Recoverable Resource Estimate of Identified Onshore Geopressed Geothermal Energy in Texas and Louisiana

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Geopressed Geothermal Resource

• **Geopressed Geothermal**
  - Reservoirs characterized by pore fluids under high confining pressures and high temperatures with correspondingly large quantities of dissolved methane
  - Soft geopressure: Hydrostatic to 15.83 kPa/m
  - Hard geopressure: 15.83–22.61 kPa/m (lithostatic pressure gradient)

• **Common Geopressed Geothermal Reservoir Structure**
  - Upper thick low permeability shale
  - Thin sandstone layer
  - Lower thick low permeability shale

• **Three Potential Sources of Energy**
  - Thermal energy (Temperature > 100°C – geothermal electricity generation)
  - Chemical energy (natural gas)
  - Mechanical energy (pressurized fluid)
Introduction

Motivation

• The Gulf Coast geopressured geothermal resource is the most extensive of any region in the United States

Goals

• Estimate the geopressured geothermal resource in the Gulf Coast for combined production of natural gas and electricity
  o Total heat in place and recoverable thermal energy
  o Total geothermal electricity generation potential
  o Total natural gas that could be recovered with geothermal fluid
• Fully utilize previously published datasets
• Incorporate results from reservoir modeling of geopressured geothermal reservoirs in the estimate
Background and Methodology

1. Determine geopressed geothermal resource regions within Texas and Louisiana
   - Five formations identified within Texas: Lower Wilcox, Lower Claiborne, Upper Claiborne, Vicksburg-Jackson, and Lower Frio

2. Collect all relevant data on five formations in Texas and geopressed geothermal region in Louisiana
   - Sand and shale thickness, depth to geopressure, porosity, and temperature

3. Complete resource estimate using spatial analysis of Texas formations and Louisiana
   - Populate a grid of cells (A = 1 km²) region with data
   - Estimate geopressed geothermal resource for each grid cell

Background

- Previous work includes detailed multiphase flow reservoir modeling of geopressed geothermal fairways in the Frio and Wilcox formations (Esposito and Augustine 2011)
- Reservoir modeling provided insight on geothermal brine and natural gas flow rate profiles over a long-term time frame, reservoir pressure and temperature changes with time, and potential recovery factors
The total resource and the recoverable energy are calculated for each cell within the geopressed area of the formation and then summed over the entire formation to obtain the formation estimates.

Geopressed Geothermal Resource Estimate

- Area
- Thickness
- Porosity & Salinity
- Temp Gradient

Resource Estimate per Cell

Recoverable Resource per Cell

Formation Total Energy Estimate
Thermal Energy
Methane Quantity

Formation Recoverable Energy Estimate
Thermal Recovered
Methane Recovered
Texas Geopressured Formation Areas

Multiple formations are present at the same location but at different depths

**Spatial Analysis Criteria**

1. Total sand thickness must be greater than 30 m
2. A pressure gradient of 11.3 kPa/m falls above or within sandstone
3. Porosity data is available
4. Some regions in formation have temperatures above 100°C

<table>
<thead>
<tr>
<th>Formation</th>
<th>Geopressed Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Wilcox</td>
<td>42,534</td>
</tr>
<tr>
<td>Lower Claiborne</td>
<td>1,439</td>
</tr>
<tr>
<td>Upper Claiborne</td>
<td>5,785</td>
</tr>
<tr>
<td>Vicksburg-Jackson</td>
<td>26,821</td>
</tr>
<tr>
<td>Lower Frio</td>
<td>42,334</td>
</tr>
</tbody>
</table>
Lower Wilcox Geopressured Area

Depth to Midpoint of Wilcox (meters)

Sand Thickness of Wilcox (meters)

Thickest

Shale Thickness of Wilcox (meters)

<table>
<thead>
<tr>
<th>Depth Range</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2,300</td>
<td>Lightest</td>
</tr>
<tr>
<td>2,301 - 2,700</td>
<td>Light</td>
</tr>
<tr>
<td>2,701 - 3,100</td>
<td>Medium Light</td>
</tr>
<tr>
<td>3,101 - 3,500</td>
<td>Medium</td>
</tr>
<tr>
<td>3,501 - 3,900</td>
<td>Medium Dark</td>
</tr>
<tr>
<td>3,901 - 4,300</td>
<td>Dark</td>
</tr>
<tr>
<td>4,301 - 4,700</td>
<td>Darker</td>
</tr>
<tr>
<td>4,701 - 5,100</td>
<td>Darkest</td>
</tr>
<tr>
<td>&gt; 5,101</td>
<td>Darkest</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness Range</th>
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</tr>
</thead>
<tbody>
<tr>
<td>&lt; 200</td>
<td>Lightest</td>
</tr>
<tr>
<td>201 - 400</td>
<td>Light</td>
</tr>
<tr>
<td>401 - 600</td>
<td>Medium Light</td>
</tr>
<tr>
<td>601 - 800</td>
<td>Medium</td>
</tr>
<tr>
<td>801 - 1,000</td>
<td>Medium Dark</td>
</tr>
<tr>
<td>1,001 - 1,200</td>
<td>Dark</td>
</tr>
<tr>
<td>1,201 - 1,400</td>
<td>Darker</td>
</tr>
<tr>
<td>1,401 - 1,600</td>
<td>Darkest</td>
</tr>
<tr>
<td>&gt; 1,601</td>
<td>Darkest</td>
</tr>
</tbody>
</table>

<table>
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<td>Medium Light</td>
</tr>
<tr>
<td>601 - 800</td>
<td>Medium</td>
</tr>
<tr>
<td>801 - 1,000</td>
<td>Medium Dark</td>
</tr>
<tr>
<td>1,001 - 1,200</td>
<td>Dark</td>
</tr>
<tr>
<td>1,201 - 1,400</td>
<td>Darker</td>
</tr>
<tr>
<td>1,401 - 1,600</td>
<td>Darkest</td>
</tr>
<tr>
<td>&gt; 1,601</td>
<td>Darkest</td>
</tr>
</tbody>
</table>
Lower Claiborne Geopressured Area

Depth to Midpoint of Lower Claiborne (meters)

Sand Thickness of Lower Claiborne (meters)

Shale Thickness of Lower Claiborne (meters)

Very limited sand leads to small area of interest
Upper Claiborne Geopressured Area

Very limited sand leads to small area of interest
Vicksburg-Jackson Geopressedured Area

Depth to Midpoint of Vicksburg-Jackson (meters)

Sand Thickness of Vicksburg-Jackson (meters)

Shale Thickness of Vicksburg-Jackson (meters)

Deepest

Thickest
Lower Frio Geopressured Area

- Multiple areas of thick shale
- Includes an offshore buffer of 10 km
## Texas Geopressured Formation Summary

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lower Wilcox</th>
<th>Lower Claiborne</th>
<th>Upper Claiborne</th>
<th>Vicksburg Jackson</th>
<th>Lower Frio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Sand Thickness</td>
<td>185</td>
<td>8</td>
<td>48</td>
<td>114</td>
<td>123</td>
</tr>
<tr>
<td>Average Shale Thickness</td>
<td>725</td>
<td>922</td>
<td>411</td>
<td>1,286</td>
<td>681</td>
</tr>
<tr>
<td>Midpoint Depth</td>
<td>Min 1,904</td>
<td>2,795</td>
<td>2,732</td>
<td>2,427</td>
<td>1,814</td>
</tr>
<tr>
<td></td>
<td>Max 5,571</td>
<td>4,217</td>
<td>3,486</td>
<td>6,278</td>
<td>5,712</td>
</tr>
<tr>
<td></td>
<td>Avg 3,436</td>
<td>3,833</td>
<td>3,142</td>
<td>4,524</td>
<td>3,989</td>
</tr>
<tr>
<td>Average Porosity</td>
<td>11.3</td>
<td>17.7</td>
<td>21.3</td>
<td>13.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Total Area (km²)</td>
<td>46,944</td>
<td>28,783</td>
<td>17,741</td>
<td>28,567</td>
<td>117,223</td>
</tr>
<tr>
<td>Area of Interest (km²)</td>
<td>42,534</td>
<td>1,439</td>
<td>5,785</td>
<td>26,821</td>
<td>42,334</td>
</tr>
<tr>
<td>Area of Interest to Total Area</td>
<td>0.91</td>
<td>0.05</td>
<td>0.33</td>
<td>0.94</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Data on any shale present in the geopressured region was not available. In this analysis, the formation only consisted of sandstone.

Greatest depth to geopressure near coast
Temperature Estimation at Reservoir Midpoint

• **Input Data:**
  - AAPG bottom hole temperature (BHT) measurements
    - More than 27,000 data points for United States
  - Correct BHT using the Kehle correction up to 3,930 m
    \[
    \Delta T = -1.73 \times 10^{-10} Z^3 - 1.28 \times 10^{-7} Z^2 + 7.97 \times 10^{-3} Z -0.565 \ [°C]
    \]
  - After 3,930 m use linear equation (Blackwell et al. 2010)
    \[
    \Delta T = 19 + 3.28 \times 10^{-4} (Z-3,930) \ [°C]
    \]

• **Temperature Interpolation (MATLAB):**
  - Fluid temperature is calculated at the grid cell midpoint
  1. Delaunay triangulation of the scattered data locations
    - Input: x, y, depth (z), and corrected BHT
  2. Linear interpolation of temperature to midpoint of grid cell
    - Temp (x, y, z) \rightarrow Gridded: x, y, midpoint (z) points
Temperature Data

Location of data points from AAPG BHT database selected for analysis

Bottom hole temperature data points used for analysis
Total # of points: 3646

Bottom hole temperature data points used for the analysis
Total # of points: 3707
The midpoint temperature in all five formations increases towards the coast due to the significant dipping in each formation.

Maximum temperature of 273°C occurs in southern Vicksburg Jackson.
Resource Estimate Assumptions

- Sand and shale thickness is uniform throughout the grid cell area of 1 km²
- Sandstone is located in center of formation and bounded by upper and lower shale
- Pressure gradient at midpoint depth is 15.83 kPa/m

<table>
<thead>
<tr>
<th>Heat Capacity, Enthalpy, and Entropy calculations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th order polynomials in terms of temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid Density at Reservoir Conditions ($\rho_R$):</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_R = \rho_0 \left(1 - \frac{(P_R - P_0)}{E}\right)/(1 + \beta(T_R - T_0))$ [kg/m³]</td>
</tr>
<tr>
<td>o E : bulk modulus for water (2.1 x 10⁹ Pa)</td>
</tr>
<tr>
<td>o $\beta$ : volumetric temperature expansion coefficient (0.0004 m³/m³ °C)</td>
</tr>
<tr>
<td>o $P_0$ : reference pressure</td>
</tr>
<tr>
<td>o $T_0$ : reference temperature</td>
</tr>
<tr>
<td>o $\rho_0$ : reference fluid density</td>
</tr>
<tr>
<td>o $P_R$ : reservoir pressure</td>
</tr>
<tr>
<td>o $T_R$ = reservoir temperature</td>
</tr>
<tr>
<td>o $T_R$ = reservoir temperature</td>
</tr>
</tbody>
</table>
Texas: Total Heat in Place (Sandstone and Shale)

**Heat in Place Method**

1. **Total mass** ($m_T$): 
   
   $$m_T = \varphi \cdot \rho \cdot A \cdot (z_{sand} + z_{shale})$$

2. **Heat in place** ($J_T$):
   
   $$J_T = m_T \cdot c_P \cdot (T_R - T_0)$$
   
   with $T_0 = 25$ °C

### Formation Total (J)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Total (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicksburg-Jackson</td>
<td>2.67E+21</td>
</tr>
<tr>
<td>Lower Wilcox</td>
<td>1.78E+21</td>
</tr>
<tr>
<td>Lower Frio</td>
<td>1.74E+21</td>
</tr>
<tr>
<td>Upper Claiborne</td>
<td>1.89E+20</td>
</tr>
<tr>
<td>Lower Claiborne</td>
<td>1.10E+20</td>
</tr>
</tbody>
</table>
Total Recoverable Energy Calculations

1. **Recoverable Mass** \( (m_{\text{wh}}) \)

\[
m_{\text{wh}} = RF \cdot V_T \cdot \varphi \cdot \rho
\]

- **RF** : recovery factor
- **\( V_T \)** : total volume
- **\( \varphi \)** : porosity
- **\( \rho \)** : fluid density

2. **Exergy** \( (E) \)

\[
E = m_{\text{wh}}[h_{\text{wh}}-h_0-T_0(s_{\text{wh}}-s_0)]
\]

- **\( h_{\text{wh}} \)** : fluid enthalpy
- **\( h_0 \)** : reference enthalpy
- **\( T_0 \)** : reference temperature
- **\( s_{\text{wh}} \)** : fluid entropy
- **\( s_0 \)** : reference entropy

3. **Electricity Generation Potential** \( (W_e) \)

\[
W_e = E \cdot \eta_u
\]

- **\( \eta_u \)** : utilization efficiency

---

**Geothermal Power Conversion**

\[
y = 0.0032x - 0.16
\]

\[
y = 0.4
\]

---

*Williams et al. 2008*
Texas: Recovery Factors from Reservoir Modeling

Recoverability Factor (RF) = Volume Recovered/Total Pore Volume

Frio Recoverability Factors:
• Data were collected for five fairways
  o Developed 9 unique reservoir models
• Recovery factor was calculated:
  o 20-year average: 0.325%
  o RF 100-year average: 0.486%
• Frio 20-year average RF of 0.325% was also applied to Vicksburg Jackson

Wilcox Recoverability Factors:
• Data were collected for six fairways
  o Developed 12 unique reservoir models
• Recovery factor was calculated:
  o 20-year average: 0.685%
  o 100-year average: 0.870%
• Wilcox 20-year average RF of 0.685% was also applied to Lower and Upper Claiborne

Source: Esposito and Augustine 2011
Texas: Electricity Generation Potential

<table>
<thead>
<tr>
<th>Formation</th>
<th>Total Electricity (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicksburg-Jackson</td>
<td>1,032</td>
</tr>
<tr>
<td>Lower Wilcox</td>
<td>939</td>
</tr>
<tr>
<td>Lower Frio</td>
<td>429</td>
</tr>
<tr>
<td>Lower Claiborne</td>
<td>54</td>
</tr>
<tr>
<td>Upper Claiborne</td>
<td>46</td>
</tr>
</tbody>
</table>

The graph shows the total electricity generation potential (MWe) for different temperature ranges and formations. The formations include Lower Wilcox, Lower Frio, Lower Claiborne, and Upper Claiborne. The table lists the total electricity generation potential for each formation.
Heat in Place Method: Only Sandstone

1. Total mass \( (m_T) \):
\[
m_T = \varphi \cdot \rho \cdot A \cdot (z_{sand})
\]
\( \rho = 0.25 \)

2. Heat in place \( (J_T) \):
\[
J_T = m_T \cdot c_P \cdot (T_R - T_0)
\]
with \( T_0 = 25^\circ C \)

1) Multiple regions in Louisiana resource region have temperatures less than 100°C

2) Large portion of resource below 100°C

Louisiana: Heat in Place (Sand)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Total Heat in Place (10^18J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>100-110</td>
<td>90</td>
</tr>
<tr>
<td>110-120</td>
<td>80</td>
</tr>
<tr>
<td>120-130</td>
<td>70</td>
</tr>
<tr>
<td>130-140</td>
<td>60</td>
</tr>
<tr>
<td>140-150</td>
<td>50</td>
</tr>
<tr>
<td>150-160</td>
<td>40</td>
</tr>
<tr>
<td>160-170</td>
<td>30</td>
</tr>
<tr>
<td>170-180</td>
<td>20</td>
</tr>
</tbody>
</table>

Formation | Total (J)  
----------|------------
Louisiana | 3.47E+20
Evaluation by Bassiouni (1980):
- For the top 63 prospects, recovered electrical energy was provided
- For the top 15 prospects sandstone pore volume was estimated using sandstone thickness

Recovery Factor Estimate:
The total volume recovered for the top 15 prospects was estimated using assumptions presented in Bassiouni (1980). Recovery factors were estimated by dividing the estimated volume recovered by the sandstone pore volume.

Louisiana recovery factor is much higher from the sandstone based on available data from Bassiouni (1980) than from Frio and Wilcox reservoir modeling.
Summary:
Due to high recovery factors for Louisiana based on results from Bassiouni (1980), the electric energy potential is equivalent to the five formations in Texas. This is true even though the resource is at on average a lower temperature and covers a smaller surface area.
Natural Gas Recoverability Estimate

Summary:
- 10% < 45 scf/bbl
- 90% < 170 scf/bbl
- 53% between 45–85 scf/bbl

Natural Gas ($V_{NG}$)

$V_{NG} = m_{wh} \cdot \rho^{-1} \cdot GWR_{ave}$

- $\rho$: density
- Density is a function of depth, pressure, and temperature (lb/bbl)
- $GWR_{ave}$: average produced gas water ratio from reservoir modeling results for all fairways at 83 scf/bbl

Results from 19 of the 21 reservoir models excluding the two anomalous outliers were used to calculate $GWR_{ave}$.
## Gulf Coast Total Recoverable Natural Gas

<table>
<thead>
<tr>
<th>Formation</th>
<th>Total Natural Gas (scf)</th>
<th>Total Mass Produced (kg)</th>
<th>Average Flow Rate of Gas (MMscf/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louisiana</td>
<td>9.52E+13</td>
<td>1.75E+14</td>
<td>13,040</td>
</tr>
<tr>
<td>Lower Wilcox</td>
<td>1.37E+13</td>
<td>2.49E+13</td>
<td>1873</td>
</tr>
<tr>
<td>Lower Frio</td>
<td>6.92E+12</td>
<td>1.25E+13</td>
<td>948</td>
</tr>
<tr>
<td>Vicksburg Jackson</td>
<td>6.82E+12</td>
<td>1.21E+13</td>
<td>934</td>
</tr>
<tr>
<td>Upper Claiborne</td>
<td>1.98E+12</td>
<td>3.66E+12</td>
<td>272</td>
</tr>
<tr>
<td>Lower Claiborne</td>
<td>9.52E+11</td>
<td>1.51E+12</td>
<td>114</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.25E+14</strong></td>
<td><strong>2.29E+14</strong></td>
<td><strong>1.71E+04</strong></td>
</tr>
</tbody>
</table>

### Assumptions:

1. All fluid is fully saturated with natural gas at reservoir conditions.
2. Some free phase gas is present in the pore space representing between 1%–5% of pore volume.
3. Presence of potential gas layers is not included in estimate.
Results and Conclusions

- Estimated recoverable electricity generation potential:
  - **Texas**: 2.5 GW
  - **Louisiana**: 2.6 GW

- Highest quality resource is in southern Vicksburg Jackson due to collocation of high temperatures and thick sands
  - **Total of ~1,000 MW electricity generation potential**

- Large quantity of natural gas could be produced in conjunction with geopressed geothermal resource
  - **1.25 x10^{14} scf of natural gas**

- More data for each formation as well as data on sandstone permeability would improve overall analysis

- Louisiana estimate is quite high and is based on limited data on recovery factors. Should be treated as less certain than estimate for Texas.
This work was funded by the Department of Energy Geothermal Technologies Program.
We would like to acknowledge Arlene Anderson for her input and support.
We would also like to recognize Billy Roberts for his significant contribution to the spatial analysis and cartography.

THANK YOU!

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References and data sources for spatial analysis: