Developments in CO₂ capture with amino acid salt solutions

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## Siemens preferred solutions for CO₂ capture

### IGCC / Pre-combustion carbon capture

- “Technology units proven or ready”, integration in new build IGCC plants:
  - Gasification technology with multi-fuel capability
  - Scrubbing Technologies from oil & gas
  - Advanced F-class LC Gas Turbine
  - Alternative route for chemical / fuel production / SNG and hydrogen economy
- ✓ Master technological / contractual complexity

### Post-combustion carbon capture

- “Scalable” market introduction, for new build and retrofit steam power plants:
  - Enhancement potential for solvents, scrubbing process and for integration into the power plants
  - Siemens develops process based on amino acid salt formulations
  - Preferred solution for CCS demo projects
- ✓ Master scale-up from pilot to demo plant

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Siemens solutions are ready for the implementation in the upcoming CCS demonstration projects.
Amino acid salt is the basis of our solvent

Solvents based on amino acid salts are economic, have low environmental impact and are easy to handle.

- Amino acid salt is the basis of our solvent
- No vapor pressure
- Chemically stable
- Naturally present
- Salts have no vapor pressure
  - No thermodynamic solvent emissions
  - Not inflammable
  - Not explosive
  - Odorless
  - No inhalation risk
- Negative ion is less sensitive to O₂
  - Low degradation
- Amino acids are naturally present
  - Biodegradable
  - Nontoxic
  - Environmentally friendly
Solvent reclaiming: minimize solvent refill and waste for disposal

Development of reclaimer enables minimization of solvent make-up

Capture process

No loss of solvent!

Solvent make-up

Solvent deactivation due to degradation (thermal, O₂, NOₓ, SOₓ, etc...)

Solvent recycling

Waste

Solvent Reclaiming
Upscaling from lab to demonstration plant
Pilot plant at E.ON SPP „Staudinger“ Germany and in USA

March 2010:
~ 4,000 operating hours

Footprint of capture plant for
800 MW SPP, approx.: 25,000 m²

Upscaling via slip-stream demo plants, upscaling design tools validated

Start of operation September 2009

CO₂ Absorber/Desorber

FGD

Pilot Plant in USA
- Flue gas from a coal-fired power plant
- Pilot plant size: approx. 2.5 MWₑₑ slip stream
- Funding by DoE: 15 million US$
- Start up in mid 2012
Siemens PostCap™ technology

- No predictable solvent emissions, no additional washing steps required, nitrosamines not volatile
- State of the art reclaiming system with very limited solvent losses, FGD polishing not required
- Limited solvent degradation (O₂, SOₓ, NOₓ, thermal), “easy to handle” (not flammable, no inhalation risk)
- Energy consumption for regeneration, June 2011: 2.7 GJ/tCO₂ (target < 2.2 GJ/tCO₂)

Optimal integration in power plant

- June 2011: 6% pts. efficiency drop / target < 5 % pts.
- < 30min response time to full capacity
Post-combustion capture on a 800 -900 MW steam plant
Post-Combustion for combined cycles
Drivers and capture process design challenges

Main driver is capture readiness
- State-of-the-art combined cycle (w/o capture) already features specific CO₂ reduction (g/kWh) of
  - 66% compared to average CO₂ emissions from installed global steam power plant capacity
  - more than 50% compared to state-of-the-art steam power plant CO₂ emissions
- EU legislation calls for capture ready feature for new plants with an output > 300 MWₑₑ

Combined cycle capture design challenges
- Low carbon dioxide concentration in flue gas
- High oxygen content in flue gas
- Operation with frequent load changes
- Little integration options for low temperature waste heat from the capture plant
Solvent and process optimization for CCPP with post combustion capture

<table>
<thead>
<tr>
<th>SPP vol-%</th>
<th>CCPP vol-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>14</td>
</tr>
<tr>
<td>O₂</td>
<td>3</td>
</tr>
<tr>
<td>Specific Fluegas Flow kg/MW el,gross</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Lower CO₂ content
- Higher O₂ content
- Higher solvent loadings and driving force
- Slower reaction kinetics
- Higher specific energy demand for regeneration
- Higher solvent degradation
- Higher solvent consumption
- More flue gas
- Larger absorber diameter

Solvent and process optimization is needed to account for GT flue gas properties
Illustration of a CO₂ capture plant for a CCPP (420 MWₑₜₐₚₑ)
Contract Study for combined cycle power stations
Final task: load change behaviour

**TASK 1**
Adaptation and optimization of Siemens PostCap process for CCGT

**TASK 2**
Definition of Capture Ready CCGT and PP performance evaluation

**TASK 3**
Evaluation of load change behaviour of CCS-CCGT

2009 2010 2011
Jan 09 – Mar 10
Jul 09 – Jun 10
Jan 10 – Feb 11
Capture Ready Requirements

Relevant power plant components / interfaces

Stack:
Consider later flue gas connection to capture unit and flue gas flow switch devices

Turbine building:
Sufficient space for modification of turbines, retrofit of steam extraction and condensate return lines

Steam turbines / Reheating:
Adaptability for steam extraction; options for modification of turbines depend on required operating modes.

Auxiliary electric supply:
Sufficient space for additional auxiliary transformer(s), switchgear and cable routes

Cooling system:
Sufficient space for additional circulation pumps and service water system, sufficient space for extension of cooling capacity

Water supply / Waste water treatment:
Sufficient space for corresponding retrofit measures; Provision of additional water utilization rights

Elaboration of capture ready measures requires insight into an appropriate capture process
Capture Ready Requirements
Influence of Siemens Steam Turbine Configurations

SST-3000
Combined IP/LP turbine; axial exhaust

Determines process steam extraction options

SST-5000
Combined HP/IP turbine; lateral exhaust

Given steam turbine concept influence capture plant retrofit scenario.
Capture Retrofit Scenarios:
Process steam supply options for SST-3000 and SST-5000

Steam extraction from the reheat line:

- Interface localization at pipe bridge possible
- HRH extraction avoids influence on steam generator design
- Not affected by potential capture-ready / capture-retrofit measures with regard to process steam extraction
- For avoidance of permanent throttling losses
- Optional Back Pressure Turbine
- Re-boiler Carbon Capture Plant

Hot Reheat
Cold Reheat
Capture Retrofit Scenarios:
Additional process steam supply option for SST-5000

Steam extraction from the crossover line:

- Extraction line routing requires adaptation in the turbine hall concept.
- Steam extraction at the required pressure level from the crossover pipe possible.
- Requires throttle flap in the crossover pipe.

Diagram:
- LP Main Steam
- Cold Reheat
- Hot Reheat
- Re-boiler Carbon Capture Plant
- Turbine Hall area
- Extraction line routing
- Reboiler Carbon Capture Plant
- Steam extraction at the required pressure level from the crossover pipe possible
- Requires throttle flap in the crossover pipe

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CCGT with 100% flue gas capture plant (420 MWₜₐₚₜ)
Capture plant start-up after 8h shut-down: Standard

A = Start GT
B = Synchronize GT
C = Increase GT Load/Temp to req. Steam Temperature (ST)
D = Start ST
E = Synchronize ST
F = Steam Bypass Closed
G = GT at Full Load
H = Combined Cycle Full Load
Capture plant start-up after 8h shut-down: Using waste steam during start-up

GAS TURBINE & CAPTURE PLANT

Flue gas flow
Desorber Temperature
Capture Rate

STEAM TURBINE

Utilize HRSG-Steam for Desorber heat up

Legend:
A = Start GT
B = Synchronize GT
C = Increase GT Load/Temp to req. Steam Temperature (ST)
D = Start ST
E = Synchronize ST
F = Steam Bypass Closed
G = GT at Full Load
H = Combined Cycle Full Load
# Plant performance summary for different fuels

**Steam Power Plant**

<table>
<thead>
<tr>
<th>Δ(\eta_{\text{net}})</th>
<th>Capture Process</th>
<th>Δ(\eta_{\text{net}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.5 %-pts.</td>
<td>Optimized(^1)</td>
<td>-6.9 %-pts.</td>
</tr>
<tr>
<td>-6.0 %-pts.</td>
<td>Optimized w/o compression(^2)</td>
<td>-5.6 %-pts.</td>
</tr>
</tbody>
</table>

\(^1\) “Optimized” means capture process configuration and operating conditions are adapted to the specific flue gas conditions of the underlying power plant.

\(^2\) “w/o Compression” – the numbers consider the power demand of the capture process, but not of the usually required subsequent compression of the CO\(_2\) for transport.
Targets for capture process development

**Minimum Thermal Energy Demand**
- Optimization of Process Configuration
- Optimization of Design Parameters
  - Column Heights
  - Column Diameters
  - Feed Points
  - Etc.
- Optimization of Operating Parameters

**Maximum Power Plant Efficiency**
- Influence of Steam Extraction at a Certain Temperature
- Auxiliary Power Requirements of Capture Plant
- Power Plant Efficiency Including Capture Plant

**Minimum Separation Cost and LCOE**
- Process Optimization
- Equipment Design
- Investment Cost Estimation
- Cost of CO2 Avoided / LCOE

\[
\Delta E_{el} = \frac{COE_{capture} - COE_{reference}}{CO_2 \text{ emission}_{reference} - CO_2 \text{ emission}_{capture}}
\]
Further process improvements continue

- Scale-Up
  - Large distributors
  - Train concept

- Equipment Optimization
  - Efficiency
    - Pressure drop
    - Type of equipment (e.g. packing)

- Investment Costs
  - Size
  - Material

- Process Conditions
  - Pump around
  - Desorber pressure
  - Process temp.

- Process Optimization
  - Power Plant Integration
    - Low temperature heat integration
    - Adaption of turbine operating characteristics

- Process Configuration
  - Heat integration
  - Split loop configuration

- Solvent Optimization
  - Corrosiveness
    - Additives
    - Equipment material
  - Kinetics
    - Activation
    - Enhanced mass transfer
  - Chemical Stability
    - Additives
    - Structure of solvent
  - Capacity
    - Concentration of AAS
    - Solubility
    - New functional AAS

Risk/contingency adders lead to higher capex in “first-of-a-kind” demonstration projects.
PostCap™ technology is ready for large scale demonstration on coal & CCGTs

Amino acid salt solution offers high efficiency, low environmental impact and thus lower capex and opex

Scale up to demonstration size is within the experience of the process industry

Significant improvements are achievable from “first-of-a-kind” demonstration projects to a mature market beyond 2020

CCS now needs early demonstration & secure rewards for long-term investment