dicalcium ferrite, so the water-splitting step is the oxidation of ferrous iron by steam to magnetite, $3FeO + H_2O \rightarrow Fe_3O_4 + H_2$, and magnetite is returned to wustite by a reductant supplied from the surface, which closes the cycle. Free lime in the slag buffers the fluid and fixes the CO_2 released during regeneration as $CaCO_3$ (O'Connor et al., 2021). This cycling requires several hundred degrees Celsius, so the formation supplies pore space and confinement while the reaction enthalpy comes from the surface; unlike serpentinization, the route has so far been demonstrated only at laboratory and process scale. The third is subsurface conversion of organic-rich formations, in which hydrogen is transferred from the hydrocarbons and organic matter themselves into H_2-bearing gas by thermal, biological or chemical pathways, the reactions being pyrolysis, steam-assisted cracking and catalytic aquathermolysis (Zhao et al., 2018; Hassanpouryouzband et al., 2025); for Chinese lacustrine shale, the 300-370 °C window of Chang 7_3 shale balances conversion, product value and energy input (Zhao et al., 2026). Field tests are furthest advanced for this route, pilot in-situ oil-shale conversion having validated the multi-well layouts and in-place heating that hydrogen generation from organic-rich formations requires; SGH has reached only a borehole-scale trial in Oman, and subsurface chemical looping has not yet left the laboratory.

3. Reaction-specific production systems

ESHG requires a new completion paradigm in which the reservoir is not only a storage or drainage target but a coupled reaction, heat-transfer and production volume, and completion acts as the control hub that sets where reactants and heat enter, where products leave, and which pressure and temperature transients the reservoir experiences (Yuan et al., 2026). Because the routes differ in reactant source, heat source and temperature window, they call for scenario-specific production systems rather than a universal well pattern, yet their engineering chain is shared (Yang and He, 2026).

For completion design, ESHG can draw on mature thermal-recovery practice. Geothermal doublets circulate water continuously between an injection and a production well through natural or stimulated fractures, and where permeability is insufficient the pair is replaced by multistage-fractured horizontal wells (Gong et al., 2020); steam-assisted gravity drainage likewise operates two parallel horizontal wells continuously, the upper injecting steam and the lower producing, so that a rising steam chamber drains the interval by gravity (Pratama and Babadagli, 2024). Five completion and production modes follow from this experience. A vertical injection-production doublet with continuous circulation is the simplest and cheapest, but its swept volume and residence time are small. A vertical doublet linked by shaped-charge or blasting fractures forms a short, directed reaction path instead of a diffuse network (Wang et al., 2018). A dual-horizontal-well pair with staged fracturing, inherited from steam-assisted gravity drainage and enhanced geothermal system panels, provides a large planar reaction volume suited to thick intervals. Single-well cyclic stimulation with shock fracturing, the heavy-oil huff-and-puff analogue, alternately injects hot fluid, shuts in for reaction and produces back through one wellbore, and its periodic drawdown matches our observation that trapped H_2 must be released by pressure cycling. Single-well radial jet drilling with cyclic production reaches rock that hydraulic fractures miss and places catalyst or steel-slag slurry directly in difficult intervals (Wang et al., 2016; Li et al., 2022). These modes are a menu rather than competing alternatives, and each reaction route should select a reaction-specific combination.

3.1 SGH

For SGH, the reaction is the serpentinization described above. Hydrogen generation is thermodynamically favored between 200 and 315 °C and fastest near 300 °C, and because the reaction is exothermic the injected heat serves to overcome the kinetic barrier rather than to supply the reaction enthalpy (McCollom and Bach, 2009). Rate, not temperature, is the binding constraint: natural serpentinization yields H_2 even at 55 °C in Oman peridotites (Ellison et al., 2024), yet such rates remain well below the economic threshold, and a 10,000-

fold increase in the engineered water-rock rate is needed to close that gap (Yuan et al., 2026). Surface passivation by Fe^{3+}-bearing secondary phases is the limitation, capping feasible pH and fluid chemistry. Our experiments show that extensively serpentinized dunite can be thermally reactivated at 300 °C, releasing substantial H_2 and implying that altered ultramafic rocks containing metastable Fe-bearing phases are viable formations; completion design should therefore include active heating, not just water circulation. The recommended design is multistage-fractured horizontal well pairs operated in long-duration cyclic injection-production. Fluid with catalyst is injecting along the fracture network, shutting in to react and then drawing down through the producer to release trapped H_2, with a vertical doublet linked by shock fractures as the alternative for thin formations (Gong et al., 2020; Li et al., 2022). Field experience remains a single borehole-scale trial (Ellison et al., 2024; Galvis Silva et al., 2025).

3.2 Subsurface chemical looping

For subsurface chemical looping, the reaction is the iron redox cycle outlined above: ferrous iron in the slag is oxidized by steam to magnetite, which the reductant then returns to wustite. The water-splitting step proceeds at roughly 500-800 °C and regeneration requires comparable temperatures, because below about 570 °C wustite becomes unstable with respect to iron and magnetite. The operating temperature is therefore set by phase stability rather than kinetics, and it lies well above that of most sedimentary basins, so both the reaction enthalpy and the reductant must come from the surface. Each redox cycle is fast, on the order of minutes to hours, so the binding constraints are the batch-wise consumption of the injected solid and the maintenance of injectivity as oxidation products, fines and carbonates accumulate near the wellbore, while buffering and CO_2 fixation by free lime are designed into the same operation. The route has no field precedent, its parameters coming from laboratory and process studies in which iron-calcium materials derived from steel slag reach 84% CO conversion and 100% H_2 selectivity at 600 °C (Zhong et al., 2025). The recommended mode is the placement–regeneration cycle: a main injection well equipped with radial jet laterals is used to distribute iron-rich slurries, proppants and catalyst across selected intervals, combined with shock fracturing that creates near-wellbore pore space for filling coarse reactive particles. Following the energy storage analogy, each cycle comprises three stages of slurry placement, steam oxidation, fluid production. Prior to injecting each new batch, shock fracturing is applied to the well to remove formation damage and improve the permeability from the near-wellbore region.

3.3 Subsurface in-situ conversion

For subsurface conversion of organic-rich formations, the reactions are the pyrolysis and thermal cracking described above. The reaction is heat-driven and rate-limited by conduction in the rock, so the design problem is to deliver a controlled thermal front rather than to maximize the reaction rate. The target is a temperature window rather than a maximum: liquid hydrocarbons and H_2-bearing gas form between 300 and 370 °C, whereas higher temperatures crack the liquid products into gas at the cost of a much larger energy input, and for Chinese lacustrine shale the 300-370 °C window of the Chang 7_3 interval balances conversion, product value and energy input (Zhao et al., 2026). Heating runs over months to years, so the energy output-input ratio, not the reaction rate, is the binding constraint. This is the only route with substantial field experience, pilot in-situ oil-shale conversion having already validated the multi-well layouts and the in-place heating that the route requires. The recommended mode is volumetric pyrolysis: horizontal heater wells enlarge and homogenize the thermal panel and vertical development wells intercept bedding-parallel flow paths to recover liquids and H_2-bearing gas, with radial fracturing or controllable shock waves used to precondition the rock before heating; the procedure is staged cyclic heating, soaking and production, heating each interval to the target window and producing it while the next is heated. Microorganisms can also convert the organic matter in place to H_2 (Liu et al., 2024, 2025b).

4. Key scientific problems and challenges

Although these completion modes are technically feasible, their design still rests on assumptions that have not been tested in the field, and four scientific problems must be resolved before ESHG becomes a controllable production system. (1) Reaction Kinetics: engineered reactions must be accelerated from geological to production timescales by several orders of magnitude, yet the rate controls remain poorly quantified for serpentinization and almost unknown for the other two routes. (2) H_2 trapping and release: the dynamics of in-situ H_2 trapping and release, as observed in our serpentinization experiments, represent a key question for completion design, because the altered rock matrix inherently acts as a vast adsorption sponge for generated H_2; the completion architecture must therefore manipulate local pressure-temperature transients explicitly, transforming the reservoir from a static capillary trap into an active desorption engine. (3) Geomechanics: crucially, treating the subsurface as a reactor implies that the reservoir is no longer structurally static. ESHG triggers extreme spatiotemporal geomechanical alterations: serpentinization induces solid volume expansion of up to 40%, which risks clogging fracture networks unless reaction-driven microcracking offsets the permeability loss, whereas thermal conversion of organic-rich formations results in significant mass loss and stress redistribution, increasing the risk of formation subsidence and casing shear. Completion designs must therefore evolve from static placement strategies into dynamic engineering frameworks, ensuring wellbore integrity and sustained flow pathways throughout the severe mechanical "breathing" of the reservoir's lifecycle. (4) Sustainability and evaluation: catalyst and injectivity maintenance remain unresolved, since reactive solids are consumed, secondary phases and fines plug the near-wellbore region, and casings, cement and packers must survive thermal cycling, corrosion and hydrogen-rich fluids. Field trials must consequently be evaluated not by reaction yield alone but by H_2 recovery,

energy output-input ratio and carbon balance, under downhole monitoring of temperature, pressure, stress, microseismicity and gas composition. Taken together, these problems place the subsurface within one coupled chemical, thermal, hydraulic and biological system (Liu et al., 2024, 2025b).

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Conflicts of interest

The authors declare no competing interest.

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