ROBERT GORDON UNIVERSITY ABERDEEN

Sensitivity Analysis of Operational Parameters on an Advanced Geothermal Energy Storage System

Agga Agga

SPE Geothermal Seminar 2024

Acknowledgements

Special Thanks to

ZeGen Energy

ROSS ENERGY OFFSHORE

Kirsten Pasturel, Kenny Watt, Gillian White (ZeGen Energy)

William Harrar (Ross Offshore DK)

Presentation Outline

1. Project Background
2. Rationale for Project Work
3. Aim & Objectives
4. Methodology
5. Results and Analysis
6. Conclusions & Recommendations

Project Background

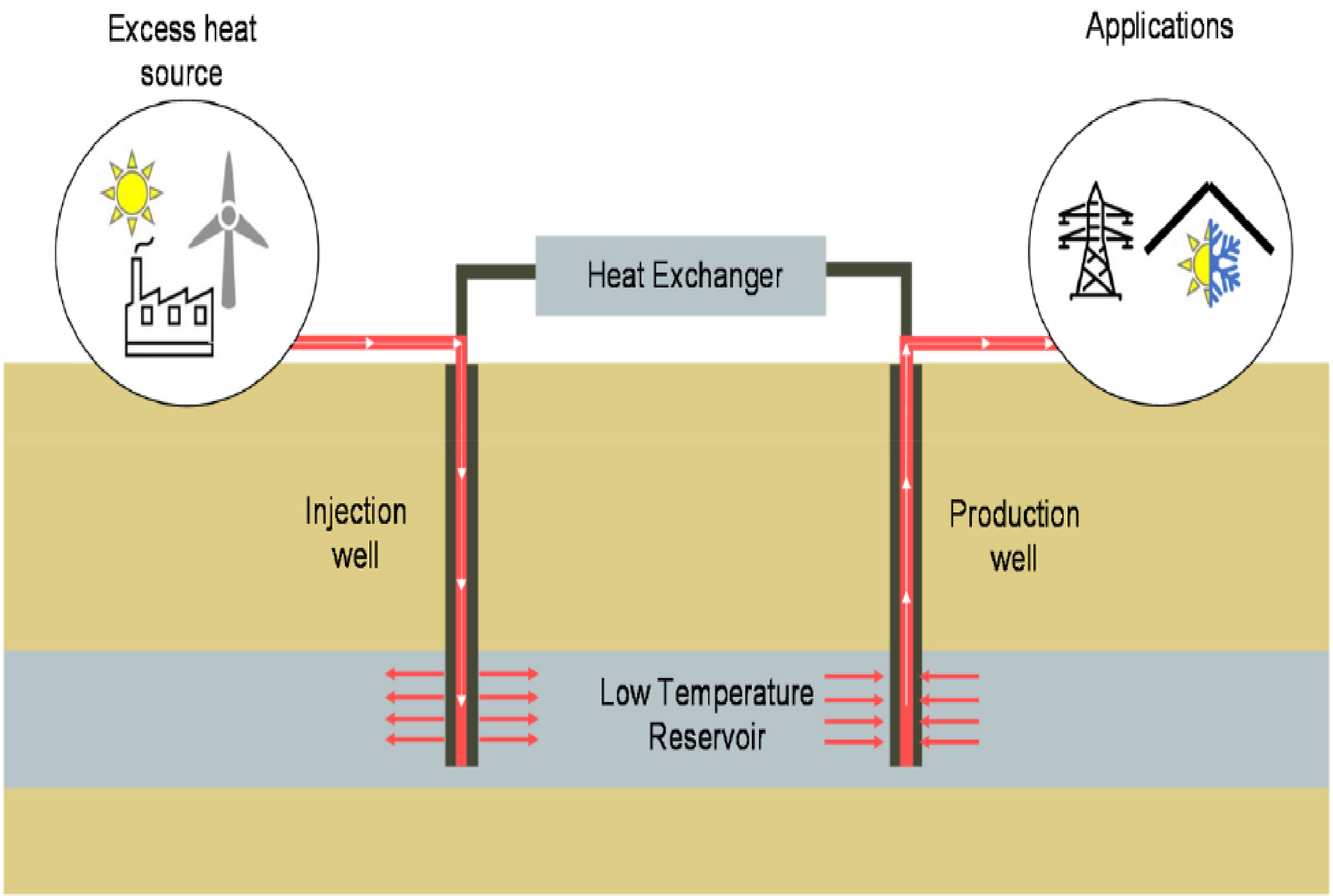


Fig 1 – A basic conceptual model of an AGES system (Jello et al. 2022)

- Ability to Store Energy
  - Thermal Energy → Subsurface Reservoirs
- Numerous Methods and Nomenclature
- Thermal Energy Storage Principle

Rationale for Project Work

- General Mismatch in Energy Generation and Energy Use
  - Lack of Transmission Availability and System Balancing Challenges (Bird et al. 2016)

Table 1 – Statistics for Curtailment of Wind Energy for countries in 2013 (Bird et al. 2016)

COUNTRY	Canada	China	Denmark	Germany (2012)	Ireland	Italy	Japan	Portugal	Spain	Sweden	United States
Electricity Generation (TWh)*	560	5,372	35	577	26	290	950	52	284	153	4,066
Wind Generation (GWh)	17,500	142,000	11,100	50,600	5,872	14,811	4,000	11,900	54,338	9,900	167,840
Wind/Electricity Generation	3.1%	2.6%	31.9%	9.8%	22.5%	5.1%	0.4%	23.0%	19.2%	6.5%	4.1%
Wind Curtailment (GWh)	-	16,230	-	358	196	152	-	-	1,166	-	-
Wind Curtailment/Generation	-	11%**	-	0.7%	3%	1%	-	-	2%	-	1-3%**

*Electricity generation statistics were sourced from national/regional resources for each country. Canadian energy generation values and wind generation data were sourced from the IEA Wind 2013 Annual Report [23]. European countries, including Denmark, Ireland, Italy, Portugal, Spain, and Sweden were sourced from total gross electricity generation statistics provided by Eurostat [24]. China electricity generation was sourced from the China Electricity Council [25]. Germany electricity generation was sourced from a 2013 monitoring report from Bundesnetzagentur [7]. Electricity generation information for Japan [26] and the United States [27] was sourced from the U.S. Energy Information Administration.

**Curtailment levels vary across individual balancing areas.

Curtailment ✗

Heat Up Injection Fluid ✓

Aim

Propose Optimum Field Development Strategy for Implementation of AGES System

Objectives

- Develop
  - Static Reservoir Model
  - Dynamic Reservoir Model

- Identify Key Operational Parameters
  - Injection/Production Mass Flow Rate
  - Injection Fluid Temperature
  - Maximum Cycle Part Durations
  - Well Patterns

- Sensitivity Analysis
  - Technical Yardsticks
    - Thermal Storage Energy Efficiency
    - Average Power and Electricity Generation
  - Economic Yardsticks
    - Net Present Value (NPV)
    - Levelized Cost of Energy (LCOE)

Methodology – Drainage Area of Study

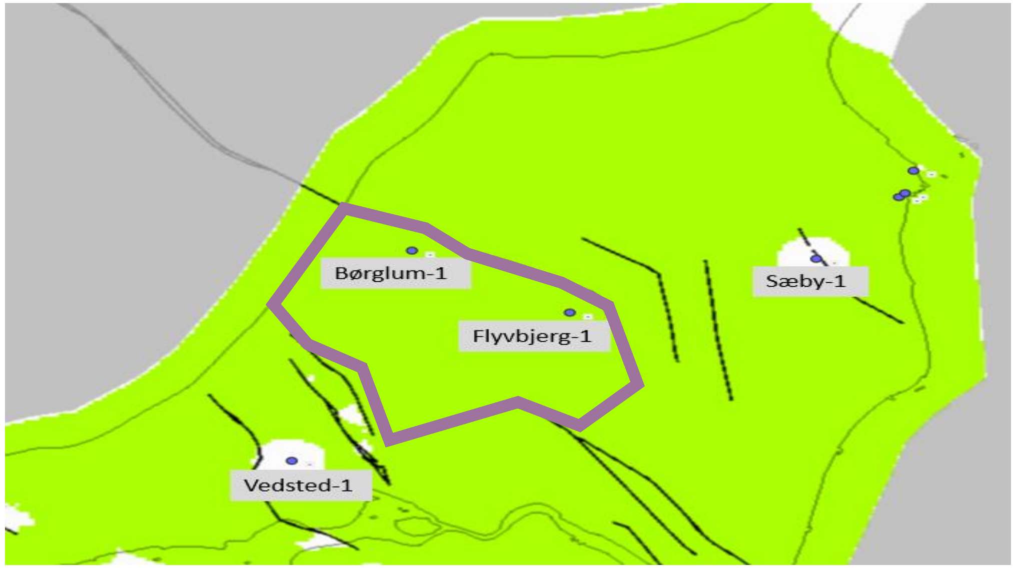


Fig 2 – Wells that Penetrate the Gassum Formation (GEUS 2023)

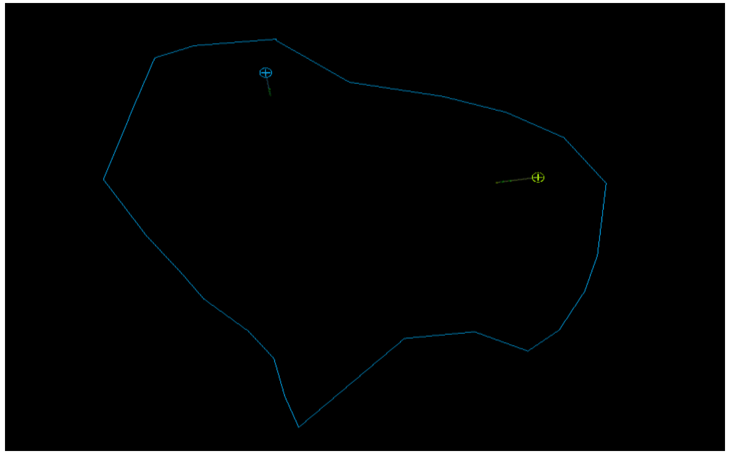


Fig 3 – Assumed Combined Drainage Area

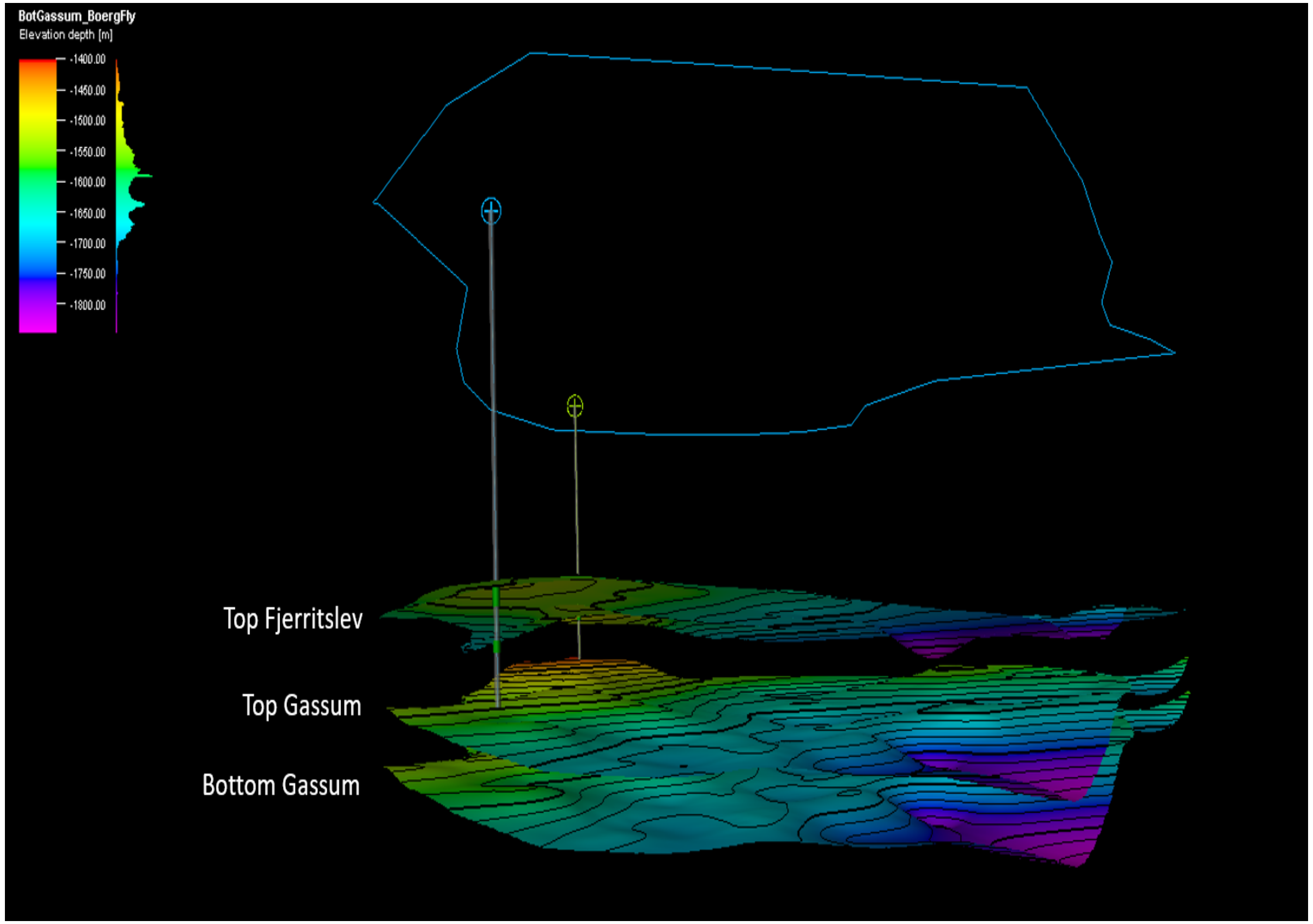


Fig 4 – Formation Surface Tops for the Assumed Combined Drainage Area

Methodology – Reservoir Modelling

Table 2 – Average reservoir properties of the Gassum Formation penetrated by Borglum-1 and Flyvberg-1 as analysed by GEUS 2023

Properties	Borglum-1	Flyvberg-1
Average Porosity (%)	29.3	-
Avg Reservoir Temperature (degC)	44	42
Formation Thickness (m)	155	197
Potential Sands (m)	82	-

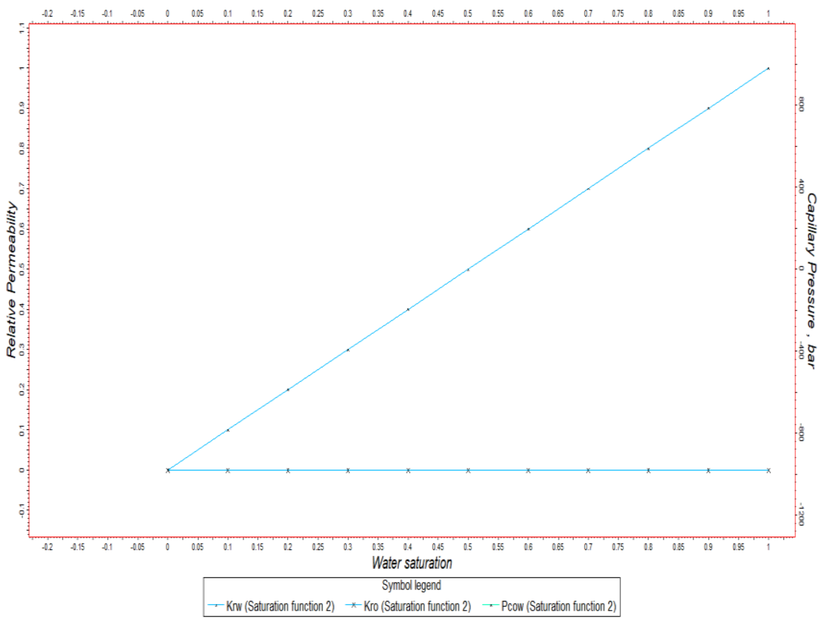


Fig 6 – Single Phase 'Rel-Perm' Curve

Table 3 – Initialisation Conditions

Initialisation Conditions	Values
Datum Depth -FWL	-972 m
Pressure at Datum Depth	102.6597 bar
Capillary Pressure at FWL	0 bar
Geothermal Gradient	27 degC/km

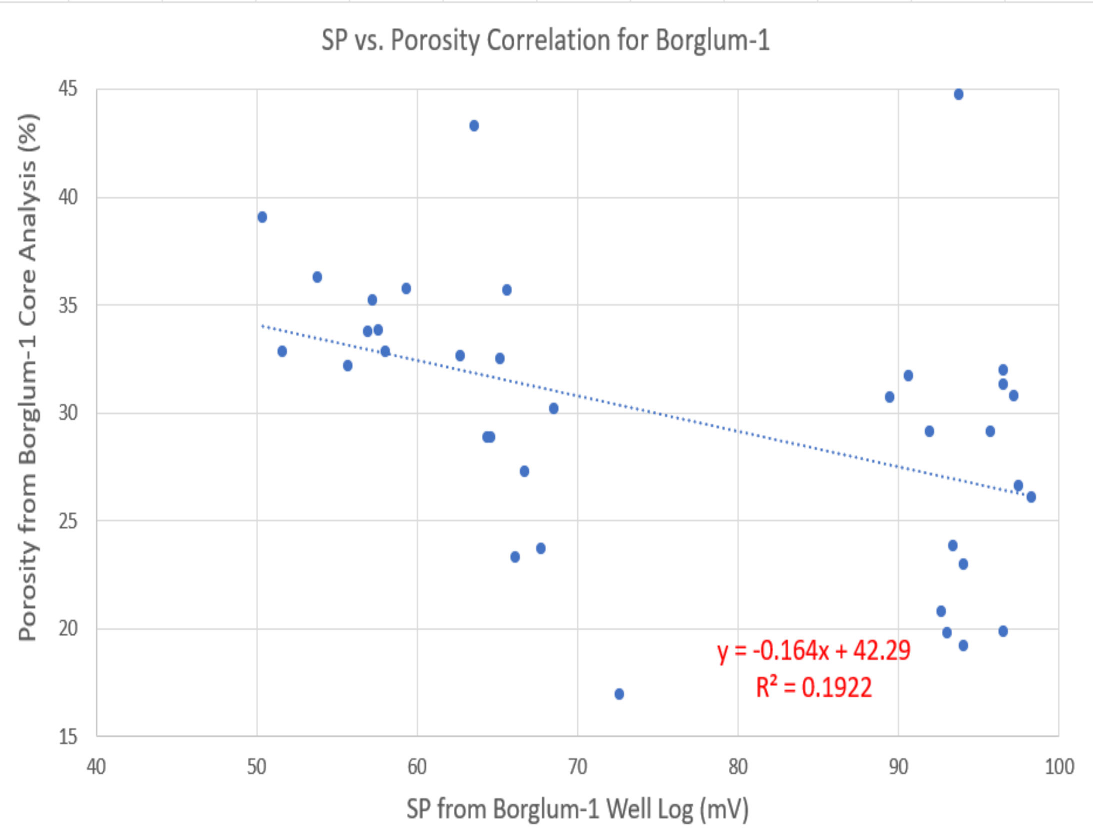


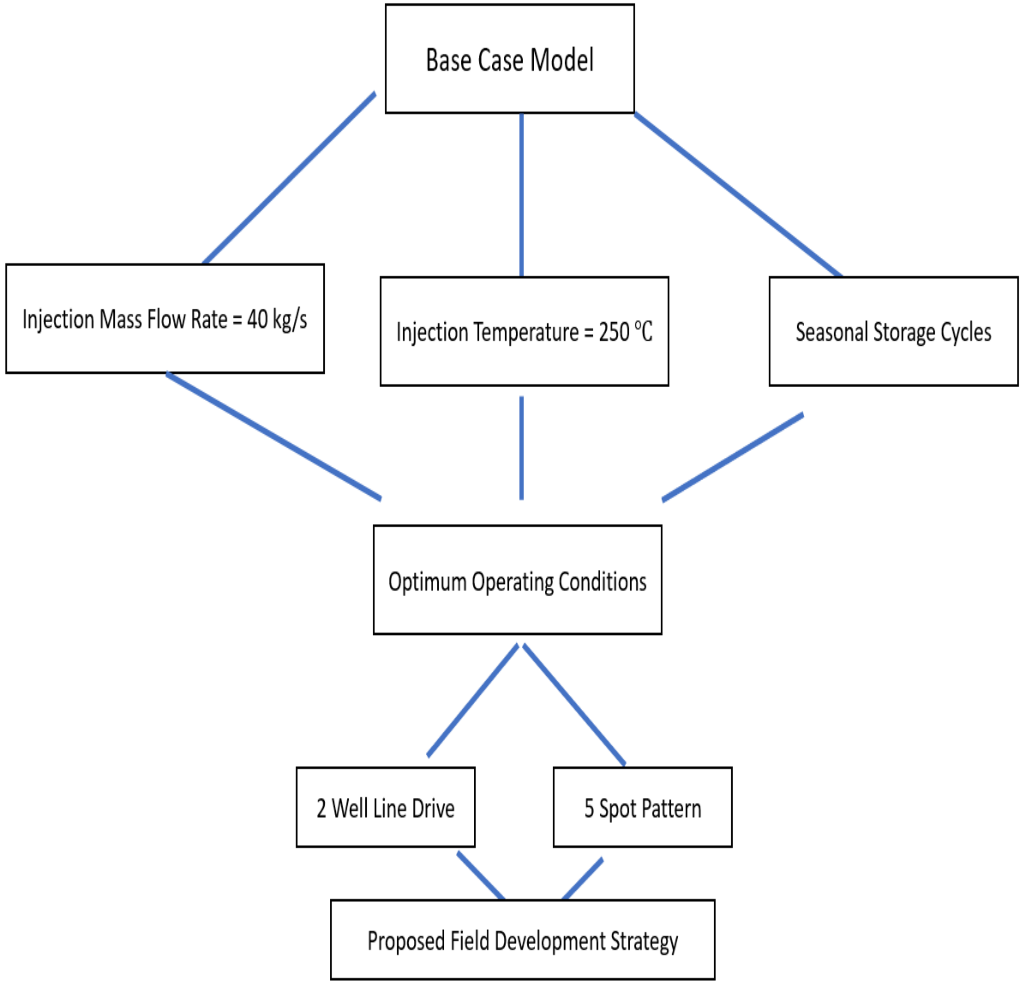
Fig 5 – SP vs. Porosity Correlation for Borglum-1 Well

Methodology – Sensitivity Analysis

Table 4 – Operating Conditions for Different Simulation Cases

Operation Conditions	Base Case Model	Case 1	Case 2	Case 3
Injection Mass Flow Rate (kg/s)	10	40	10	10
Injection Fluid Temperature (degC)	90	90	250	90
Production Mass Flow Rate Limit (kg/s)	10	40	10	10
Charging Period (days)	60	60	60	60
Well Pattern	2 Well Line Drive	2 Well Line Drive	2 Well Line Drive	2 Well Line Drive
Strategy	Borglum-1 Inj, Flyvberg-1 Prod	Borglum-1 Inj, Flyvberg-1 Prod	Borglum-1 Inj, Flyvberg-1 Prod	Seasonal Storage Both Wells

Fig 7 – Schematic of Decision Tree for Sensitivity Analysis



Methodology – Technical and Economic Yardsticks

$$\eta_s = \frac{M_{prod}}{M_{inj}}$$

$$M_{prod} = \int_{t_1}^{t_2} (\dot{q}_{prod} h_{prod})\, dt$$

Equation Set 1 – Thermal Storage Energy Efficiency (Zheng et al. 2014)

$$W_e = 0.45\, f\, W_h$$

$$f = 1 - \left(\frac{T_{rej}}{T_{prod}}\right)$$

$$W_h = \dot{q}_{prod}\, h_{prod}$$

Equation Set 2 – Average Electric Power Generation (Jello et al. 2022)

Table 5 & 6 – CAPEX and OPEX (Wendt et al. 2019)

Description	UNIT	UNIT COST ($)
Cost of AGES well	LOT	$ 2,000,000.00
Cost of Water Injection Facilities	LOT	$ 3,000,000.00
Land Cost	LOT	$ 2,000,000.00

Description	Cost
Operation & Mainteance: Energy Source	$7/MWh
Operation & Maintenance: Facilities	$25/MWh
Water Injection Cost	$0.001/kg

$$NPV = \sum \frac{Cash\ Flow, Year\ n}{(1+r)^n}$$

$$LCOE = \frac{NPV, Project\ Costs\ (\$)}{NPV, Electricity\ Produced\ (kWh)}$$

Equation Set 3 – Economic Yardsticks (Wendt et al. 2019, Jello et al. 2022)

Results & Analysis – Reservoir Models

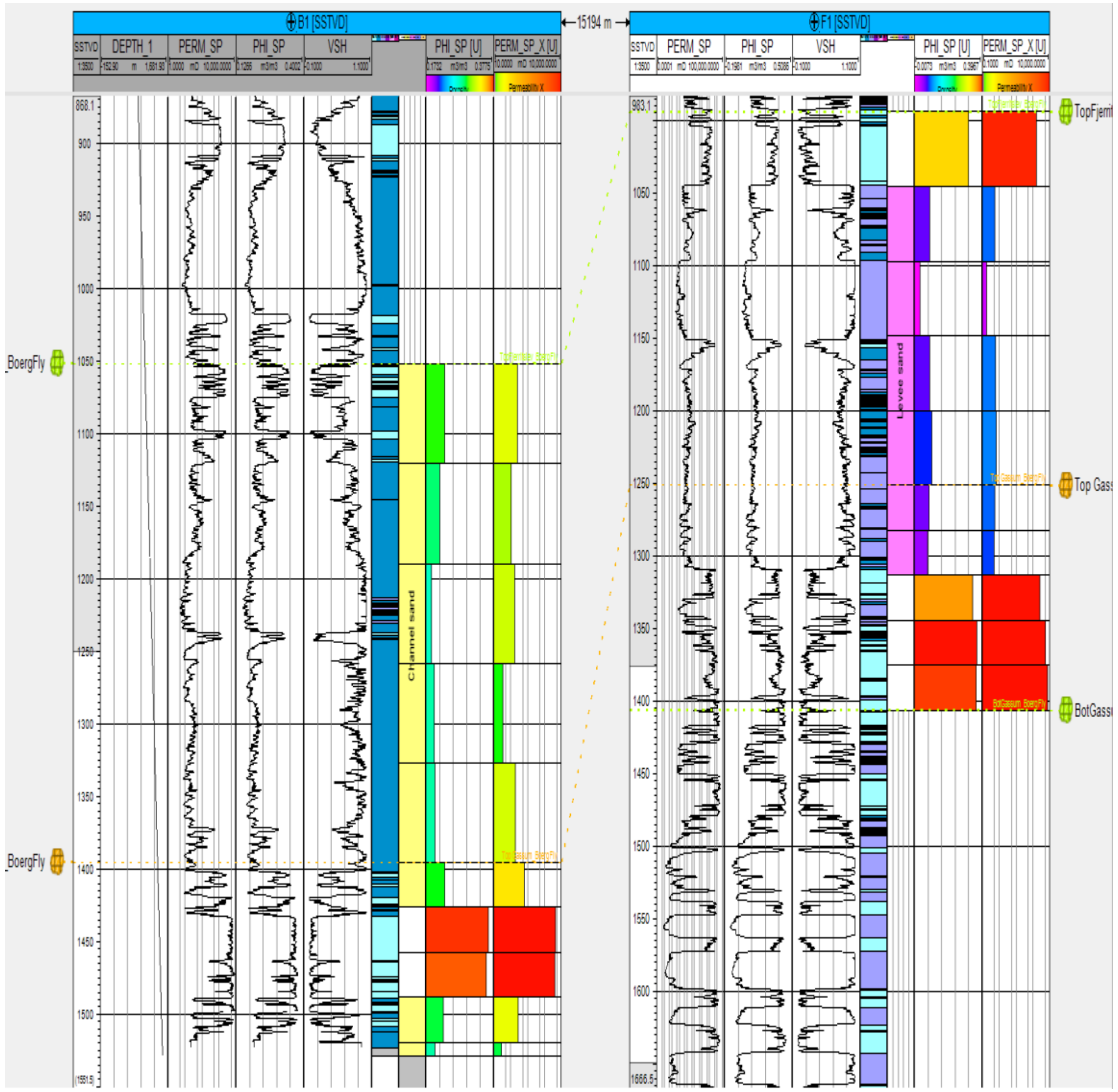


Fig. 8 – Calculated and Generated Petrophysical Well Logs

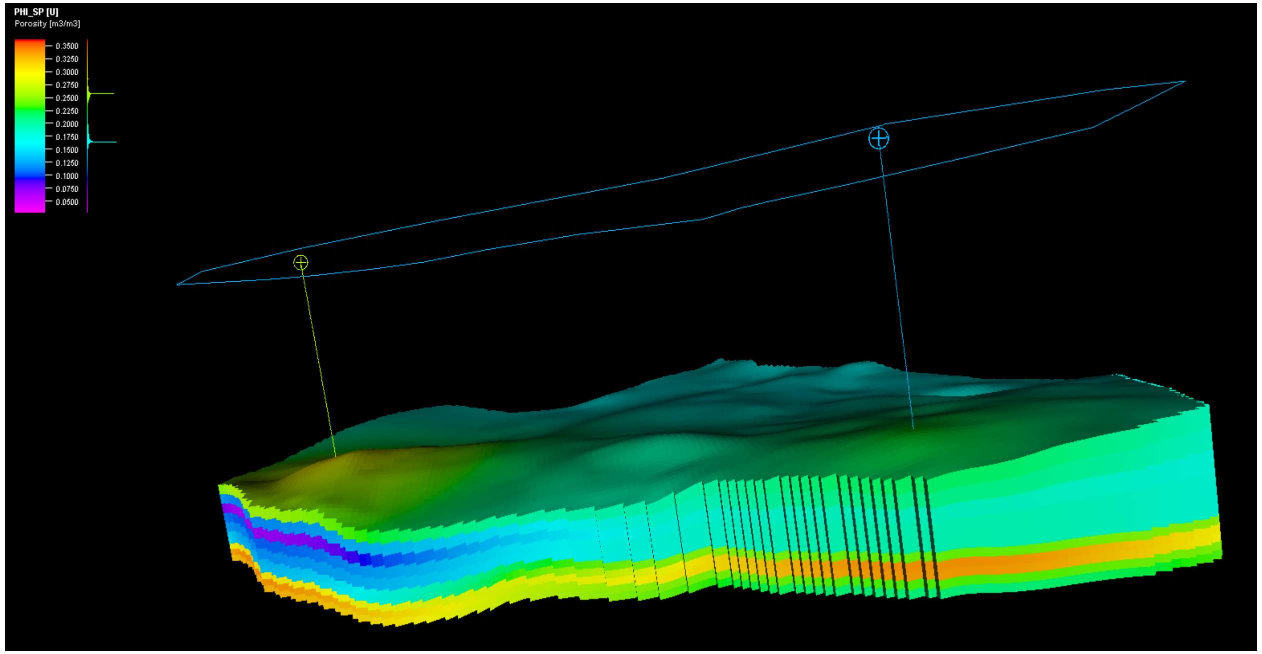
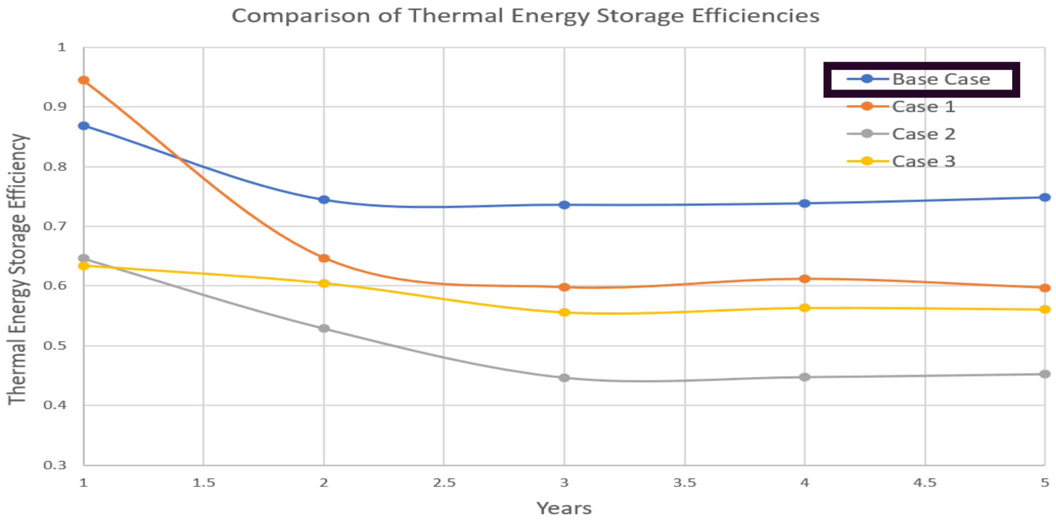


Figure 9 – Reservoir Model of Porosity (PHI_SP)

Table 7 – Critical Comparison of Petrophysical Properties

Gassum Formation	Static Reservoir Simulation		GEUS & Literature	
Petrophysical Properties	Range	Average	Range	Average
Porosity (%)	6.91-36.3	25.78	27.2-31.4	29.3
Permeability (mD)	0.7069-6585	2346	1000-10000	5000
Volumetric Heat Capacity (MJ/m^3K)	2.113-2.762	2.529	2-2.5	*
Thermal Conductivity (W/mK)	3-3.99	3.5	3-4	*

Results and Analysis – Simulation Cases



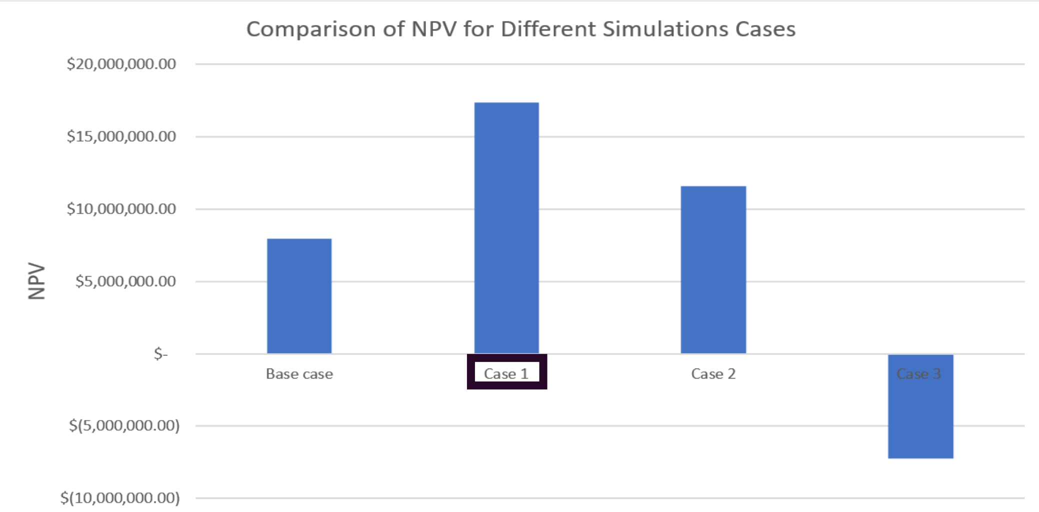
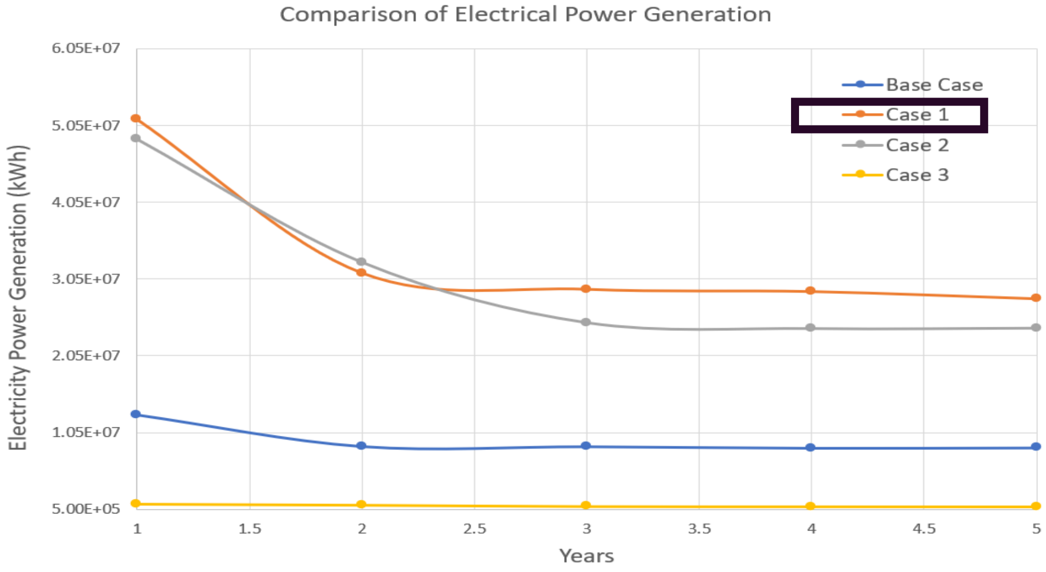
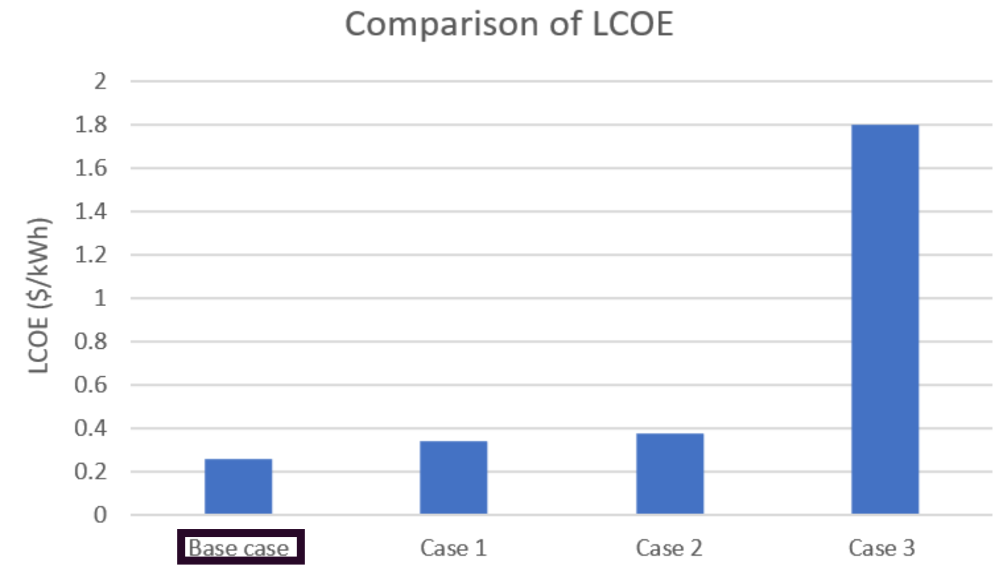


Fig 10 & 11 – Technical Yardsticks Applied to Simulation Results

Fig 12 & 13 – Economic Yardsticks Applied to Simulation Results





Results and Analysis – Field Development Plan

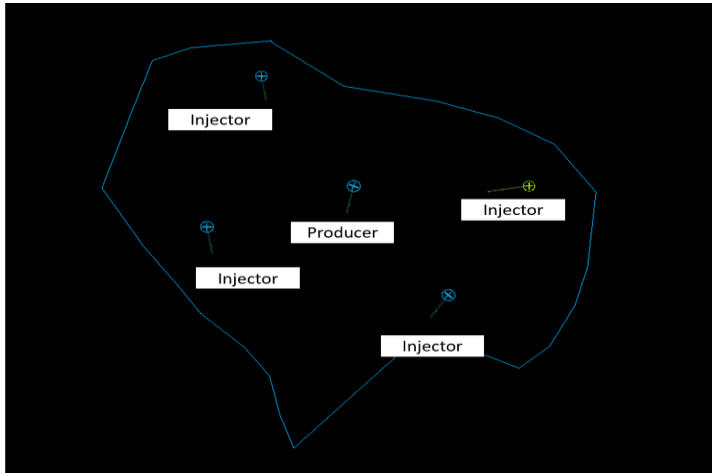


Fig 14 – 5 Spot Well Pattern on Assumed Drainage Area

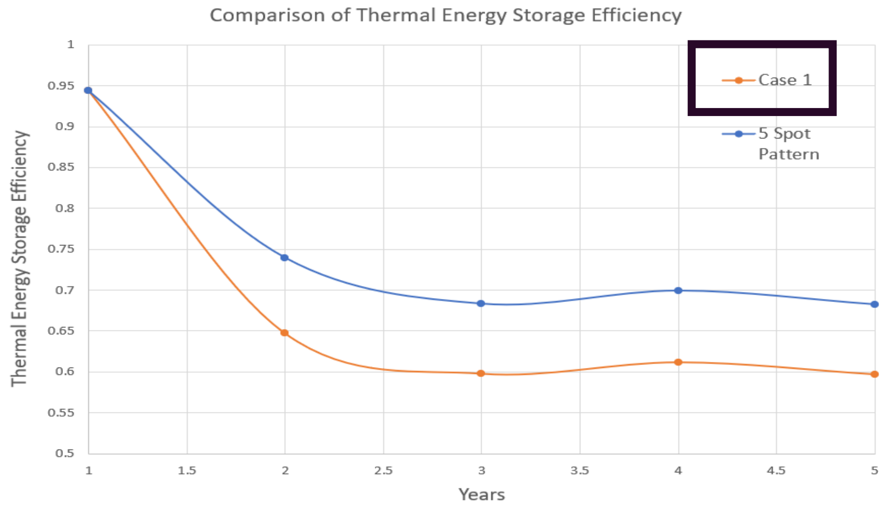


Fig 15 – Case 1 vs. 5 Spot Pattern Thermal Energy Storage Efficiency

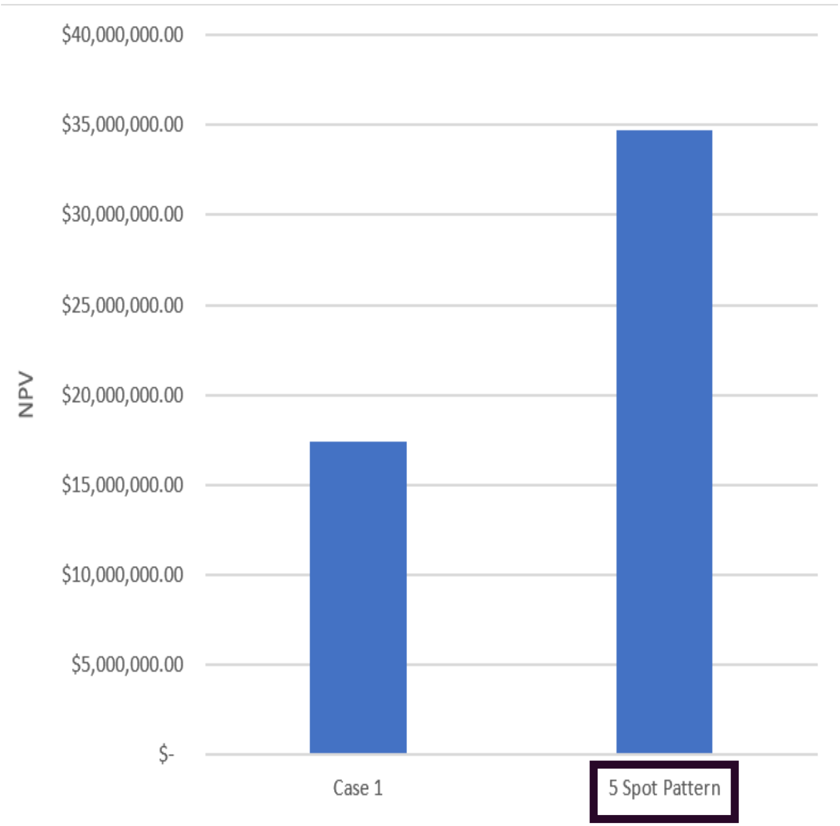


Fig 16 – Case 1 vs. 5 Spot Pattern NPV

- 5-Spot
  - 4 Injector, 1 Producer
- Injection Mass Flow Rate
  - 40 kg/s for each well
- Injection Fluid Temp.
  - 90 °C
- Charging Period
  - 3 months before production

Conclusions & Recommendations

- AGES is Novel and Unique
  - Combatting issues of Energy Storage and Curtailment of Energy
  - Implementation of AGES in Conjunction with Renewable Energy System → Flexibility
- Optimum Field Development Plan
  - Injection Fluid Temperature = 90 °C
  - Injection Mass Flow Rate = 40 kg/s
  - 5 Spot Well Pattern
  - 3 Months Charging Period
- Technical and Economic Yardsticks
  - Thermal Energy Storage Efficiency – 70%
  - Average Power Generation – 150 mn kWh
  - NPV – US$35 Million
  - LCOE – 0.4 $/kWh
- Further Studies
  - Cost Analysis Considering Incremental CAPEX
  - Adding extra petrophysical properties

References

BIRD, L., 2016. Wind and solar energy curtailment: A Review of international experience. Renewable and Sustainable Energy Reviews, 65(2016), pp. 577-586.

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND, 2023. Geothermal energy WebGIS portal. [online]. Available from: https://data.geus.dk/geoterm/ [Accessed 25 August 2023].

JELLO, J. et al., 2022. Advanced geothermal energy storage systems by repurposing existing oil and gas wells: A full-scale experimental and numerical investigation. Renewable Energy, 199(2022), pp. 852-865.

WENDT et al., 2019. Flexible Geothermal Power Generation utilizing Geologic Thermal Energy Storage. Idaho National Laboratory: Idaho Falls, Idaho.

ZHENG, Q., 2014. Design of a high-temperature subsurface thermal energy storage system. Clemson University Tiger Prints, 5(2014).

Thank you