CCUS technology: an efficient method to generate electricity using the low-medium temperature geothermal reservoir

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Outline

• 1. Introduction
• 2. World geothermal electricity utilization
• 3. Geothermal use status in China and Canada
• 4. CCUS technology to generate electricity from low-medium hydrothermal reservoir
• 5. Great potential of CCUS in Canada
• 6. Conclusions
1. Introduction - geothermal energy

- **Huge amount** *(140×10^6 EJ up to 5 km) (WEC, 1994)*

- **Clean**
  - less CO₂ emission

- **Sustainable**
  - oil reserve ≈ 46 years (SBC)
  - geothermal ≈ 280,000 years

http://athene.as.arizona.edu/~lclose/teaching/images/lect8.html
1. Introduction - geothermal energy reserves

15% of the energy is from geothermal sources.

- Coal: 22.6%
- Natural Gas: 21.7%
- Oil: 35.1%
- Other Renewables: 0.7%
- "Modern" Biomass: 1.4%
- Traditional Biomass: 9.3%
- Hydro: 2.3%
- Nuclear: 6.9%

(data source: Bertani, 2010)
1. Introduction - worldwide geothermal energy utilization

- Direct use:
  - Bathing and swimming: 30%
  - Horticulture: 8%
  - Industry: 4%
  - Aquaculture: 4%
  - Conventional district heating: 22%
  - Geothermal heat pumps district heating: 32%

- Electricity purpose:
  - Dual flash: 41%
  - Single flash: 20%
  - Dry steam: 27%
  - Binary: 11%
  - Back pressure: 1%

2004 level
(data source: Lund et al., 2005)

2010 level
(data source: Bertani, 2010)
2. World geothermal electricity status in 2015

(Bertani, 2010)
2. World geothermal electricity distribution

(redrawn from Gupta and Roy, 2007)
2. World geothermal electricity - distribution

(redrawn from Gupta and Roy, 2007)
3. Geothermal use status in China - heat flux

(Tao and Shen, 2008)
3. Geothermal use status in China - electricity

- 150-160 °C, 21.5 MW
- 92 °C, 300 kW
- 98 °C, 300 kW

(Zhang et al., 2014)
3. Geothermal use status in Canada

No geothermal electricity!

(Raymond et al., 2015)
Questions

- Can we use low-medium geothermal resources to generate electricity?
- How could we?
- How to ensure a clean production (low or zero $\text{CO}_2$ emissions)?
CO₂ Capture Utilization Storage

- Enhanced Oil Recovery (EOR) (current 16; 24 in the next 5 years)
- Enhanced Gas Recovery (EGR) (5 in the next 5 years)
- Enhanced Coalbed Methane (ECBM)
- Enhanced Geothermal System (EGS)
4. CCUS in geothermal power plant - CO$_2$ as circulation fluid

- Drying out of the reservoir
- Water content in the CO$_2$-rich phase

(Randolf and Saar, 2011)
4. CCUS in geothermal power plant

CO₂ as a pressure-support fluid

(Buscheck et al., 2012)
4. CCUS in geothermal power plant

**Stage 1**
- Production fluid: water
- CO₂ used to increase the reservoir pressure
- Like conventional binary cycle geothermal power plant

**Stage 2**
- Production fluid: Both CO₂ and water
- CO₂ and water used to extract heat from hot reservoir
- CO₂ (low specific enthalpy), but higher flow rate

**Stage 3**
- Production fluid: CO₂ + limited water
- CO₂ used to extract heat from reservoir
- CO₂-based binary cycle geothermal power plant
4. CCUS in geothermal power plant - simulation runs

CO₂ injection time and simulation time
35 years
4. CCUS in geothermal power plant - simulation runs

- Temperature
- CO$_2$ saturation

0.1 year
- 5.0 years
- 10 years
- 35 years

Caprock
4. CCUS in geothermal power plant - simulation runs

CO₂ storage + increased heat extraction efficiency!
5. Great potential of CCUS in Canada

Population distribution

https://openmedia.ca/blog/why-your-high-cell-phone-bills-have-nothing-do-size-canada
5. Great potential of CCUS in Canada

http://www.thecanadianencyclopedia.ca/en/article/petroleum/
5. Great potential of CCUS in Canada

Electricity Generation in Canada by Province and Fuel Type, 2008

Source: Statistics Canada, Report #57-003-X
5. Great potential of CCUS in Canada
6. Conclusions

- 1) 15% world energy consumption can be provided by geothermal utilization economically in 2050 (11.5% contributes from geothermal power plant)
- 2) Top three countries in geothermal electricity: the United States, Philippines, and Indonesia; China very negligible amount; Canada no geothermal electricity.
- 3) CCUS technology provides an efficient way to reduce CO$_2$ emissions and increase heat extraction efficiency.
- 4) Great potential to apply CCUS in Canada, especially in ON and QC provinces.
Thank you!
Worldwide CO₂ Storage Activities

50 Acid Gas injection sites in North America

4 New CO₂-EOR Pilots in Canada

70 CO₂-EOR projects in U.S.A.

Key
- **Depleted Oil Field**
- **ECBM projects**
- **EOR projects**
- **Gas production Fields**
- **Saline aquifer**

(IEA, 2007)
Structure of Earth (crust-mantle)

**Upper crust**
- Aluminosilica belt (granite layer) (poro 0.3-0.7%)

**Lower crust**
- Density 2.9 kg/m³, average chemical composition is similar to basalt
- Simatic belt - basalt
- Depleted with respect to the upper crustal rocks

**Mantle**
- Density 3.1-3.3 kg/m³, average chemical composition is similar to olivine
- Three types of mantle (page 8 in textbook): original mantle; depleted mantle; altered enriched mantle

Average depth 17 km
Moho surface
Geothermal power plants

**Single Flash Power Plant**

- **Turbine**
- **Generator**
  - **Steam**
  - **Condensate**
  - **Cooling Tower**
  - **Direct Use**

**Binary Cycle Power Plant**

- **Turbine**
- **Generator**
- **Heat exchanger with working fluid**

**Flash Steam Power Plant**

- **Turbine**
- **Generator**
- **Load**

**Dry Steam Power Plant**

- **Turbine**
- **Generator**
- **Load**

**Production well**

**Injection well**

**Rock layers**

**Production well**

**Injection well**

**Rock layers**

**Heat exchanger with working fluid**

**geothermal zone**

**production well**

**injection well**
Binary Cycle Power Plant Example
Convergent (Active) continental margin
World seismic belts
Development of CCS and CCUS worldwide

- The existed large-scale projects:
  - 16 (EOR); 4 (deep saline formation-DSF)

- In the next 5 years, more projects will be in operation:
  - 24 (EOR); 5 (EOR&EGR); 25 (DSF)

(Global CCS Institute, 2014)
2. World geothermal electricity status in 2012

(GEA, 2012)
Combined geothermal power plant system
Potential in the future

China’s Industrial CO₂ Emissions for one year
Total: 354 Mt

Oil and Gas Reservoirs
17,760 Mt

Unminerable Coal Areas
840 Mt

Total: 69,110 Mt

(LICO2N Website)

Oil and Gas Reservoirs
11.8 Gt

Unminerable Coal Areas
12 Gt

China’s Industrial CO₂ Emissions for one year
Total: 5.18 Gt

Deep Geological Formation
50,510 Mt

Deep Saline Formation
3066 Gt

99%

(Li et al., 2011)
Geothermal power plant status in China and Canada

- **Low-medium temperature geothermal reservoir (7)**
  - Houheyao in Huailai of Hebei Province (87°C, 200 kW) (shut in)
  - Tangdongquan in Zhaoyuan of Shandong Province (98°C, 300 kW) (shut in)
  - Reshuicun in Xiangzhou of Guangxi Province (79°C, 200 kW) (shut in)
  - Xiongyue in Gaixian of Liaoning Province (90°C, 200 kW) (shut in)
  - Wentang in Yichuanxian of Jiangxi Province (67°C, 200 kW) (shut in)
  - Deng wu in Fengshun of Guangdong Province (92°C, 300 kW) (in operation)
  - Huitang in Ningxiang of Hunan Province (98°C, 300 kW) (in operation)

- **High temperature geothermal reservoir (2)**
  - Yangbajing in Tibet Province (150-160°C, 21.5 MW)

In total, with an installed capacity of $24.78 \text{ MW} \approx 1.3 \times 10^8 \text{ kW} \cdot \text{h/ year.}$

In Canada, however, there is no geothermal type power plant. Several small-scale projects are in design. They are located at the western and northern part of Canada. About 95% of the geothermal direct utilization is from heat pumps.
Worldwide geothermal energy consumption

- **Direct use:**
  - District heating system (54%): operation depth several hundreds of meters. It should be noted that 32% comes from heat pumps (operation depth less than several tens of meters)
  - Bathing and swimming (including balneology) (30%)
  - Horticulture (greenhouses and soil heating) (8%)
  - Industry (4%)
  - Aquaculture (mainly fish farming) (4%)

- **Electricity purpose:**
  - Geothermal electric power plant: most > 2 km in depth (> 150 °C)
  - **Conventional geothermal power plant**
    - back pressure (1.35% in MW)
    - binary (11% in MW)
    - single flash (41.3% in MW)
    - double flash (19.5% in MW)
    - dry steam (26.9% in MW)
  - **EGS (in research stage)**
  - CPG
China geothermal energy consumption

- China geothermal use
- Bathing and swimming (~ 55%)
- Conventional district heating (~ 14%)
- Geo-thermal heat pumps used for space heating (~ 14%)

(Bertani, 2009)
3. Geothermal use status in China - hot water

(Liu et al., 2015)
Sedimentary basins in Canada

(Bachu, 2003)
## CCS projects in Canada

<table>
<thead>
<tr>
<th>Project</th>
<th>Operator</th>
<th>Start time</th>
<th>Use</th>
<th>Scale</th>
<th>Investment</th>
<th>Location</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weyburn-Midale project</td>
<td>Cenovus, Apache</td>
<td>2000</td>
<td>EOR</td>
<td>2.2 Mt CO2/yr</td>
<td>$5.2B</td>
<td>Weyburn, Saskatchewan; Beulah, North Dakota</td>
<td>first fully-integrated, large-scale CCS project in the world; pipeline 323 km</td>
</tr>
<tr>
<td>Quest project</td>
<td>Shell</td>
<td>2015</td>
<td>saline storage</td>
<td>1.2 Mt CO2/yr</td>
<td>$1.35B</td>
<td>Fort Saskatchewan</td>
<td>first commercial-scale CCS in oil sands facility, only for CO2 storage</td>
</tr>
<tr>
<td>Alberta CO2 Trunk Line</td>
<td>Enhanced Energy</td>
<td>2014</td>
<td>EOR</td>
<td>1.7 Mt CO2/yr</td>
<td>$1.2B</td>
<td>Agrium, Northwest Upgrading, Fairborne Energy</td>
<td>large-scale CO2 pipeline</td>
</tr>
<tr>
<td>Boundary Dam project</td>
<td>SaskPower</td>
<td>2014</td>
<td>EOR</td>
<td>1.0 Mt CO2/yr</td>
<td>$1.24B</td>
<td>Estevan, Saskatchewan</td>
<td>full scale; at a 100MW coal-fired electricity power plant (retrofit); integrated 'clean coal' demonstration project</td>
</tr>
<tr>
<td>Fort Nelson project</td>
<td>Spectra Energy</td>
<td>planning phase</td>
<td>EOR + saline</td>
<td>2.0 Mt CO2/yr</td>
<td>$3.4B</td>
<td>Fort Nelson, British Columbia</td>
<td>full scale; at a natural gas processing plan</td>
</tr>
</tbody>
</table>
## CCS costs

<table>
<thead>
<tr>
<th>CO₂ Capture</th>
<th>Pulverized Coal</th>
<th>Subcritical</th>
<th>SuperCritical</th>
<th>Ultra-supercritical</th>
<th>Supercritical Oxyfuel</th>
<th>Ultra-supercritical Oxyfuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Plant</td>
<td>No, Yes</td>
<td>1,302</td>
<td>1,335</td>
<td>1,437</td>
<td>1,335</td>
<td>1,437</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,689</td>
<td>1,724</td>
<td>1,845</td>
<td>1,893</td>
<td>1,937</td>
</tr>
<tr>
<td>Flue Gas Cleanup</td>
<td>246, 323</td>
<td>228</td>
<td>300</td>
<td>204</td>
<td>228</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>292</td>
<td></td>
<td>273</td>
<td>318</td>
<td></td>
</tr>
<tr>
<td>CO₂ Capture</td>
<td>-</td>
<td>792</td>
<td>-</td>
<td>749</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td>673</td>
<td>-</td>
<td>210</td>
</tr>
<tr>
<td>CO₂ Compression</td>
<td>-, 89</td>
<td>-</td>
<td>84</td>
<td>-</td>
<td>76</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total Plant Cost¹ ($/kWe)</td>
<td>1,549</td>
<td>2,895</td>
<td>1,563</td>
<td>2,857</td>
<td>1,641</td>
<td>2,867</td>
</tr>
</tbody>
</table>

### COE

- **Capital Charges² ($/kWh)**
  - 3.41, 6.81, 6.34, 6.71, 3.86, 6.74, 3.44, 6.89, 3.86, 6.81
- **Operating Costs ($/kWh)**
  - 2.99, 4.64, 2.85, 4.33, 2.60, 3.86, 2.85, 4.01, 2.60, 3.56
- **CO₂ TS&M² ($/kWh)**
  - - , 0.47 , - , 0.40 , - , 0.38 , - , 0.40 , - , 0.36
- **Total³ ($/kWh)**
  - 6.40, 11.88, 6.29, 11.44, 6.46, 10.98, 6.29, 11.30, 6.46, 10.73
- **Increase in COE (%)ᵃ**
  - - , 85 , - , 82 , - , 75 , - , 80 , - , 71
- **$/ton CO₂ avoidedᵃ**
  - - , 75 , - , 68 , - , 61 , - , 57 , - , 50

*(DOE, 2008)*
### CCS costs

#### Integrated Gasification Combined Cycle

<table>
<thead>
<tr>
<th>CO₂ Capture</th>
<th>GE Energy</th>
<th>E-Gas</th>
<th>Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Base Plant</td>
<td>1,323</td>
<td>1,566</td>
<td>1,272</td>
</tr>
<tr>
<td>Air Separation Unit</td>
<td>287</td>
<td>342</td>
<td>264</td>
</tr>
<tr>
<td>Gas Cleanup/CO₂ Capture</td>
<td>203</td>
<td>414</td>
<td>197</td>
</tr>
<tr>
<td>CO₂ Compression</td>
<td>-</td>
<td>68</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Plant Cost¹ ($/kWe)</strong></td>
<td>1,813</td>
<td>2,390</td>
<td>1,733</td>
</tr>
</tbody>
</table>

#### COE

<table>
<thead>
<tr>
<th>Capital Charges² ($/kWh)</th>
<th>4.53</th>
<th>5.97</th>
<th>4.33</th>
<th>6.07</th>
<th>4.94</th>
<th>6.66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Costs ($/kWh)</td>
<td>3.27</td>
<td>3.93</td>
<td>3.20</td>
<td>4.09</td>
<td>3.11</td>
<td>3.97</td>
</tr>
<tr>
<td>CO₂ TS&amp;M³ ($/kWh)</td>
<td>-</td>
<td>0.39</td>
<td>-</td>
<td>0.41</td>
<td>-</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Total³ ($/kWh)</strong></td>
<td>7.80</td>
<td>10.29</td>
<td>7.53</td>
<td>10.57</td>
<td>8.05</td>
<td>11.04</td>
</tr>
<tr>
<td>Increase in COE (%)⁴</td>
<td>-</td>
<td>32</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>$/ton CO₂ avoided⁵</td>
<td>-</td>
<td>35</td>
<td>-</td>
<td>45</td>
<td>-</td>
<td>46</td>
</tr>
</tbody>
</table>

References:

2. "Pulverized Coal Oxycombustion Power Plants" November 2007 Presentation

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Cost of electricity with CCS technology $ 104/MW-hour
without CCS technology $ 59/MW-hour
## CCS costs

### CBO’s Illustrative Calculations of the Estimated Reduction in the Cost of Electricity from CCS-Equipped Plants

(2010 dollars per megawatt-hour)

<table>
<thead>
<tr>
<th>Description</th>
<th>Levelized Cost of Electricity&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs When the First CCS Plant Goes into Operation</td>
<td></td>
</tr>
<tr>
<td>Initial CCS Plant</td>
<td>104</td>
</tr>
<tr>
<td>Coal-Fired Plant Without CCS</td>
<td>59</td>
</tr>
<tr>
<td>CCS Cost Differential (Percent)</td>
<td>76</td>
</tr>
<tr>
<td>Costs After Investment in 210 Gigawatts of CCS Capacity Worldwide</td>
<td></td>
</tr>
<tr>
<td>CCS Plant After 210 Gigawatts of Worldwide Investment</td>
<td>74</td>
</tr>
<tr>
<td>Coal-Fired Plant Without CCS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>55</td>
</tr>
<tr>
<td>CCS Cost Differential (Percent)</td>
<td>35</td>
</tr>
</tbody>
</table>

**Memorandum:**
Cost Reduction for CCS Plant per 100 Gigawatts of New Investment (Percent)

14

(Congressional Budget Office, 2008)
Mobility of CO₂

CO₂ (red line)
water (blue line)

(Pruess, 2007)
1. Introduction - utilization of geothermal energy

http://explore-house.eu/en/2014/02/12/deep-geothermy/
1. Introduction - methods to geothermal electricity
2. World geothermal electricity utilization

Installed capacity and produced electricity (Bertani, 2010)
3. Geothermal use status in Canada - electricity

- The South Meager Creek Project

Hydrothermal type with T of 220-275 °C

(Bertani, 2010)
3. CO2 phase state