

Introduction: Chile has more than 300 geothermal areas. The work aims to estimate the electrical potential of high enthalpy systems.

Objectives: Identify the potential of geothermal plays (>200°C) using USGS Method

Method: Based on USGS Method (Heat in Place method) and Monte Carlo approach

Selection of geothermal systems
→ classification
indicated, inferred, measured

Parameters:

- Areas, thickness, temp.
- Volumetric heat capacity
- Abandonment temp.
- Recovery factor
- Condenser temp.
- Electric conversion efficiency
- Plant load factor
- Plant/Project life

Recovery factor
 $R_6 = \frac{q_w}{q_R}$

Single flash power plant
 $m_{stm} = \alpha \frac{T_R - T_{sep}}{h_{g1}(T_{sep})}$

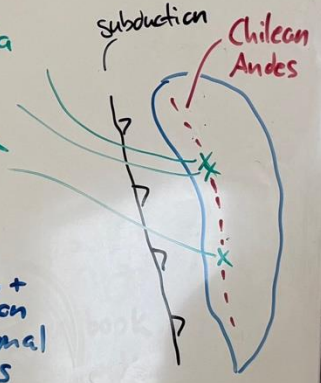
Heat stored in reservoir
 $Q_R = \rho C V (T_R - T_c)$

Monte Carlo approach for variability
100'000 sampling ranges of A, h, Tr, R6

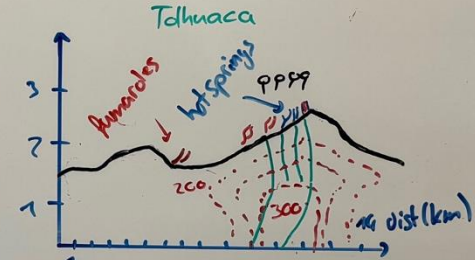
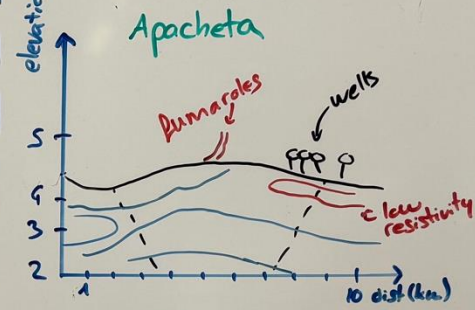
$W_A = m_{stm} (h_{stm} - h_w - T_{EK} (S_{stm} - S_w))$
 $W_e = \frac{W_A \eta_{Lu}}{\gamma_{flood}}$

Results: 3 indicated
6 inferred
65 potential areas

Apacheta
El tatio
Tolhuaca



- Graben
- convection + conduction
- high thermal gradients



- subduction
- 2 reservoirs
- Shallow reservoir
↳ not commercial (<1 MWe)

	Area [km ²]	Thickness [m]	Temp. [°C]	Potential [MWe]	Total [MWe]
Apacheta	4-25	880-1120	212-256	99 ± 58	659 ± 439
El Tatio	11.5-30	150-650	213-260	59 ± 32	
Tolhuaca	4-8	1000-1400	250-300	70 ± 30	

Discussion:

- high incertitude for recovery factor → ⚠ low perm. system
- double flash plant → 15-25% more power output
- if up-flaw zone not reached → temp. could be underestimated
- incertitudes with geology, geothermometers
- Apacheta has extensive surface features → large system, high variability (U, T)

Conclusion:

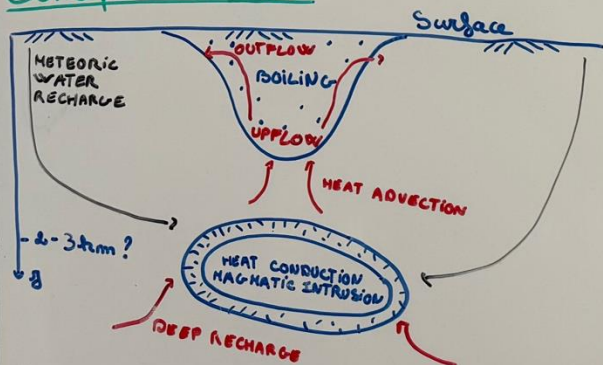
- Electric potential evaluated to 4.4% of the installed electric capacity of Chile
- USGS Method gives a rough estimation of potential + comparison possible
- FEM could give us more accurate results concerning thermodynamics of the system

The thermal structure and temporal evolution of high enthalpy geothermal systems

- Scott; Driesner; Weins 2016, presented by Fallouix; Pierre; Blazy

Introduction Most electricity from geothermal resources comes from high-enthalpy (HE), magma-driven systems
 → Study long-term undisturbed evolution

Conceptual model

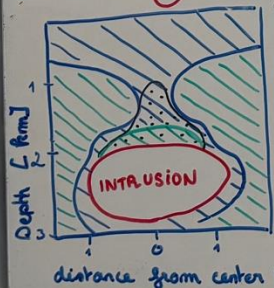


Methods 2D finite elements with parameters that can vary:

- Host rock permeability ranging 10^{-14} - 10^{-16} m² (high, intermediate, low)
- T_{BDT} , Temperature of Brittle Ductile Transition near the intrusion (permeability dependent): 360°, 450°, 550°
- Initial geometry and depth intrusion → 2-3 km to top asymmetric mesh.

Results

① INCIPIENT STAGE (1.5 ka)



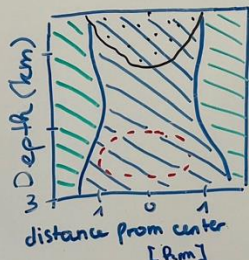
- Upflow plumes begin to rise from the intrusion
- Near-surface temperature remains low

② MAIN STAGE (3 ka)



- Upflow plumes reaches the surface, eliminating cold water resistance
- Vertically continuous boiling zone

③ WANING STAGE (7 ka)



- Temperature in the intrusion (T_{BDT})
- Intrusion becomes permeable so it is very rapidly cooled by fluids
- The top of the system (surface) doesn't change from the main stage
- Temperature inversion ↔

LEGEND

- fluid goes from super-critical to 2 phases conditions
- ▨ liquid flows downward
- ▧ upflow plume
- initial intrusion

• Effect of host rock permeability

- high permeability ($\geq 10^{-14}$ m²) ⇒ more fluid mixing ⇒ shallow boiling (≤ 1 km) ⇒ multiple upflow plumes
- intermediate permeability ($\sim 10^{-15}$ m²) ⇒ boiling zone extends from surface to the intrusion
- low permeability ($\leq 10^{-16}$ m²) ⇒ conduction dominates, convection very low.

• Effect of intrusion geometry

- oblate ⇒ multiple upflow zones
- prolate ⇒ single upflow zone
- Not a key parameter

• Effect of intrusion depth

- Deeper: may develop several plumes. Longer path to the surface ⇒ more cooling
- Best depth $\sim 2-3$ km
- Intrusion deeper than 3 km ⇒ boiling only above ~ 1 km, even in permeable rocks

• Effect of T_{BDT}

- For an increasing T_{BDT} :
- high permeability ⇒ vertically extensive boiling
- intermediate permeability ⇒ large super-critical water zones near the intrusion.

Discussion

• Model vs real: differences

- the simulation is 2D. 3D would be different
- heterogeneities

• Thermal structure & boiling depths

- boiling depth and thickness depend mainly on permeability
- Lateral gradients in temperature and enthalpy reflect distance from the intrusion and are useful in exploration.

• Number & configuration of upflow plumes

- determined by permeability and intrusion geometry
- low permeability = single plume
- high permeability = multiple plumes

• System evolution and lifetime

- The main stage represents only part of a system's lifespan.

• Implication for geothermal exploration

- Permeability & heat source characterization
- Super-critical resource potential
- identifying active heat source
- identifying the natural state: blind resources

Conclusion

- * Permeability = dominant control on
 { thermal structure, boiling depth, system geometry
- * Intrusion depth & geometry affect
 { number of plumes, configuration
- * The stage of the thermal evolution influences thermal signatures at depth
- * The modelling framework provides guidance for exploration
 { identifying super-critical zones, distinguishing incipient/main/waning systems

Hydrothermal characterization of wells GRT-1 and GRT-2 in Rittershoffen, France: Implications on the understanding of natural flow systems in the rhine graben

Barjard, Genter, Dulnaïs, Maerer, Hehn, Rosillette, Vidal, Schmittbuhl

Intro: Description of the implementation of 2 geothermal wells in Rittershoffen (France) to power a bio-refinery

Goal: Characterize a large scale natural hydrothermal system

Methods: Well drilling + measuring + productivity/injectivity test + reservoir stimulation

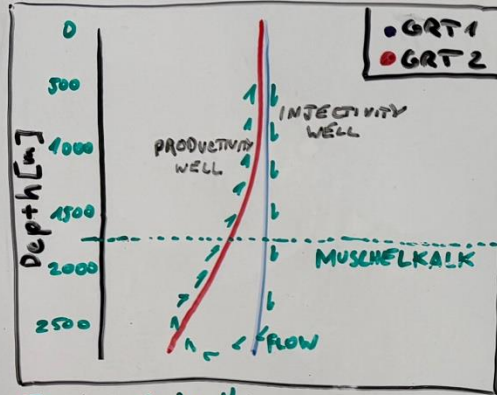


Figure 1 - Wells geometry

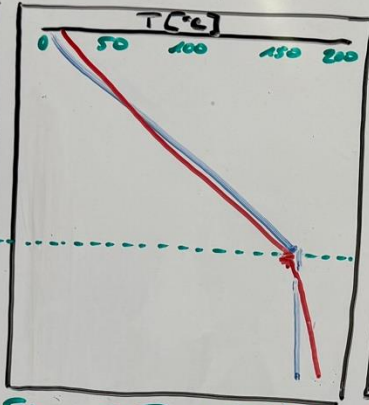


Figure 2 - Temp profiles

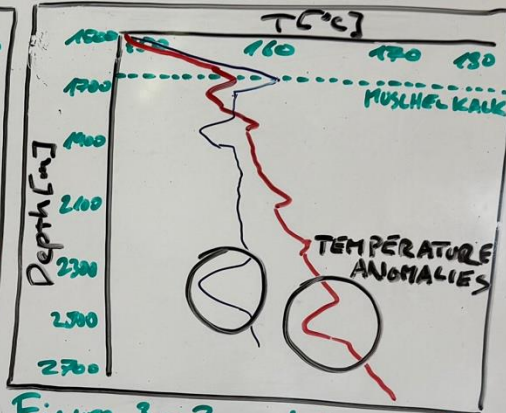


Figure 3 - Zoomed temp. profiles

Results:

	GRT-1	GRT-2
Conductivity $K \frac{m}{s}$	$6 \cdot 10^{-8}$	$5 \cdot 10^{-7}$
Permeability k, m^2	$1 \cdot 10^{-15}$	$9.2 \cdot 10^{-15}$
Rayleigh number Ra	11.1	92.4 (536 for fractures)

Effect of Stimulation on GRT-1:

Productivity values [l/s/bar]:
 0.45 **Thermal** → 1.3 **Chemical + Hydro** → 2.5

Productivity of GRT-2 [l/s/bar]:

between 2.8 and 3.5

Conclusion: Project was judged to be economically viable \$

Discussion:

- From ~1700m: presence of fluids, conduction → convection
- Anomalies in temperature at ~2400m: fluid circulation, possibly connected to reservoir
- Hypotheses for temperature difference between GRT-1 and GRT-2:
 - Shorter cooling period after drilling for GRT-2
 - Upflow in GRT-2, downflow in GRT-1
- Connection of wells to reservoir confirmed through the use of tracers (14 days travel)

TIMELINE

GRT 1

- Drilling operations: 2012
- Prod. tests: Jan 2013
- Ther. stimulation: Apr 2013
- Chemical and hydraulic stimulation: Jun 2013

GRT 2

- Drilling operations: early 2014
- Prod. tests 1: Aug 2014
- Prod. tests 2: Sept 2014
- Prod. tests 3: Sept 2014 - Oct

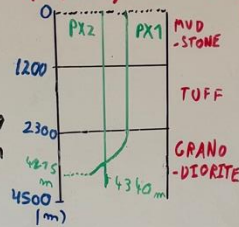
- Stimulation of GRT-1
 - Productivity values much lower than GRT-2
 - Less disruptive methods first
 - Thermal stimulation first to map existing fractures in the reservoir
 - Acceptable levels of induced seismicity (no effects could be felt) - 1.2 and 1.7 on the Richter scale

Observations and analyses of the first two hydraulic stimulations in the Pohang geothermal development site, South Korea

Park, Kim, Xie, Yoo, Min, M. Kim, Yoon, Y. Kim, Zimmermann, Guinot and Meier.

Introduction: EGS require hydraulic stimulation to increase permeability.

This study reports on the initial hydraulic and seismic response of the PX-2 and PX-1 boreholes at the Pohang EGS site to understand the stimulation mechanism and induced earthquake potential.



Methods: Two stimulations:

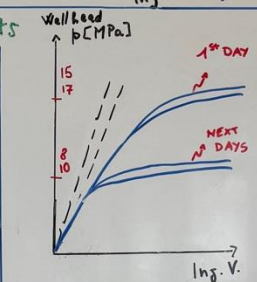
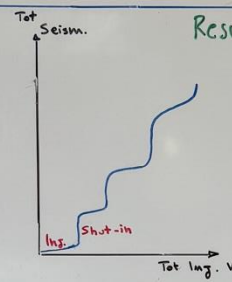
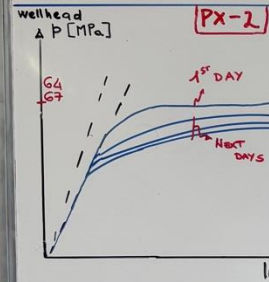
PX-2: Vertical, 4.3 km depth.

PX-1: Inclined, 4.2 km depth.

Separated by ~600 m at the bottom.

Data acquisition: Hydraulic data (WHP, injection rate, injected volume) and seismic data (magnitude and rate).

Analysis: Injectivity was assessed using differential injectivity and wellhead injectivity.



- Transmissivity change: Reversible non-linear, highly pressure-dependent.
- Max seismic event: ML 1.7 (85 h after shut-in).
- Behavior consistent with hydraulic jacking / tensile opening.

- Transmissivity change: More gradual, permanently increased by 6.4 times, less pressure-dependent.
- Max. seismic event: ML 2.2 (27 h and 24 h after shut-in).
- Irreversible aperture increase, shear dilation.

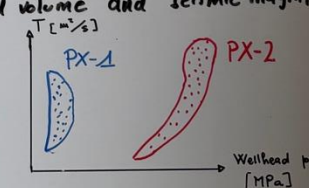
Well	Mechanisms	Cause	Evidence	Discussion
PX-2	Tensile fracture extension + hydraulic jacking.	Heavy mud + LCM.	Abrupt reversible opening at 64-67 MPa.	
PX-1	Shear dilation + hydraulic jacking	Without heavy mud and LCM.	Gradual aperture increase, low operational pressure.	

- Drilling-induced damage
 - PX-2: Extremely low initial transmissivity. Required high-pressure jacking. Heavy mud → clogged natural fractures.
 - PX-1: No heavy mud → undamaged fracture network.

Conclusion

- The stimulations in PX-2 and PX-1 confirmed the complexity of EGS, showing dramatically different hydromechanical characteristics in the same reservoir formation.
- The difference in response between the wells highlights the critical importance of proper drilling and completion operations, with close consideration of the subsequent stimulation strategy, particularly regarding the use of materials like heavy mud and LCM that can damage the reservoir.

• Seismicity: Both wells showed a close correlation between the cumulative injected volume and seismic magnitude



- Similar transmissivity reached, different pressure dependency.

Mineral scaling in two-phase geothermal pipelines: Two case studies

Jamero, Zarrouk, Mroczek (2017)

Intro: Mineral scaling is a common issue in geothermal power facilities. Changes in fluid temperature or chemistry can cause minerals to precipitate, creating deposits that restrict fluid flow, reduce plant efficiency and increase maintenance costs.

Methods: Representative scale samples from multiple locations along the pipelines were examined to determine the mineral composition in order to understand why scaling occurs.

Case study 1: Pad A



- Well 1: high enthalpy, steam-dominated
- Well 2 and 3: liquid-dominated, neutral pH

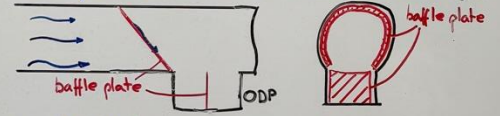
Mineral composition: mostly iron deposits and silica
Small amount of entrained highly-mineralized brine in Well 1 steam mixing with water-dominated fluid of Wells 2 and 3

→ Increase in SSI causes massive scaling.

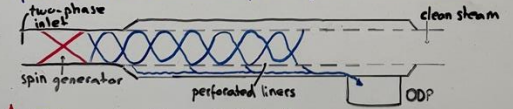
Recommended solutions

Goal: Handling of the small flow rate of brine from Well 1.

- Baffle plates: Redirect side walls flow to ODPs.



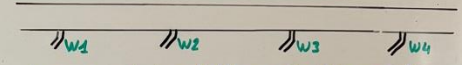
- BLISS/In-line vortex separator: Uses centrifugal force to redirect the droplets against the side walls.



- ⚠ Entrained solids could block the perforated liners.
- Throttling of Well 1: Reduces the entry of super saturated brine in the two-phase header.
- ⚠ Decrease in steam production → lower power output.

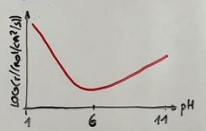
- Branch-line geometry modification:
 - Extension of branch-line: enables droplets to fall down
 - ⚠ Would need to be extremely long.
 - Increase diameter: decreases steam velocity and reduces erosion
 - ⚠ Replacement of existing pipelines

Case study 2: Pad B



- Wells 1 and 4: slightly acidic (pH ~ 5.5)
- Well 2: acidic (pH ~ 3.5), low flow-rate
- Well 3: acidic (pH ~ 3.5), silica saturated (SSI = 1.3)

Mineral composition: mostly silica and iron sulfide.
Change in pH due to mixing of Wells 1 and 3 fluids causes massive silica scaling.



Silica solubility decreases for neutral pH.
Ref.: The mechanism, rate and consequences of basaltic glass dissolution (Oethers, Gislason, 2002).

Recommended solutions

Goal: Handling of the SSI of well 3 before mixing.

- Throttling of well 3: Minimizes its flow to the header.
- ⚠ Well 3 is high enthalpy and high mass-flow rate → lower power output.
- Separate two-phase header: Well 3 could be completely separated from the other wells.
- ⚠ Heavy construction work and additional pipeline.
- pH modification: Acid dosing to return the pH back to 3.5 to keep the silica suspended in the solution.
- ⚠ Corrosion issues + large acid amounts needed.

Conclusion

Mineral scaling in two-phase pipelines is usually due to the mixing of incompatible fluids within a common header. For both pads engineering solutions are available to mitigate scaling, each offering technical benefits but also involving economic or production-related trade-offs.
Geothermal plants require solutions specific to the well layout and well fluid characteristics to reduce scaling.

Abiotic hydrogen generation from biotite-rich granite:

A case study of the Soultz-sous-Forêts [♥] geothermal site, France

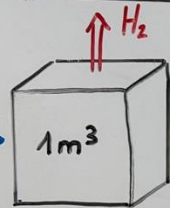
(By Murray, Clément, Fritz, Fleury, Schmittbuhl, Bordmann; 2020)
Tristan SALZMANN, Arnaud TIECHE and Aurora VILLAIN (Group 6)

Introduction: Hydrothermal alteration of a biotite-rich granite could lead to H₂ generation (clean energy source). Some parameters of the reactions have been varied to see their impact on H₂ production.

Method / Modelling approach:

Input solution:

Geothermal
Na-Cl brine
pH = 4.8
T = 130 to 200 °C
Eh = -100 to -300 mV

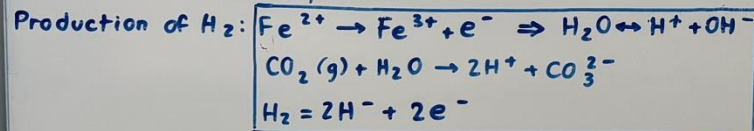


Output solution:

Geothermal
Na-Cl brine

Representative reactive cell: granite

- Depth: 3500 m
- Brine circulating at 6 cm/yr (Darcy rate)
- Porosity: 1%
- Composition: plagioclase, quartz, K-Feldspar, biotite and amphibole



Fe²⁺ and Fe³⁺ (Fe) come from biotite and magnetite.

Results:

Effect of temperature and redox potential:

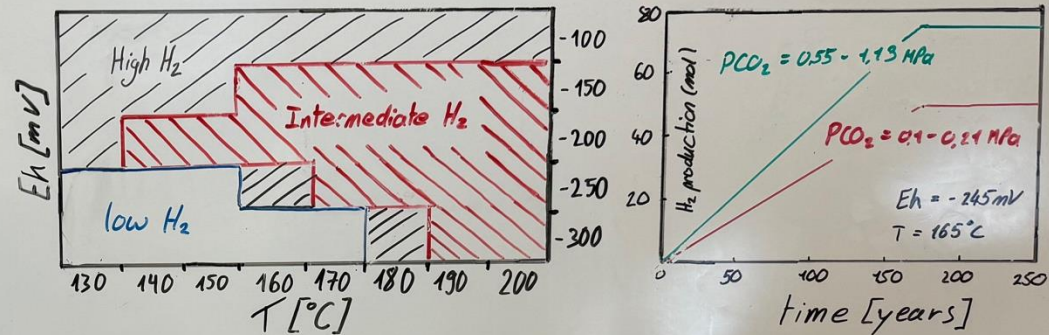
- 3 main zones of H₂ generation
- If P_{CO₂} passes a threshold, H₂ production raises

Hydrogen production:

Temperature, Eh and CO₂ have an impact on H₂ production

Thresholds above which H₂ production increases:

- Eh ≥ -100 mV
 - P_{CO₂} ≥ 0.21-0.55 MPa
- } high H₂ production



Discussions:

- ### Evolution of the brine
- pH stays ~ 5 (CO₂-buffered)
 - Fe released is instantly precipitated
 - Brine composition almost doesn't change

CO₂ effect

More CO₂ → lower pH → higher Eh → more Fe²⁺ oxidation → more H₂ produced

- ### System assumption
- Open system: H₂ escapes → reaction continues
 - Closed system: H₂ accumulates → reaction stops

⇒ Efficient H₂ generation requires open circulation

Comparison with H₂ production during serpentinisation of ultramafic rocks:

- Same Fe-oxidation mechanism
- Ultramafic rocks contain far more Fe²⁺ than granite
- Granite therefore produces less total H₂

Conclusion:

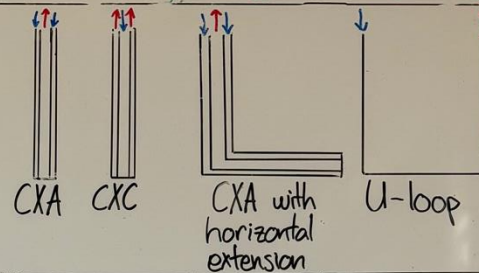
- Volume of the granite reservoir: approx. 1 km³ → 102 kt of H₂ (UB)
- Other possibilities to generate H₂ (e.g. pyrite and radiolysis of water)

Q: How can an EGS serve as an active destabiliser of the biotite in a reservoir given that this mineral has survived over geological time in the quasi-closed system?

TECHNO-ECONOMIC PERFORMANCE OF CLOSED-LOOP GEO-THERMAL SYSTEMS FOR HEAT PRODUCTION AND ELECTRICITY GENERATION

↳ By F. Beckers; Rangel-Jurado; H. Chandrasekar; A.J. Hawkins; P.M. Fulton; J.W. Tester

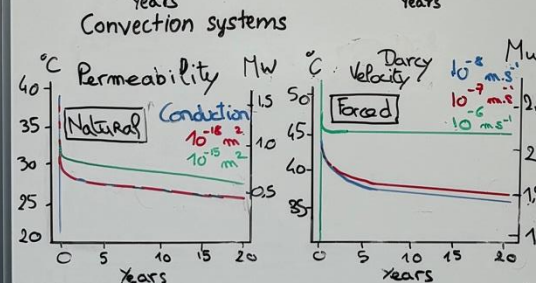
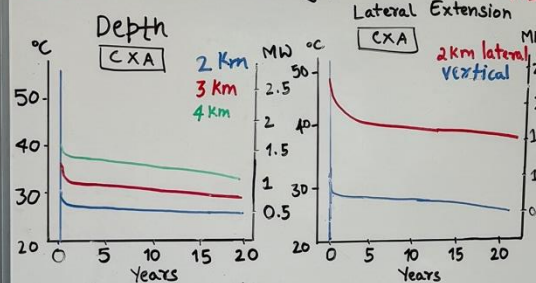
Introduction: Advanced Geothermal Systems (AGS) or Closed-Loop systems, are giant heat exchangers that extract heat from deep rock primarily by conduction without producing or handling geological fluids.
Parameters: Reservoir depth, Temperature, Re-injection temperature, mass flow rate and working fluid.
 Costs assume all wells are drilled from scratch



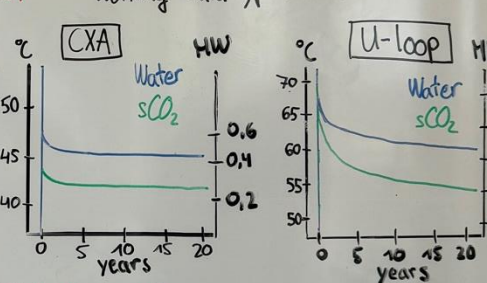
Methodology: 40 test cases with co-axial and U-loop configurations. Heat transfer simulation conducted using:
 a) slender Body Theory (SBT)
 b) COMSOL Multiphysics
 c) Analytical solution for wellbore heat transmission

Goals of AGS:
 • heat extraction from low permeability formations
 • lowering the risk of induced seismicity
 • no reservoir simulation is required
 • reusing abandoned or ill-producing wells

Results: Conduction Systems



HEAT Working fluid type (both)



Capital and Levelized cost of AGS:

Co-axial base case → \$3.4 Million (\$5800/kW)
 U-loop base case → \$8.6 Million (\$4200/kW)
LCOH: Co-axial → \$37/MWh, U-loop → \$52.2/MWh
 Existing geo-thermal systems → \$15 to \$105/MWh
LCOE: Co-axial → \$1315/MWh, U-loop → \$825/MWh
 U-loop system at 500°C, 2km depth, \$200/m drilling cost → \$83/MWh
 Hydrothermal systems → \$60 to \$80/MWh

Electricity production:

• low flow rates (2-2.5 kg/s) and higher injection temperature (~80°C) are required.
 • Average production temperature for the base case is 33°C and 14 kW. With CO₂, we get 23 kW
 • for U-loop, we can have much higher flow rates (10-15 kg/s) with similar electricity production of 51 kW and 32 kW
 • At high temperatures → water is better than CO₂ with an electricity production of 133 kW (104 kW for CO₂) [Co-axial] and 857 kW to 741 kW [U-loop]

Conclusion:

• Conduction → large area of contact with rocks and higher temperature increase production.
 • Convection → output increases but requires higher permeability or Darcy velocities.
 • Drilling cost significantly impact the total capital cost.
 • Considering AGS for heat direct-use is recommended.

SOCIAL SHAPING OF DEEP GEOTHERMAL PROJECTS IN ALSACE: politics, stakeholder attitudes and local democracy.

Authors: Charot, Heimlich, Musseran, Serrano, Zoungbana, Bodin, 2018

Goal: WHAT ARE THE FACTORS THAT INFLUENCE THE ACCEPTANCE OF DEEP GEOTHERMAL PROJECTS?
presented by Colin, Sven and Solène

INTRODUCTION:

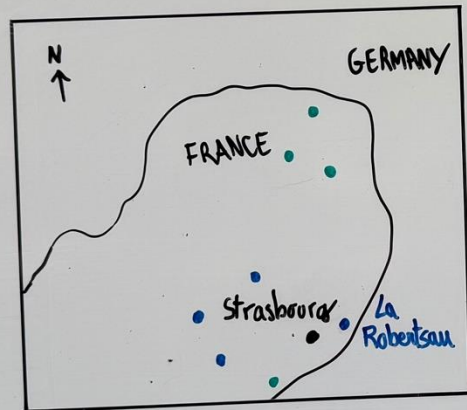
- > State directive law on the energetic transition
Grenelle law => financial support
- ⊕ > EDF: price of geothermal energy: 0,2 €/kWh
- > Not integrated in a regional plan
- ⊖ > Felt too risky
- > Imposed

METHODS:

Sources: Public inquiries, medias, interviews

2 categories of study cases:

- ANCHORED
Project locally developed
- UNBOUND
Project external developed



Northern Alsace map

DISCUSSION:

- Dialog local/promoters + population involvement => ↑ coherence + ↑ acceptance
- Significance of their social identity to build their opinion
- Vulgarisation of the information + adaptation of the project to the region

Oppositions do not come from IRRATIONAL FEARS or SELFISHNESS.

RESULTS:

ANCHORED

UNBOUND

1) Huge effort of dialog

1) No/poor communication

2) Included in the climatic plan of cities

2) No precise energetic plan

3) Part of the social identity
• political parties
• used to drilling projects
→ oil
→ geothermy

3) Impact of politicians
• Encouragement to oppose a project by neighbours
• Willingness of sovereignty restoration
• Against if it's not in their political plan

4) Strategy to revive the industrial sector

4) Assessment errors
→ Oberhausbergen

5) Implication of the local industries

5) Induced risks
• groundwater pollution
• seismicity (hydraulic fracturing)

FOCUS ON LA ROBERTSAU
"do not add risk to risk"

Ingrained militancy
→ social identity

Democratic city
→ no dialog
not appreciated

Home to Strasbourg politicians
→ power mobilisation

Tailor-made risk governance for induced seismicity of geothermal energy projects: an application to Switzerland

by Evelina Tutmevyte and Stefan Wiemer. 2017

Intro: This study aims to develop a clear approach to anticipate and govern induced seismicity risk early in project planning, to support both safe deployment and social acceptability of geothermal energy.

Methods: The authors reviewed past induced-seismicity cases and existing guidelines, then combined Swiss hazard, exposure and governance insights to build simple indicators of how important induced seismicity is for a given geothermal project.



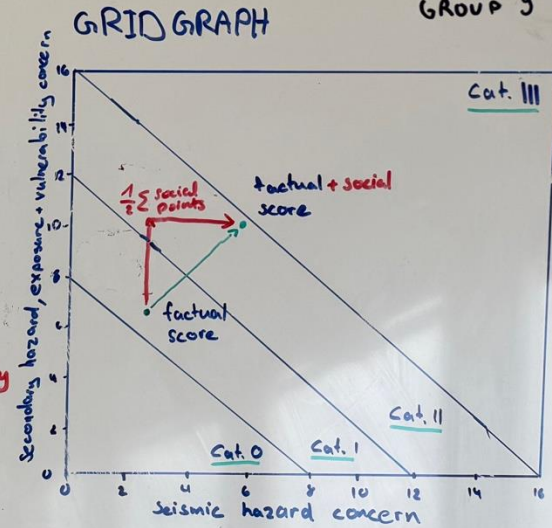
Discussion:

- Applicable everywhere → regional flexibility
- Not a replacement of in-depth risk assessment
- Subjectivity of social concern:
 - ↳ use of a formal evaluation process with multiple independent actors
- Easy to do an early evaluation of a project with GRID → simple indicators
- Hybrid approach: performance and prescriptive

Results:

- **GRID**: Geothermal Risk of Induced seismicity
- Classification of induced seismicity concern in 4 categories, which recommend governance measures.
- Consideration of 3 concern factors:
 - Seismic hazard
 - Secondary hazard, exposure and vulnerability
 - Social
- Who evaluates the GRID?
 - At least 3 independent parties:
 - ↳ project operators, licensing authority and independent experts
- When should GRID be evaluated?
 - Before, during and after the operations

OSCAR, JEAN, AARNE
GROUP 3



- Subdivision of 3 concern factors into indicators
- Each indicator is rated with points:
 - 0 points ↔ little concern
 - 1 point ↔ medium concern
 - 2 points ↔ high concern

Seismic Indicators	Secondary Indicators	Social Indicators
• Injection depth • Injection volume • ...	• exposed population • industrial activity • ...	• Lack of trust • Opposing stakeholders • ...

Governance Measures	Cat. 0	Cat. I	Cat. II	Cat. III
Initial hazard and risk assessment	none	empirical, scenario-based hazard assessment	= Cat. I + scenario-based risk assessment	probabilistic hazard and risk assessment
Social site characterization	none	voluntary	necessary	necessary
Information and outreach on induced seismicity	none	necessary	necessary	necessary
Seismic monitoring	none	single stations	seismic network	seismic network
Traffic light system	none	voluntary, magnitude-based	magnitude-based	adaptive, in parallel to magnitude-based
⋮				

Conclusion: GRID offers a simple way to compare and manage induced seismicity, with transparent and reproducible indicators. As an adaptive tool, GRID should be regularly updated with new science and project experience and expanded to include broader economic, social and environmental considerations.