Flexible Integration of the sCO$_2$ Allam Cycle with Coal Gasification for Low-Cost, Emission-Free Electricity Generation

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Allam Cycle: A new opportunity for truly clean, low cost coal power

Patented, oxy-fuel, high-pressure, sCO₂ cycle invented and developed by 8 Rivers Capital

Major performance, cost and environmental benefits vs. non-capture systems

- Higher gross output leads to high net efficiencies with full carbon capture
- Simpler cycle significantly reduces cost
- No air emissions. Capture inherent to the semi-closed loop process

Core process being demonstrated with NET Power’s 50MWth gas-fired power plant

- NET Power is collaborating with 8 Rivers, Exelon, CB&I and Toshiba
- 50MWth FEED study and full combustor testing both complete.
- $140M program is fully-funded and underway. Commissioning in 2016.

Coal cycle builds on the core natural gas development program

- Same process fueled by a coal gasifier
- Two feasibility studies completed with UK DECC, Lignite Energy Council, ALLETE/Minnesota Power, Dakota Gasification, EPRI and Progressive Energy Ltd.
- Further development, including syngas combustor program, now underway
Increased performance, lower capital cost and reduced system complexity create a lower projected LCOE

Notes
- Total Plant Cost and O&M costs were estimated for lignite-fired system in conjunction with EPRI; AACE Class 5 estimate
- Cost data for other technologies is taken from NETL baseline reports (Vol. 3, 2011)
Core Allam Cycle operation

- **High performance** – 58.9% LHV on natural gas with full carbon capture, equivalent costs
- **Extremely simple, flexible** – single turbine, simple process, 100% turndown capability
- **Validated** – extensive design, key components piloted, demonstration program underway

Coal fueled cycle builds on this platform to approach 50% HHV with full carbon capture, no other air emissions, and expected capital costs lower than SCPC, IGCC.
Allam Cycle Coal simplifies power from coal gasification

Additional required components:

1. Gasifier Island
2. Low-grade HX Syngas compression
3. Potential downstream DeSNO_x Process

### Efficiency (100% CCS) | LHV | HHV
--- | --- | ---
Gross Turbine Output | 76.3% | 72.5%
Coal handling & milling ASU | -0.2% | -0.2%
CO\textsubscript{2}, Syngas Compressor | -9.1% | -8.7%
Other Auxiliaries (CO\textsubscript{2} pump, compressor, gasifier, etc.) | -6.5% | -6.1%

Net Efficiency | 50.3% | 47.8%

- High efficiency with existing gasifier technologies
- Minimal gasifier integration required, low complexity
- Overall process simplification
Potentially eliminates pre-combustion sulfur clean-up

- Elimination of AGR significantly reduces capital and operational costs – 2% HHV improvement
- Can exploit well-demonstrated reactions as used in other oxy-combustion systems

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Relative Reaction Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO + ½ O₂ → NO₂</td>
<td>(1) Slow</td>
</tr>
<tr>
<td>2 NO₂ → N₂O₄</td>
<td>(2) Fast</td>
</tr>
<tr>
<td>2 NO₂ + H₂O → HNO₂ + HNO₃</td>
<td>(3) Slow</td>
</tr>
<tr>
<td>3 HNO₂ → HNO₃ + 2 NO + H₂O</td>
<td>(4) Fast</td>
</tr>
<tr>
<td>NO₂ + SO₂ → NO + SO₃</td>
<td>(5) Fast</td>
</tr>
<tr>
<td>SO₃ + H₂O → H₂SO₄</td>
<td>(6) Fast</td>
</tr>
</tbody>
</table>

Converts SOₓ and NOₓ into sulfuric and nitric acids

- Uniquely facilitated by Allam Cycle conditions

- Initial Allam Cycle DeSNOₓ design shows promise, further work ongoing:
  1. High levels of removal of SOₓ and NOₓ
  2. Low cost – significantly reduced equipment, chemicals and maintenance
  3. Low parasitics – pump-around is the only power consumption
Allam Cycle Coal is a highly flexible system

Completed work to date confirms cost and performance advantage and shows the Allam Cycle maintains high performance across various coal types and gasification technologies.

### Allam Cycle Cases

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Gasifier Type</th>
<th>Heat Recovery</th>
<th>CCS</th>
<th>Efficiency (%HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous</td>
<td>Entrained flow, dry-feed</td>
<td>Slagging</td>
<td>Y</td>
<td>49.7</td>
</tr>
<tr>
<td>Lignite</td>
<td>Moving bed</td>
<td>Slagging</td>
<td>Y</td>
<td>48.2</td>
</tr>
<tr>
<td>Bituminous</td>
<td>Entrained flow, dry-feed</td>
<td>Slagging</td>
<td>Y</td>
<td>47.8</td>
</tr>
<tr>
<td>Lignite</td>
<td>Entrained flow, dry-feed</td>
<td>Slagging</td>
<td>Y</td>
<td>47.4</td>
</tr>
<tr>
<td>Bituminous</td>
<td>Entrained flow, slurry</td>
<td>Slagging</td>
<td>Y</td>
<td>46.8</td>
</tr>
<tr>
<td>Lignite</td>
<td>Fluidized bed</td>
<td>Non-slagging</td>
<td>Y</td>
<td>43.3</td>
</tr>
</tbody>
</table>

### NETL Coal Benchmark Cases

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Gasifier Type</th>
<th>Heat Recovery</th>
<th>CCS</th>
<th>Efficiency (%HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous</td>
<td>Entrained flow, dry-feed</td>
<td>Slagging</td>
<td>N</td>
<td>42.1</td>
</tr>
<tr>
<td>Lignite</td>
<td>Entrained flow, dry-feed</td>
<td>Slagging</td>
<td>N</td>
<td>37.6</td>
</tr>
<tr>
<td>Bituminous</td>
<td>SCPC</td>
<td>N/A</td>
<td>N</td>
<td>39.3</td>
</tr>
<tr>
<td>Lignite</td>
<td>SCPC</td>
<td>N/A</td>
<td>N</td>
<td>38.7</td>
</tr>
</tbody>
</table>
Flexibility enabled by Allam Cycle and steam cycles differences

• Not sensitive to syngas composition (i.e. CO/H₂ ratio, CH₄ concentration)
  • High pressure and temperature of recycle fluid facilitates stable combustion
  • No shift reactions required
  • Full BTU content of the syngas is realized

• More capacity for the utilization of lower grade heat
  • CO₂ more flexible than steam – no issues with loss of latent heat
  • Improves the performance of quench-type and slurry-fed systems.
  • Syngas coolers offer further improvement but cost must be considered
  • Cold-gas efficiency is the primary determinant of system efficiency

• Enables optimization for cost and simplicity while maintaining performance
Environmental benefits extend beyond just air emissions

Analysis of ND lignite-fired Allam Cycle Coal system vs. NETL baselines

**Water Usage (gpm/MW\textsubscript{NET})**

- **No CCS**
  - Shell: 3.0
  - Siemens: 4.0
  - Allam Cycle + Siemens: 2.4

- **CCS**
  - Shell: 7.8
  - Siemens: 6.2
  - Allam Cycle + Siemens: 1.1

**NETL Technology Cases**

Taken from NETL baseline reports (Vol. 3, 2011)

**50-60% reduction in water consumption vs. IGCC non CCS using ND Lignite;**

**Major reductions come from:**
1. elimination of steam cycle;
2. reduced cooling duty (higher efficiency, utilization of low-grade heat);
3. semi-closed cycle captures and condenses combustion derived water.
Development pathway

Core Allam Cycle will be further validated by ongoing NET Power natural gas demonstration

Use of existing gasifier with minimal integration provides dramatic improvement with coal-based fuel

Next steps

1. Work closely with gasifier vendor to optimize design
2. DOE/Toshiba/8RC – design and test syngas combustor (Ongoing)
3. Validation of DeSNO\textsubscript{X} process (Ongoing)

Followed by full demonstration

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Key components piloted
8 Rivers, Toshiba, CB&I and Exelon supporting NET Power demonstration
$140M program, site in Texas
Commissioning in 2016

>10% efficiency improvement
>30% cost reduction
>50% water savings

All vs. non capture coal systems
THANK YOU!

Q&A

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