

Integrating Heat Extraction with Stimulated Geological Hydrogen Generation: An Assessment of Strategies to Optimize Operational Efficiency

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ABSTRACT

Achieving Net Zero Emissions (NZE) by 2050 will require expanded deployment of geothermal and other low-carbon energy systems capable of providing reliable heat and power. Engineered geological hydrogen generation in ultramafic formations shares strong conceptual and operational similarities with geothermal systems, including fluid circulation, subsurface heat extraction, and surface power conversion. During stimulated geological hydrogen production, hydrogen is co-produced with high-temperature water that transports significant geothermal energy to the surface. This thermal energy is commonly dissipated during surface cooling prior to reinjection, representing a missed opportunity for power generation and increased operational cost.

This study investigates the feasibility of integrating a geothermal binary power system with engineered geological hydrogen production to recover waste heat and enable a self-sustaining surface operation. An integrated framework is developed that couples laboratory-scale serpentinization-based hydrogen-generation experiments with field-scale thermal-production forecasting and Organic Rankine Cycle (ORC) modeling. Hydrogen generation rates are scaled to field conditions using fracture-surface-area-based geometric scaling across three reservoir scenarios: low-temperature uncatalyzed, low-temperature catalyzed, and high-temperature catalyzed. A 20-year production lifecycle is simulated, and the co-produced injected fluid is evaluated as the primary heat source for a closed-loop ORC.

Results show that low-temperature uncatalyzed systems provide insufficient thermal power, while high-temperature catalyzed systems generate substantial geothermal power but may involve higher capital and operational risks. A low-temperature catalyzed scenario is identified as a marginal yet viable geothermal case, capable of meeting the minimum 3 MW power threshold required for self-sustaining surface operations. Sensitivity analysis demonstrates that reservoir decline management through restimulation is critical for maintaining long-term geothermal power output.

These results highlight the potential to repurpose geothermal binary power concepts to improve energy efficiency, thermal recovery, and sustainability in engineered subsurface energy systems.

1. INTRODUCTION

Net Zero Emissions (NZE) by 2050 is one of the scenarios outlined by the International Energy Agency (IEA) for achieving net-zero CO₂ emissions in the global energy sector (World Energy Outlook, 2021). Under the NZE pathway, hydrogen is expected to play a central role in decarbonizing hard-to-abate sectors, with global hydrogen demand projected to increase substantially by 2050. Meeting this demand would require producing several hundred million tonnes of hydrogen annually. The electricity required for hydrogen production in the NZE scenario is estimated to reach on the order of 15,000–20,000 TWh per year by 2050, corresponding to well over half of today's global electricity generation and exceeding the current electricity production of any single country (IEA, 2021; Osselin et al., 2021). Achieving these targets will therefore require unprecedented scaling of electrolyzer deployment, massive expansion of clean electricity generation, and the development of complementary hydrogen supply pathways beyond conventional electrolysis.

Geological hydrogen can be generated both naturally and through engineered stimulation of subsurface water–rock reactions. In both cases, hydrogen is produced by serpentinization, a geochemical process in which water reacts with iron-rich ultramafic rocks such as peridotite and dunite. This reaction typically occurs at elevated temperature and pressure, commonly in the range of 150–400 °C. Iron-bearing minerals within these rocks, including olivine and pyroxene, act as the primary electron donors, driving the reduction of water and forming molecular hydrogen alongside secondary minerals such as serpentine-group phases, brucite, and magnetite (Joseph, 2017). In natural settings, serpentinization proceeds at geological timescales, whereas engineered stimulation aims to enhance reaction rates and hydrogen yield by increasing fluid–rock contact and reaction efficiency.

During engineered hydrogen generation, water is injected into the reservoir, and heat transfer occurs between the geologic formation and the injected water. This processing results in the production of high-temperature fluid. Produced fluid from the geological formation passes through surface facilities, which include a separator (or knock-out drum), before the hydrogen is taken for final use (fuel cell, electricity, or industrial use). A separator has a maximum flow rate it can handle, which generally requires the high-temperature fluid to be cooled. This cooling-down process consumes energy and adds to the overall project's operational cost. The thermal energy captured during the cooling process is typically dissipated, meaning we miss the opportunity to utilize the energy we captured and increase the thermal footprint of surface operations (Angelina, 2025). We proposed adding an Organic Rankine Cycle (ORC) to the surface facility to recover the waste heat. Beyond maximizing thermal energy utilization, this addition to the facility has the potential to transition the

hydrogen generation system into a circular, self-powered system without depending on other energy sources. ORC can effectively convert captured thermal energy into a reliable on-site power supply for essential surface operations, such as water treatment and reinjection. The proposed system is shown in Figure 1. The end purpose of this study is to investigate the feasibility of a self-sustaining hydrogen generation system to reduce overall project cost; however, in this study, we focus on thermodynamic modeling.

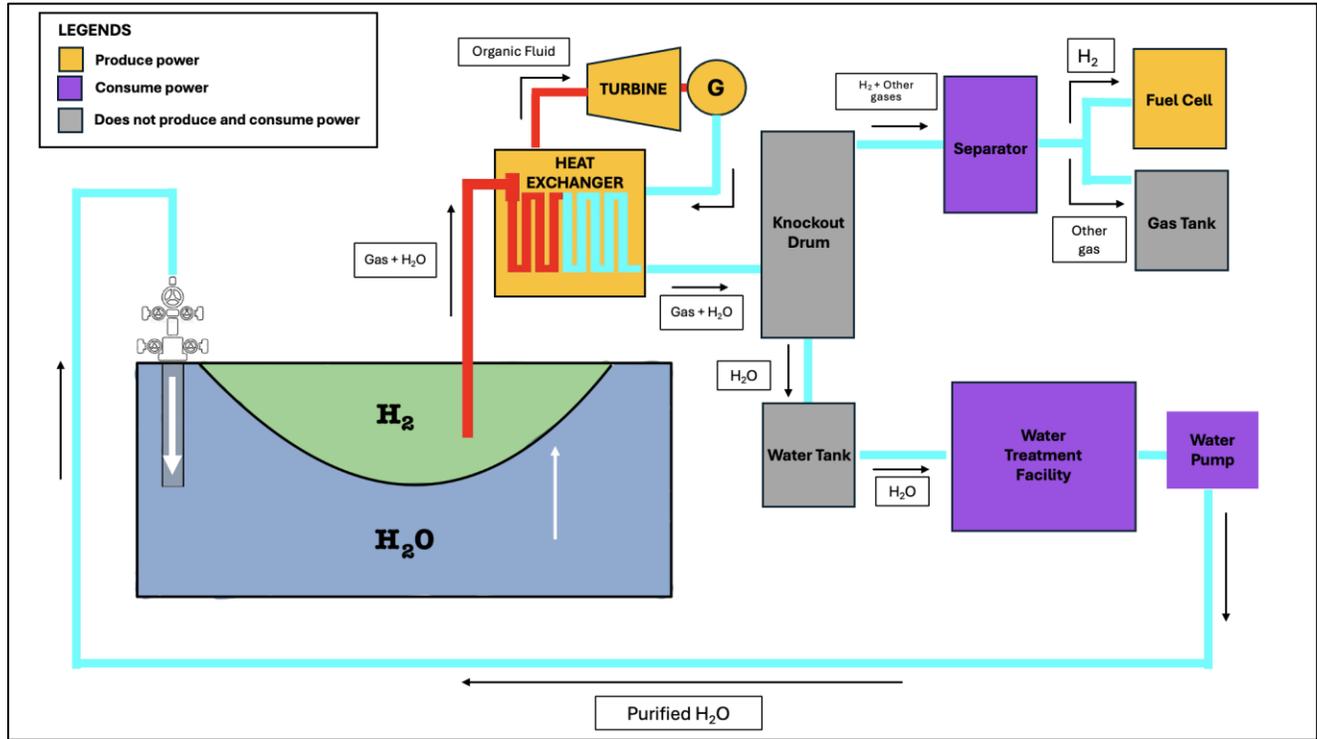


Figure 1: Purposed system for hydrogen generation with addition of Organic Rankine Cycle (ORC) and water treatment facility into the conventional hydrogen generation system

2. METHODOLOGY

The methodology of this study uses integrated framework to bridges laboratory-scale geochemical experiment results with field-scale thermodynamic modeling. The objective is to evaluate the feasibility of a self-sustaining energy from its internal hydrogen generation facility by coupling it with binary power plant. This process includes using experimental data to simulate a 20 years production lifecycle followed by a thermodynamic modeling and analysis of the surface binary power plant

2.1 Data Acquisition and Field-scaling

In this section, we combined data from 2 published studies by Galvis-Silva et al. (2025) and Tarter et al. (2025) to establish a representative field-scale production dataset. Laboratory-scale geochemical hydrogen generation rates were obtained from the experimental results by Galvis-Silva et al. (2025). To bridge the gap in converting these data to field-scale, the results of the study conducted by Tarter et al. were applied.

The primary dataset from the experiment is an original 13-day record of hydrogen generation results from stimulated serpentinization. This experimental original data served as the primary source for defining both the initial hydrogen generation and decline rates. An equation was established by applying a regression analysis to the 13-day production data. The relationship expressed in Equation (1) is used to forecast the production, extending it into a 20-point data set representing a 20-year operational cycle

$$l = (-5 \times 10^{-9})t + (2 \times 10^{-7}) \quad (1)$$

Where l is the laboratory hydrogen generation rate in m³/day and t is time in year. The integrated dataset is shown in Table 1, column 1, where the initial 13 entries are the empirical laboratory results and the subsequent 7 values represent the forecasted production data derived from the established Equation.

To convert the dataset we obtained, a geometric scaling factor was calculated based on the surface area. The experimental samples used by Galvis-Silva et al. have a specific surface area of 0.00585 m². Meanwhile, the results of modeling conducted by Tater et al. showed that stimulation by rock fracturing in ultramafic rocks can provide a surface area of 1×10^6 m² for each individual fracture created.

The total field-scale surface area is then determined by the temperature and the presence of a catalyst. In the calculation to determine field-scale hydrogen production, the laboratory generation rates are multiplied by a volumetric scaling factor derived from the ratio of the total stimulated reservoir surface area to the laboratory sample surface area. The total stimulated surface area for each scenario is calculated as follows. Equations (2), (3), and (4) are in the correct order for each scenario mentioned before.

- Low temperature uncatalyzed case (100 °C): A single stimulation event is modeled to produce 10 fractures

$$q = l \times 100 \times \frac{10^6 \text{ m}^2}{5.85 \times 10^{-3} \text{ m}^2} \quad (2)$$

- Low temperature catalyzed case (100 °C): The addition of the catalyst is assumed to enhance the fracturing efficiency, resulting in 30 fractures created during a single stimulation event

$$q = l \times 300 \times \frac{10^6 \text{ m}^2}{5.85 \times 10^{-3} \text{ m}^2} \quad (3)$$

- High-temperature catalyzed case (200 °C): Under optimal thermal and chemical conditions, stimulation is projected to generate 50 fractures.

$$q = l \times 500 \times \frac{10^6 \text{ m}^2}{5.85 \times 10^{-3} \text{ m}^2} \quad (4)$$

Where q is the field scale hydrogen production rate in m^3/day , l is the laboratory scale hydrogen production rate, and $\frac{10^6 \text{ m}^2}{5.85 \times 10^{-3} \text{ m}^2}$ is the volumetric scaling factor.

In this model, hydrogen is produced alongside water in the gas (steam) phase. To evaluate the ORC's power generation potential, a volumetric ratio of 30% hydrogen and 70% steam was assumed for the total fluid. This ratio will then determine the total mass rates for the three scenarios using volumetric balance.

2.2 Thermodynamic Modeling

Thermodynamic modeling uses a commercial programming language to evaluate the performance of the Organic Rankine Cycle. The simulation was conducted to predict the power output from the captured thermal energy of wasted heat during the hydrogen generation process and to evaluate its use to power the entire hydrogen generation cycle.

The simulation modeled a closed-loop ORC using R245fa as its organic working fluid, which flows into the turbine so the produced fluid from the reservoir does not contact the turbine, as it is corrosive and could damage it. R245fa is chosen as the working fluid because it has a low boiling point of 15.3 °C, which is ideal for a low-to-medium temperature geothermal system; it has good thermodynamic efficiency, can operate at low operating pressure, is thermally stable, is non-flammable, and is nontoxic (Kong, 2019). The simulation uses CoolProp libraries to obtain fluid properties under different pressure and temperature such as enthalpy, entropy, and fluid density. Since the working fluid used in this study is not water, it is easier to find this property for R245fa using this library.

In addition to fluid properties, the net power output calculation requires the mass of the fluid that will flow into the heat exchanger. This parameter is essential for modeling the heat transfer process within the primary heat sources, which is the produced fluid, with the organic working fluid. By utilizing the volumetric production rates data that we have, we can convert them into the mass flow data. We need to know the fluid density, which we can obtain by calculating it using Equation (5), which is derived based on a unit volume (1 m^3) of multiphase produced fluid.

$$\rho_{total} = (\rho_H \times 0.3 \text{ m}^3) + (\rho_W \times 0.7 \text{ m}^3) \quad (5)$$

Where in the Equation ρ_{total} , ρ_H , and ρ_W is the density of total volume, density of hydrogen, and density of water in kg/m^3 .

2.3 Sensitivity Analysis on Different Decline Rates

Based on the results of data acquisition and field scaling, the highest performing production was selected as the baseline for the next sensitivity analysis. To mitigate the natural decline of hydrogen production and maximize thermal energy recovery, the impact of well restimulation was evaluated. Restimulation can be achieved through mechanical refracturing, catalyst addition, and the use of microorganisms. This section assesses the viability of restimulation as a strategy to extend the projects' lifecycle and maintain self-sustained power generation.

The baseline decline rates were obtained by performing a regression analysis on the baseline dataset chosen in the previous step. The coefficient in the forecasting equation was used as a reference point for the sensitivity analysis, in which the decline rates were varied to evaluate the impact of well-performance improvement on the long-term project.

3. RESULT

This section presents the findings from the 20-year production forecast and the power generation analysis. The main focus is to determine the threshold at which the co-produced thermal energy becomes sufficient to create a self-powered hydrogen production system. Results are categorized by stimulation efficiency, highlighting how restimulation can impact both cumulative hydrogen generation volume and power produced from the Organic Rankine Cycle. The projected hydrogen generation over 20 years at field scale is shown in Table 1.

Table 1: Data acquisition and scaling from laboratory to field scale for hydrogen generation rate

Day	Laboratory Scale	Field Scale		
	Hydrogen generation rate, l (m ³ /day)	Low temp uncatalyzed, q (m ³ /day)	Low temp catalyzed, q (m ³ /day)	High temp catalyzed, q (m ³ /day)
1	3.11327E-08	532.18	1596.55	2660.92
2	1.39383E-07	2382.62	7147.85	11913.08
3	1.52679E-07	2609.90	7829.69	13049.48
4	1.54507E-07	2641.15	7923.46	13205.76
5	1.45576E-07	2488.48	7465.43	12442.39
6	1.36363E-07	2330.99	6992.98	11654.97
7	1.46527E-07	2504.74	7514.23	12523.71
8	1.31018E-07	2239.63	6718.89	11198.15
9	1.43342E-07	2450.29	7350.87	12251.46
10	1.40953E-07	2409.45	7228.36	12047.27
11	1.23593E-07	2112.70	6338.09	10563.48
12	9.60392E-08	1641.70	4925.09	8208.48
13	7.37415E-08	1260.54	3781.62	6302.69
14	6.51927E-08	1114.41	3343.22	5572.03
15	5.62612E-08	961.73	2885.19	4808.65
16	4.73298E-08	809.06	2427.17	4045.28
17	3.83983E-08	656.38	1969.14	3281.91
18	2.94668E-08	503.71	1511.12	2518.53
19	2.05354E-08	351.03	1053.10	1755.16
20	1.16039E-08	198.36	595.07	991.78

Following the data scale-up step, the subsequent phase of this study involves a thermodynamic simulation to quantify the power generation potential of each scenario. The result of this ORC analysis serves as the selection criteria for the potential case, which is then subjected to a sensitivity analysis to optimize and evaluate its long-term operational.

The result of the thermodynamic modeling is presented in Table 3. Initial observations indicate that the low-temperature, uncatalyzed scenario generates insufficient power to support project operations and was therefore excluded from further analysis. According to Angelina's (2025) sustainability criteria for the hydrogen generation cycle to become self-sustaining, a minimum power output of 3 MW is required. While the high-temperature-catalyzed case significantly exceeds this requirement, the results show that restimulation may not be needed for its viability. By then, it was decided that the low-temperature catalyzed case would be selected for the sensitivity analysis, as it represents a marginal production scenario in which restimulation and performance optimization are most likely influencing the ability of this scenario to self-power the hydrogen generation cycle.

To establish a baseline for the sensitivity analysis, the total fluid production rates from the low-temperature catalyzed case were subjected to a regression analysis, as shown in Figure 2. From this analysis, we obtain baseline decline rates of 1675 m³/year. To evaluate the impact of reservoir management strategies, the decline rate was varied to 500 m³/year to simulate an optimized restimulation program and to 2000 m³/year to represent the risk associated with poor reservoir maintenance and rapid depletion.

Table 2: 20 years total fluid production

Year	Total Produced Fluid		
	Low temp uncatalyzed, q_{total} (m3/day)	Low temp catalyzed, q_{total} (m3/day)	High temp catalyzed, q_{total} (m3/day)
1	1773.95	5321.84	8869.73
2	7942.06	23826.17	39710.28
3	8699.65	26098.96	43498.27
4	8803.84	26411.53	44019.21
5	8294.93	24884.78	41474.63
6	7769.98	23309.95	38849.91
7	8349.14	25047.43	41745.71
8	7465.43	22396.30	37327.17
9	8167.64	24502.92	40838.19
10	8031.51	24094.53	40157.56
11	7042.32	21126.96	35211.60
12	5472.32	16416.95	27361.59
13	4201.80	12605.39	21008.98
14	3714.68	11144.05	18573.42
15	3205.77	9617.31	16028.84
16	2696.85	8090.56	13484.26
17	2187.94	6563.81	10939.69
18	1679.02	5037.06	8395.11
19	1170.11	3510.32	5850.53
20	661.19	1983.57	3305.95

Table 2: 20 years power generated from 3 cases

Year	Power Generated, KW		
	Low temp uncatalyzed	Low temp catalyzed	High temp catalyzed
1	368	1103	1839
2	1646	4939	8232
3	1803	5410	9017
4	1825	5475	9125
5	1720	5159	8597
6	1611	4832	8053
7	1731	5192	8653
8	1548	4643	7738
9	1693	5079	8465
10	1665	4995	8324
11	1460	4380	7299
12	1134	3403	5671
13	871	2613	4355

14	770	2310	3850
15	665	1994	3323
16	559	1677	2795
17	456	1367	2268
18	348	1044	1740
19	242	727	1213
20	137	411	685

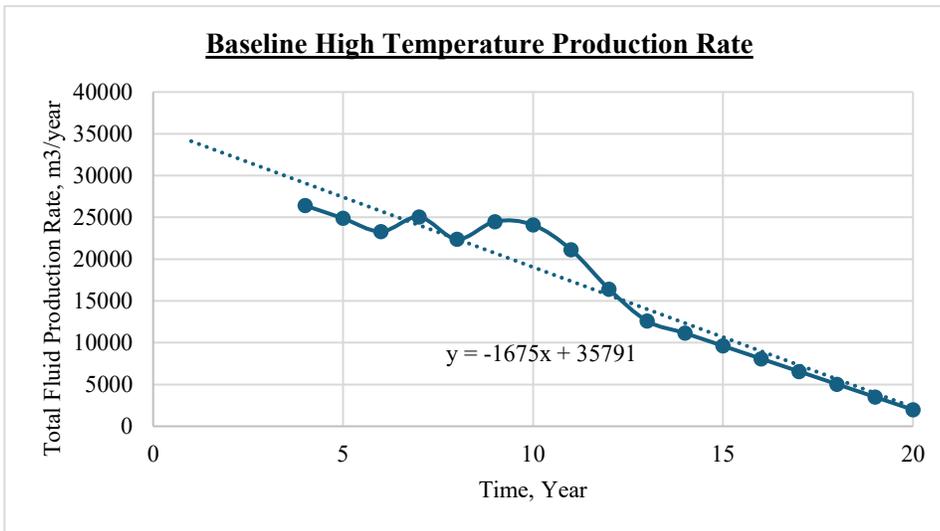


Figure 2: Graph for regression analysis

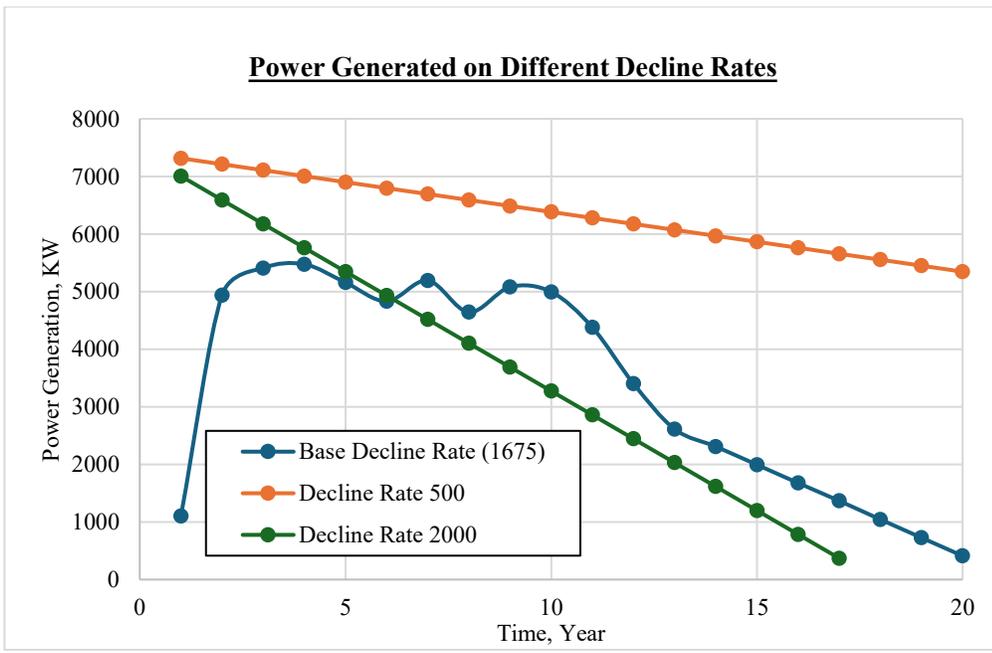


Figure 3: Graph of power generated from the low temperature case with the catalyst and three different decline rates as a sensitivity analysis

3. DISCUSSION

The results of this study show that the transition to a self-sustaining hydrogen production system is technically feasible with the addition of chemical and mechanical restimulation processes. The results indicate that the introduction of a catalyst overcomes this problem of a slow serpentinization process at low temperature. Catalyst helps the slow geochemical reaction by lowering its activation energy.

As shown in the comparison between the uncatalyzed and catalyzed scenarios, the assumed increase in surface area with catalyst addition into the reservoir is the deciding factor in determining the minimum 3 MW power needed, as defined by Angelina (2025). This suggests that the synergy between the chemical reaction and mechanical stimulation of fracturing can improve reservoir performance.

A significant finding in this study is the relationship between the fluid's mass flow and the ORC efficiency. In the high-temperature catalyzed case, the system produced a significant surplus of energy beyond what was required and could last for 15 years of production. While this suggests a high degree of operational safety, it also implies that this high-temperature reservoir will not need aggressive restimulation, potentially lowering long-term operational expenses.

On the other hand, the low-temperature catalyzed case produced power near the 3 MW requirement. This case was then subjected to a sensitivity analysis, which was conducted to highlight the critical relationship between production longevity and reservoir decline management. Varying the decline rate from the baseline of 1,675 m³/year, this study highlights that the technical success of a project depends on the efficiency of reservoir management. When the decline rates were suppressed to 500 m³/year, which represents a successful restimulation program, which could be a secondary catalyst injection, secondary fracturing, or a combination of both, the power output remained consistently above the power required for a self-sustainable project lifecycle of 3 MW. Meanwhile, the decline rate of 2,000 m³/year represents poor management, as shown by the rapid decline in power output. This project can only last for 10 years, because in the upcoming year, the power generated does not exceed 3 MW, and the reservoir stops producing after year 16.

While this study provides a robust framework for evaluating the feasibility of a hydrogen generation cycle for power independence, the model has several limitations, including its reliance on a 30/70 hydrogen-to-steam ratio and a constant fracture aperture that may vary with mineral precipitation over time. Additionally, this evaluation does not include any costs associated with the restimulation process.

In the future, reactive reservoir production modeling will be included to investigate how mineral precipitation could affect 20-year production rates. In addition, a techno-economic analysis (TEA) will be conducted.

4. SUMMARY

This study demonstrates that the use of catalyst-stimulated engineered geological hydrogen systems, combined with waste heat recovery, offers a viable pathway for self-sustainable hydrogen generation from stimulated ultramafic rock systems. Modeling various thermal and chemical scenarios showed that the use of a catalyst and mechanical stimulation are critical factors in overcoming the limitation of low geochemical rates, which is generally a problem in serpentinization. Specifically, reduced activation energy and increased surface area allow the system to meet the 3 MW power threshold required for the project to be self-sustaining. While a high-temperature reservoir (200 °C) offers significant power output, it poses safety issues and has a high capital cost at the beginning of the project. The low-temperature-catalyzed scenario provides a feasible alternative, showing that reservoir decline can be managed through restimulation.

The sensitivity analysis confirms that project longevity is highly dependent on the reservoir's decline rate. A managed decline rate of 500 m³/year ensured that the facility could remain energy-independent throughout its 20-year life cycle. These findings suggest that for engineered geological hydrogen to be commercially competitive, field development strategies must prioritize long-term healthy reservoir monitoring and periodic chemical intervention over initial peak production rates.

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Angelina et al.

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