Analysis of SMR Thermal Augmentation with CHP Turbine Exhaust

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Relevant Characteristics of Typical CHP Turbine

Solar Turbines
• Taurus 60
• 5.74 MW

Air intake

Exhaust:
• Temperature: 510°C (950°F)
• Mass flow: 171,690 lb/h
• Back-pressure allowance: sufficient for steam generator heat exchanger (inches water column)
• Oxygen content: 15 vol%

Sources:
• Solar turbines performance specifications: Taurus 60, 5.74 MW turbine
Typical SMR System Configuration

Sources:
- R. Elshout, "Hydrogen Production By Steam Reforming", Chemical Engineering [www.che.com](http://www.che.com), May 2010 issue, page 34
Typical SMR System Configuration

Note: Internal pressure is sub-atmospheric.

Sources:
Modeling of Typical SMR System

NREL replicated typical SMR model, using ASPEN Plus

Efficiency: 76.3% LHV (without utilities)
Production scale: 1,000 kg/day

Key observations:
- high quality heat drives gas consumption for process heat
- low quality heat exceeds steam generation demand
- gas consumption reduction can be achieved by high quality heat > 880°C

Process conditions source:
Integration Concept

- SMR combustion air intake is manifolded to accept CHP exhaust
- Fuel is combusted into CHP exhaust to increase heat quality
  - adiabatic flame temperature ~1470°C
- Hand-off pressure = ambient (consistent with SMR construction)
Combustion oxidant can be either fresh air or CHP exhaust

Operating conditions examined:
- Reactor outlet temperature 815°C, 880°C
- PSA hydrogen recovery extent: 90%, 97%

Performance metrics:
- Natural gas consumption (process & combustor)
- Low quality heat impact
- Hydrogen production impact
## Performance Summary

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>SMR-out temperature</td>
<td>°C</td>
<td>815</td>
<td>815</td>
<td>880</td>
<td>815</td>
<td>880</td>
</tr>
<tr>
<td>PSA H₂ recovery %</td>
<td>mol/mol</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
<td>97%</td>
<td>97%</td>
</tr>
<tr>
<td>High quality heat requirement</td>
<td>kW-thermal</td>
<td>563,744</td>
<td>616,786</td>
<td>673,342</td>
<td>585,414</td>
<td>678,731</td>
</tr>
<tr>
<td>Steam generation heat required</td>
<td>kW-thermal</td>
<td>480,869</td>
<td>480,869</td>
<td>480,869</td>
<td>480,869</td>
<td>480,869</td>
</tr>
<tr>
<td>Low quality heat available (steam generation)</td>
<td>kW-thermal</td>
<td>503,602</td>
<td>503,602</td>
<td>606,113</td>
<td>503,602</td>
<td>606,113</td>
</tr>
<tr>
<td>Methane used in production stream</td>
<td>mmBTU HHV/kgH₂</td>
<td>0.156</td>
<td>0.156</td>
<td>0.133</td>
<td>0.144</td>
<td>0.123</td>
</tr>
<tr>
<td>Rafinate used in combustion stream</td>
<td>mmBTU HHV/kgH₂</td>
<td>0.054</td>
<td>0.054</td>
<td>0.032</td>
<td>0.041</td>
<td>0.020</td>
</tr>
<tr>
<td>Fresh methane used in combustion stream</td>
<td>mmBTU HHV/kgH₂</td>
<td>0.010</td>
<td>0.001</td>
<td>0.022</td>
<td>0.008</td>
<td>0.030</td>
</tr>
<tr>
<td>Total methane use</td>
<td>mmBTU HHV/kgH₂</td>
<td>0.165</td>
<td>0.156</td>
<td>0.155</td>
<td>0.152</td>
<td>0.153</td>
</tr>
<tr>
<td>Feedstock use efficiency (excluding CHP heat &amp; electricity)</td>
<td>HHV</td>
<td>81.3%</td>
<td>86.0%</td>
<td>86.8%</td>
<td>88.4%</td>
<td>87.9%</td>
</tr>
<tr>
<td>Feedstock use efficiency (excluding CHP heat &amp; electricity)</td>
<td>LHV</td>
<td>76.3%</td>
<td>80.7%</td>
<td>81.5%</td>
<td>83.0%</td>
<td>82.5%</td>
</tr>
<tr>
<td>Total CH₄ consumption reduction</td>
<td></td>
<td>0.0%</td>
<td>5.5%</td>
<td>6.3%</td>
<td>8.1%</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

Initial indication shows as much as 8% fuel consumption reduction.

**Integration ratio:** 1 MW CHP can augment 14,000 kg/day SMR
Supply Chain Models Examined

Central Production

Central SMR

Delivery trucks

H₂ dispensing

Forecourt Production

Distributed SMR

H₂ dispensing

Semi-Central Production

Semi-Central SMR

H₂ dispensing

H₂ dispensing

H₂ dispensing

Distribution pipe (~2 miles/station, 0.7 inch ID)
H2A Analysis, Current Technology, Central SMR Basis

<table>
<thead>
<tr>
<th>Case</th>
<th>Central SMR</th>
<th>Central CHP+SMR</th>
<th>Forecourt SMR</th>
<th>Forecourt CHP+SMR</th>
<th>Semi-Central SMR</th>
<th>Semi-Central CHP+SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Capacity (kg/day)</td>
<td>379,387</td>
<td>379,387</td>
<td>1,500</td>
<td>1,500</td>
<td>4,500</td>
<td>4,500</td>
</tr>
<tr>
<td>Per-Station Dispensing Capacity (kg/day)</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
</tr>
</tbody>
</table>

Production Costs ($/kg)

<table>
<thead>
<tr>
<th></th>
<th>Central SMR</th>
<th>Central CHP+SMR</th>
<th>Forecourt SMR</th>
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<th>Semi-Central SMR</th>
<th>Semi-Central CHP+SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>$ 0.32</td>
<td>$ 0.32</td>
<td>$ 0.58</td>
<td>$ 0.57</td>
<td>$ 0.42</td>
<td>$ 0.42</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>$ 0.06</td>
<td>$ 0.06</td>
<td>$ 0.19</td>
<td>$ 0.19</td>
<td>$ 0.13</td>
<td>$ 0.13</td>
</tr>
<tr>
<td>Feedstock Costs</td>
<td>$ 1.23</td>
<td>$ 1.13</td>
<td>$ 1.14</td>
<td>$ 1.05</td>
<td>$ 1.14</td>
<td>$ 1.05</td>
</tr>
<tr>
<td>Other Variable Costs</td>
<td>$ 0.07</td>
<td>$ 0.07</td>
<td>$ 0.11</td>
<td>$ 0.11</td>
<td>$ 0.11</td>
<td>$ 0.11</td>
</tr>
<tr>
<td>Total</td>
<td>$ 1.70</td>
<td>$ 1.59</td>
<td>$ 2.03</td>
<td>$ 1.93</td>
<td>$ 1.81</td>
<td>$ 1.72</td>
</tr>
</tbody>
</table>

Delivery Costs ($/kg)

<table>
<thead>
<tr>
<th></th>
<th>Central SMR</th>
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<th>Forecourt SMR</th>
<th>Forecourt CHP+SMR</th>
<th>Semi-Central SMR</th>
<th>Semi-Central CHP+SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery Cost to Station</td>
<td>$ 2.50</td>
<td>$ 2.50</td>
<td>$ -</td>
<td>$ -</td>
<td>$ 0.08</td>
<td>$ 0.08</td>
</tr>
</tbody>
</table>

Dispensing Costs ($/kg)

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<th>Semi-Central SMR</th>
<th>Semi-Central CHP+SMR</th>
</tr>
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<tbody>
<tr>
<td>Compression Storage &amp; Dispensing</td>
<td>$ 2.46</td>
<td>$ 2.46</td>
<td>$ 2.46</td>
<td>$ 2.46</td>
<td>$ 2.46</td>
<td>$ 2.46</td>
</tr>
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</table>

Total Cost

<table>
<thead>
<tr>
<th></th>
<th>Central SMR</th>
<th>Central CHP+SMR</th>
<th>Forecourt SMR</th>
<th>Forecourt CHP+SMR</th>
<th>Semi-Central SMR</th>
<th>Semi-Central CHP+SMR</th>
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<tbody>
<tr>
<td>Total</td>
<td>$ 6.66</td>
<td>$ 6.56</td>
<td>$ 4.49</td>
<td>$ 4.40</td>
<td>$ 4.35</td>
<td>$ 4.26</td>
</tr>
</tbody>
</table>

- H2A Production Model values are used for production and CSD costs (**N'th plant assumption in effect**)
- ANL input was used for truck delivery costs
- H2A Components Model values were used for pipeline costs (2 miles, 0.7 inch ID pipeline per station)
H2A Analysis, Current Technology, Central SMR Basis

Cost of Hydrogen by Scenario

- Cost of dispensed hydrogen $/kg
- Production Capital Costs
- Production Fixed O&M
- Production Feedstock Costs
- Production Other Raw Material Costs
- Delivery Cost to Station
- Compression Storage & Dispensing Cost

- H2A Production Model values are used for production and CSD costs (N'th plant assumption in effect)
- ANL input was used for truck delivery costs
- H2A Components Model values were used for pipeline costs (2 miles, 0.7 inch ID pipeline per station)
• Economies of scale benefits to SMR > cost of pipeline
• H2A Production Model values are used for production and CSD costs (N\textsuperscript{th} plant assumption in effect)
• H2A Components Model values were used for pipeline costs (2 miles, 0.7 inch ID pipeline per station)
Discussion

10¢/kg is not trivial – it is in the order of magnitude of investor rate of return

8% fuel reduction = 8% reduction in GHG emissions

H₂ can be distributed to nearby fueling stations (lowest cost delivery method)
  - Less delivery GHG emissions & trucks on the road
  - Semi-central SMR can get lower cost Natural Gas
    (industrial vs. commercial)

Leverage of economies of scale
  - on-site technical support (no travel time and expense for service)
  - higher up-time due to on-site technician support
  - available infrastructure (natural gas, utilities, cooling)
  - industrial zoning may allow easier permitting

Adiabatic flame temperature reduction = reduction in NOx emissions

**Reduced market entry cost for renewables:**
  - Power to Gas (P2G) can sell high-value H₂ into network
  - MSW gasifiers can feed into network with lower distribution cost
Questions?
Levelized Hydrogen Delivery Cost Reduction Path
(Input from Amgad Elgowainy, ANL)

Levelized H₂ Delivery Cost (2007$/kg)

- Infrastructure Storage
- Tube-Trailer
- LH₂ Truck
- Pipeline
- Terminal
- Liquefier
- Refueling Station

5,000 FCVs
200 kg/day Station

100,000 FCVS
600 kg/day Station

1,000,000 FCVS, 1000 kg/day Station
Pipeline Cost Distribution
(Total Installed Cost)