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

Agga Agga

SPE Geothermal Seminar 2024
Special Thanks to

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

- Ability to Store Energy
  - Thermal Energy → Subsurface Reservoirs

- Numerous Methods and Nomenclature

- Thermal Energy Storage Principle

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

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

*Electricity generation statistics were sourced from national/regional sources 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.
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
Table 2 – Average reservoir properties of the Gassum Formation penetrated by Borglum-1 and Flyvberg-1 as analysed by GEUS 2023

<table>
<thead>
<tr>
<th>Properties</th>
<th>Borglum-1</th>
<th>Flyvberg-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Porosity (%)</td>
<td>29.3</td>
<td>-</td>
</tr>
<tr>
<td>Avg Reservoir Temperature (degC)</td>
<td>44</td>
<td>42</td>
</tr>
<tr>
<td>Formation Thickness (m)</td>
<td>155</td>
<td>197</td>
</tr>
<tr>
<td>Potential Sands (m)</td>
<td>82</td>
<td>-</td>
</tr>
</tbody>
</table>

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

Fig 6 – Single Phase ‘Rel-Perm’ Curve

Table 3 – Initialisation Conditions

<table>
<thead>
<tr>
<th>Initialisation Conditions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datum Depth - FWL</td>
<td>-972 m</td>
</tr>
<tr>
<td>Pressure at Datum Depth</td>
<td>102.697 bar</td>
</tr>
<tr>
<td>Capillary Pressure at FWL</td>
<td>0 bar</td>
</tr>
<tr>
<td>Geothermal Gradient</td>
<td>27 degC/km</td>
</tr>
</tbody>
</table>
## Methodology – Sensitivity Analysis

### Table 4 – Operating Conditions for Different Simulation Cases

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

### Fig 7 – Schematic of Decision Tree for Sensitivity Analysis

- **Base Case Model**
- **Injection Mass Flow Rate = 40 kg/s**
- **Injection Temperature = 250 °C**
- **Seasonal Storage Cycles**
  - 2 Well Line Drive
  - 5 Spot Pattern

**Optimum Operating Conditions**

**Proposed Field Development Strategy**

- **2 Well Line Drive**
- **5 Spot Pattern**

**Table 4 – Operating Conditions for Different Simulation Cases**


- **Base Case Model**: Injection Mass Flow Rate 10 kg/s, Injection Fluid Temperature 90 degC, Production Mass Flow Rate Limit 10 kg/s, Charging Period 60 days, Well Pattern 2 Well Line Drive, Strategy Borglum-1 Inj, Flyvberg-1 Prod.

- **Case 1**: Injection Mass Flow Rate 40 kg/s, Injection Fluid Temperature 90 degC, Production Mass Flow Rate Limit 10 kg/s, Charging Period 60 days, Well Pattern 2 Well Line Drive, Strategy Borglum-1 Inj, Flyvberg-1 Prod.

- **Case 2**: Injection Mass Flow Rate 10 kg/s, Injection Fluid Temperature 250 degC, Production Mass Flow Rate Limit 10 kg/s, Charging Period 60 days, Well Pattern 2 Well Line Drive, Strategy Borglum-1 Inj, Flyvberg-1 Prod.

- **Case 3**: Injection Mass Flow Rate 10 kg/s, Injection Fluid Temperature 90 degC, Production Mass Flow Rate Limit 10 kg/s, Charging Period 60 days, Well Pattern 2 Well Line Drive, Strategy Both Wells.
Methodology – Technical and Economic Yardsticks

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

\[ \eta_s = \frac{M_{prod}}{M_{inj}} \]
\[ M_{prod} = \int_{t_1}^{t_2} (q_{prod} h_{prod}) \, dt \]

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

\[ W_e = 0.45 \, f \, W_h \]
\[ f = 1 - \left( \frac{T_{rej}}{T_{prod}} \right) \]
\[ W_h = q_{prod} \, h_{prod} \]

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

\[ NPV = \sum \frac{\text{Cash Flow, Year } n}{(1 + r)^n} \]
\[ LCOE = \frac{NPV, Project Costs (\$)}{NPV, Electricity Produced (kWh)} \]

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

<table>
<thead>
<tr>
<th>Description</th>
<th>UNIT</th>
<th>UNIT COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of AGES well</td>
<td>LOT</td>
<td>$2,000,000.00</td>
</tr>
<tr>
<td>Cost of Water Injection Facilities</td>
<td>LOT</td>
<td>$3,000,000.00</td>
</tr>
<tr>
<td>Land Cost</td>
<td>LOT</td>
<td>$2,000,000.00</td>
</tr>
<tr>
<td>Operation &amp; Maintenance: Energy Source</td>
<td></td>
<td>$7/MWh</td>
</tr>
<tr>
<td>Operation &amp; Maintenance: Facilities</td>
<td></td>
<td>$25/MWh</td>
</tr>
<tr>
<td>Water Injection Cost</td>
<td></td>
<td>$0.001/kg</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Gasum Formation</th>
<th>Static Reservoir Simulation</th>
<th>GEUS &amp; Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrophysical Properties</td>
<td>Range</td>
<td>Average</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>6.91-36.3</td>
<td>25.78</td>
</tr>
<tr>
<td>Permeability (mD)</td>
<td>0.7069-6585</td>
<td>2346</td>
</tr>
<tr>
<td>Volumetric Heat Capacity (MJ/m^3K)</td>
<td>2.113-2.762</td>
<td>2.529</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>3-3.99</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Results and Analysis – Simulation Cases

**Fig 10 & 11 – Technical Yardsticks Applied to Simulation Results**

Comparison of Electrical Power Generation

- Comparison of Thermal Energy Storage Efficiencies
- Comparison of NPV for Different Simulations Cases
- Comparison of LCOE

**Fig 12 & 13 – Economic Yardsticks Applied to Simulation Results**
Results and Analysis – Field Development Plan

- 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


Thank you