Life-Cycle Analysis of Geothermal Technologies

May 19, 2010

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Project Overview

• Project start date: June 2009
• Project end date: not applicable (annual GTP program)
• Percent complete: not applicable
• Budget:
  – FY09: $500K (100% DOE)
  – FY10: $500K (100% DOE)
• Barriers to address
  – Energy, GHG emissions, and water impacts of GTs
• Partners/collaborators: NREL, INL, and SNL
Relevance/Impact of Research

• This project was launched in FY2009 by GTP to help develop
  – GHG emission profiles of geothermal technologies (GTs)
  – Water resource impacts of GTs
  – To address GHG and water issues of other power generation technologies for comparison purpose

• The results and tools from the effort will help GTP and stakeholders determine and communicate GT energy and GHG benefits and water impacts

• The life-cycle analysis (LCA) approach is taken to address these effects

• The process of LCA helps identify key stages and issues affecting LCA results of GTs
Life-Cycle Analysis Approach for GTs

Component Manufacturing

Raw Materials Extraction

Drill and Log Exploratory Well

Drill Injection Well
- Stimulate/Create Reservoir
- Drill Production Well

Facility Construction

Power Plant Construction

Complete and Verify Circulation Loop
- Install Operations Equipment

Decommission and Deconstruction (?)
Key Stages and Issues Are Been Addressing through This Project

- Well characterization
  - Thermal characteristics: resource temperature, thermal drawdown rate
  - Well depth and size, number of exploration, injection, and production wells
  - Type and amount of materials for well construction
  - Interacted with GETEM simulations at INL; NREL scenario development; and expert consultation

- Power plant characterization
  - Size of power plants
  - Type and amount of materials for power plant construction
  - Geothermal field power use and net power production
  - Interacted with GETEM simulations at INL and NREL scenario development

- Geothermal operation
  - Working fluid characterization
  - Makeup water requirements

- Configuration of GT LCA
- Characterization of other power generation systems for comparison
Well Characterization

EGS Scenarios

Hydrothermal Scenarios

16,400 ft

6,000 ft

Tester et al. 2006
Number of Wells

- Scenarios were developed for use in INL’s Geothermal Electricity Technology Evaluation Model (GETEM)
- Number of wells depend on several parameters including:
  - Power plant size
  - Temperature of the resource
  - Well depth
  - Flow rate
  - Producer to injector ratio

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Average Number</th>
<th>Production Wells</th>
<th>Injection Wells</th>
<th>Total Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 MW EGS</td>
<td></td>
<td>6</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>50 MW EGS</td>
<td></td>
<td>16</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>10 MW Binary</td>
<td></td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>50 MW Flash</td>
<td></td>
<td>15</td>
<td>6</td>
<td>21</td>
</tr>
</tbody>
</table>
Water Quantity and Quality

• Quantity of water
  – Account for water required for drilling, cementing, and stimulating wells.
  – Account for water required for cementing surface pipeline.
  – Calculate makeup water requirements for operations phase according to available data.

• Quality of geofluid
  – Collect, aggregate, and analyze available data on geothermal brines.
  – Calculate distributions of chemical constituents.
  – Evaluate correlations between key reservoir properties and chemical constituent concentrations.
  – Qualitatively analyze potential challenges to operations and opportunities for mineral extraction.
EGS Stimulation (Water and Fuel)

- Reservoir stimulation occurs at the injection wells
- Water-based stimulation assumed
  - Literature values provided volume and flow rate information (average: 22,390 m³, 97 L/s).

<table>
<thead>
<tr>
<th>Location</th>
<th>Basement Depth (m)</th>
<th>Temperature (°C)</th>
<th>Volume of water (m³)</th>
<th>Highest Flow Rate (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper Basin, Australia</td>
<td>4,421</td>
<td>250</td>
<td>20,000</td>
<td>48</td>
</tr>
<tr>
<td>Soultz-sous-Forêts, France</td>
<td>5,091</td>
<td>200</td>
<td>34,000</td>
<td>93</td>
</tr>
<tr>
<td>Groß Schönebeck, Germany</td>
<td>4,200</td>
<td>150</td>
<td>13,170</td>
<td>150</td>
</tr>
</tbody>
</table>

- Diesel fuel consumption is based on industry experts
  - 5.7-7.6 L/minute (1.5-2 gpm) per pump
  - 1 pump can move 1.3-1.4 m³/minute (8-9 bpm) of stimulation fluid
- Fuel consumption per job is assumed to be 118.5 m³ (31,300 gal)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Water for Stimulation (m³)</th>
<th>Diesel for Stimulation (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGS, 20 MW</td>
<td>71,019</td>
<td>376</td>
</tr>
<tr>
<td>EGS, 50 MW</td>
<td>177,152</td>
<td>937</td>
</tr>
</tbody>
</table>
Surface Pipeline

- Pipelines connect production wells to central plant to injection wells
  - Pipeline length: 1000 m
- 8-10 inch diameter pipe requires support every 19 ft.
  - Structure includes forming tubes, cement foundation, rebar, and steel support
- Insulation used for pipe and support contacts
- Installation of pipeline requires water and fuel

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Total Steel (Mg) (pipe, support, rebar)</th>
<th>Total Class A Cement (Mg) (foundation)</th>
<th>Total Forming Tube (Mg) (foundation)</th>
<th>Total Water (gallons) (foundation)</th>
<th>Diesel fuel consumption (gal)</th>
<th>Total Insulation (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGS, 20MW</td>
<td>332</td>
<td>335</td>
<td>22</td>
<td>39,148</td>
<td>63,282</td>
<td>22</td>
</tr>
<tr>
<td>EGS, 50MW</td>
<td>827</td>
<td>835</td>
<td>54</td>
<td>97,651</td>
<td>157,852</td>
<td>55</td>
</tr>
<tr>
<td>Binary, 10MW</td>
<td>155</td>
<td>157</td>
<td>10</td>
<td>18,314</td>
<td>29,604</td>
<td>10</td>
</tr>
<tr>
<td>Flash, 50 MW</td>
<td>769</td>
<td>769</td>
<td>50</td>
<td>89,959</td>
<td>145,417</td>
<td>50</td>
</tr>
</tbody>
</table>

↑ Power, ↑ # of Wells, ↑ # of Pipelines
Power Plant Construction Characterization

• Material composition of GT plants was obtained from Icarus Process Evaluator.
  – For the selected plant types, the provided quantities of rebar, structural steel, concrete, various sizes of pipes and wire and equipment were converted to weights of concrete, steel, copper, aluminum, wood, etc.

• Material composition of conventional power plants is based on extensive literature review.
Plant Material Intensity: Steel Use in Tonnes/MW

- Coal
- NGCC
- PWR
- BWR
- Hydroelectric
- Wind
- PV
- Biomass
- EGS
- GT Flash
- HT Binary

Steel Use: 0 to 400 Tonnes/MW

- Coal and NGCC have minimal steel use at 0 Tonnes/MW.
- PWR has a minimal steel use at 0 Tonnes/MW.
- BWR has a minimal steel use at 0 Tonnes/MW.
- Hydroelectric has a minimal steel use at 0 Tonnes/MW.
- Wind has a significant steel use at 1,117 Tonnes/MW.
- PV has a minimal steel use at 0 Tonnes/MW.
- Biomass has a minimal steel use at 0 Tonnes/MW.
- EGS has a minimal steel use at 0 Tonnes/MW.
- GT Flash has a minimal steel use at 0 Tonnes/MW.
- HT Binary has a minimal steel use at 0 Tonnes/MW.
Facility construction (infrastructure-related activities)
- Gather data for all power plant types (geothermal, coal, etc.) including:
  - Plant and equipment material composition
  - Construction energy (diesel for excavators, cranes) added where data available
- Construction for conventional power plants was added to GREET this time

Fuel production (e.g. drilling and delivering geothermal fluid, oil, gas, etc.)
- For most fuels, production is well characterized in GREET
- For geothermal well infrastructure, drilling energy and water requirements were estimated for binary and flash technologies

Power plant operation
- GT plant operating emissions for the flash plant were obtained from available literature
- Makeup water estimate is in process
- Operation of conventional power plants is well simulated in GREET

Integration of infrastructure construction, fuel production, and plant operation into GREET for LCA modeling
Ratio of Energy Input to Energy Output: Facility Construction Only
Ratio of Energy Input to Energy Output: All Life Cycle Stages

- **Fuel Use**
- **Fuel Production**
- **Infrastructure**
GHG Emissions of Power Generation by Life Cycle Stage in g/kWh

- **Coal**: High emissions, primarily from fuel use.
- **NGCC**: Lower emissions compared to coal, with significant fuel use.
- **PWR**: Lower emissions, with minimal fuel use.
- **BWR**: Minimal emissions, with very little fuel use.
- **Hydro**: Very low emissions due to minimal fuel use.
- **Wind**: Virtually no emissions, as it is a renewable resource.
- **PV**: Low emissions, primarily from plant infrastructure.
- **EGS**: Low emissions, with minimal fuel use.
- **GT-Flash**: Low emissions, with minimal fuel use.
- **HT-Binary**: Low emissions, with minimal fuel use.
- **Biomass**: Low emissions, with minimal fuel use.
Comparison of Geothermal GHG Emissions Due to Infrastructure (g/kWh)

Error Bars apply only to infrastructure
GHG Emission and Energy Use Key Findings

- **Plant Infrastructure Production**
  - Estimation of the material and construction needs for GT and other power technologies is complete
- **Fuel Production**
  - Estimation of GT well production is complete and has been added to GREET
- Of the renewables, GTP-flash, biomass, and PV have the highest life-cycle GHG emissions, though arising from different life cycle stages
- Life cycle GHG emissions from fossil plants are much larger than those from renewable plants
  - For coal, an order of magnitude than the largest renewable emitter
  - For efficient fossil like NGCC, 5 times larger
- With the possible exception of GT flash, GT power is in the lower segment of renewable power GHG emitters
Next Steps

- Re-examine critical issues affecting LCA results.
- Incorporate pump material information into inventory.
- Complete aggregation and integration of water quantity information.
- Continue analysis of water quality data.
  - Compare results on GHG constituents with literature estimate of GHG emissions used in the LCA for the flash plant scenario.
Supplemental Slides
Relevant Publications and Presentations

Water Use in Geothermal Plant Operations

- Estimates provided in *Energy Demands on Water Resources* were from one geothermal power production site (the Geysers)
  - 2,000 gal/MWhe withdrawal; 1,400 gal/MWhe consumption
- The Geysers is unique
  - It is the only known dry steam field in the US
  - It is the largest geothermal power producer in the world
- The majority of industry power unit installations are binary
Water Quality Data and Analysis

• Obtained five geochemical data sets
  – Great Basin Center for Geothermal Energy – Great Basin Groundwater Geochemical Database
  – USGS/Nevada Bureau of Mines and Geology – GOETHERM
  – Kansas Geological Survey – NATCARB brine database
  – Nevada Bureau of Mines and Geology – Nevada Low-Temperature Geothermal Resource Assessment
  – USGS – Chemical and Isotope Data (Mariner Database)

• Merged into a single, aggregated data set of 53,000+ data points.
  – Parameters such as location, depth, temperature, pH, and TDS.
  – Concentrations for 52 elements/ions.
GREET Expansion for Power Plant Infrastructure

Power Plant Infrastructure (Expansion)

Fuel Cycle (GREET1)

Fuel
Diesel, Electricity

Material
Steel, Iron, Al, Co, Si, Glass, Plastic, Concrete, ...

Energy

Mining
Production

Emissions
Electricity Generation Systems in GREET

1. Coal: Steam Boiler and IGCC
   - Coal mining & cleaning
   - Coal transportation
   - Power generation

2. Natural Gas: Steam boiler, Gas Turbine, and NGCC
   - NG recovery & processing
   - NG transportation
   - Power generation

3. Nuclear: Light water reactor
   - Uranium mining
   - Yellowcake conversion
   - Enrichment
   - Fuel rod fabrication
   - Power generation

4. Petroleum: Steam Boiler
   - Oil recovery & transportation
   - Refining
   - Residual fuel oil transportation
   - Power generation

5. Biomass: Steam Boiler
   - Biomass farming & harvesting
   - Biomass transportation
   - Power generation

6. Hydro-Power

7. Wind Turbine

8. Solar Photovoltaics

9. Geothermal
Life Cycle Analysis for Power Plant Infrastructure

- Material use per TWh of lifetime generation
  \[ = \frac{\text{Material Use}}{(\text{Generation Capacity} \times \text{Utility Factor} \times \text{Lifetime})} \]

- Cradle-to-Gate energy uses and emissions for materials
  - Energy uses and emissions data are obtained from
    - Fuels (diesel and electricity) from GREET1
    - Most materials from GREET2
    - Concrete and cement from NREL LCI database
    - Silicon from de-Wild-Scholten & Alsema

- Energy uses and emissions for power plant infrastructure
  \[ = \sum (\text{Material Use}) \times (\text{Cradle-to-Gate Energy Uses and Emissions}) \]

Diagram:
- Ore → Steel Mill → Finished Steel
- Cement
- Coal
- Coal Power Plant