International Training Programme on Clean Coal Technologies and Carbon Capture and Storage: Learning from the European CCT/CCS Experiences

IGCC Technology and CCS Demonstration – Spain Experience

Experiences from ELCOGAS IGCC plant

Francisco García Peña
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GASIFICATION

1. THE PUERTOLLANO ELCOGAS PLANT

2. UNAVAILABILITY REASONS
   a. First five years
   b. Last years

3. OTHER LESSONS LEARNT
   a. Carnot Project
   b. Organisation

4. R&D INVESTMENT PLAN
Gasification vs combustion

Basis: Illinois coal excluding nitrogen

Source: J. Phillips GTC, Tampa 2006
Step 1: Raw **Syngas production**

\[
\text{Carbon compound} + O_2 + H_2O \xrightarrow{400-1600^\circ C} CO + H_2 + \text{Impurities} \quad 10-40 \text{ bar}
\]

1) **Pyrolysis:**
Coal + heat → Combustion gases (CO, H$_2$, CO$_2$...)

2) **Combustion:**
\[
\begin{align*}
C + O_2 &\rightarrow CO_2 \\
H_2 + \frac{1}{2} O_2 &\rightarrow H_2O \\
CO + \frac{1}{2} O_2 &\rightarrow CO_2
\end{align*}
\]

3) **Gasification with combustion gases:**
\[
\begin{align*}
2C + O_2 &\leftrightarrow 2CO \\
C + CO_2 &\leftrightarrow 2CO \\
C + H_2O &\leftrightarrow CO + H_2 \\
CO + 3H_2 &\leftrightarrow CH_4 + H_2O \\
C + 2H_2 &\leftrightarrow CH_4 \\
CO + H_2O &\leftrightarrow CO_2 + H_2
\end{align*}
\]

Step 2: **Conditioning**
fly ash removal, particles, sulphur compounds, others.
Main gasifier types, and main Entrained Flow gasifiers in the market

Source: 2010 Gasification report, EPRI
Gasification in the world

Source: Higman Consulting GmbH
Step 1: Syngas production from **Gasification**

\[
\text{Carbon compound} + \text{O}_2 + \text{H}_2\text{O} \xrightarrow{400-1600^\circ\text{C}} \text{CO} + \text{H}_2 + \text{Impurities}
\]

Step 2: **Conditioning** → fly ash removal, particles and sulphur comp.

Step 3: “Shifting” or **water-gas reaction**

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2
\]

Step 4: \(\text{H}_2\) and \(\text{CO}_2\) **separation**

\[\text{H}_2 \quad \& \quad \text{CO}_2\]

\(\text{H}_2\) production from fossil fuels involves \(\text{CO}_2\) generation ⇒ To talk about “clean” \(\text{H}_2\) it is required to consider **CCS**
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4. R&D INVESTMENT PLAN
1. THE PUERTOLLANO ELCOGAS PLANT

THE ELCOGAS COMPANY

European company established in April 1992 to undertake the planning, construction, management and operation of a 335 MWe ISO IGCC plant located in Puertollano (Spain)
1. THE PUERTOLLANO ELCOGAS PLANT

- Coal preparation
- Laboratory and demineralised water treatment and storage
- Gasifier and gas cleaning systems
- Sulphur recovery
- Air separation unit
- Combined cycle
- Control building
- Combined cycle
1. THE PUERTOLLANO ELCOGAS PLANT

PROCESS DESCRIPTION

- Flue gas to stack
- Steam
- Hot combustion gas
- Clean syngas
- Sulfur (99.8%)
- Claus gas
- Sulfur removal
- Water treatment
- Fly ash
- Slag
- Quench gas
- Raw gas
- Filtration
- Water wash
- HP Boiler
- MP Boiler
- Gasifier
- Coal preparation
- Coal - N₂
- Limestone
- Petroleum Coke
- N₂
- O₂
- Air separation unit
- Compressed air
- Waste N₂
- Gas turbine
- Steam turbine
- Cooling tower
1. THE PUERTOLLANO ELCOGAS PLANT

MAIN DESIGN DATA

Design Fuel is a mixture 50:50 of coal & petcoke (currently operating at 45:55).

Successful tests with:
- MBM 2% (50 tpd)
- Olive oil wastes 10%
- Washed coal, Venezuela petcoke …

<table>
<thead>
<tr>
<th>COAL</th>
<th>PET COKE</th>
<th>FUEL MIX (50:50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%w)</td>
<td>11.8</td>
<td>7.00</td>
</tr>
<tr>
<td>Ash (%w)</td>
<td>41.10</td>
<td>0.26</td>
</tr>
<tr>
<td>C (%w)</td>
<td>36.27</td>
<td>82.21</td>
</tr>
<tr>
<td>H (%w)</td>
<td>2.48</td>
<td>3.11</td>
</tr>
<tr>
<td>N (%w)</td>
<td>0.81</td>
<td>1.90</td>
</tr>
<tr>
<td>O (%w)</td>
<td>6.62</td>
<td>0.02</td>
</tr>
<tr>
<td>S (%w)</td>
<td>0.93</td>
<td>5.50</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>13.10</td>
<td>31.99</td>
</tr>
</tbody>
</table>

**POWER OUTPUT AND EMISSIONS**

### POWER OUTPUT

<table>
<thead>
<tr>
<th>POWER OUTPUT</th>
<th>GAS TURBINE (MW)</th>
<th>STEAM TURBINE (MW)</th>
<th>GROSS TOTAL (MW)</th>
<th>NET TOTAL (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>182.3</td>
<td>135.4</td>
<td>317.7</td>
<td>282.7</td>
</tr>
</tbody>
</table>

### EFFICIENCY (LHV)

<table>
<thead>
<tr>
<th>EFFICIENCY (LHV)</th>
<th>GROSS</th>
<th>NET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47.12%</td>
<td>42.2%</td>
</tr>
</tbody>
</table>

### EMISSIONS

<table>
<thead>
<tr>
<th>EMISSIONS</th>
<th>g/kWh</th>
<th>mg/Nm³ (6% Oxygen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>0.07</td>
<td>25</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.40</td>
<td>150</td>
</tr>
<tr>
<td>Particulate</td>
<td>0.02</td>
<td>7.5</td>
</tr>
</tbody>
</table>
### Raw and Clean Gas Data

<table>
<thead>
<tr>
<th></th>
<th>Raw Gas</th>
<th></th>
<th>Clean Gas</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual average</td>
<td>Design</td>
<td>Actual average</td>
<td>Design</td>
</tr>
<tr>
<td><strong>CO (%)</strong></td>
<td>59.26</td>
<td>61.25</td>
<td>59.30</td>
<td>60.51</td>
</tr>
<tr>
<td><strong>H₂ (%)</strong></td>
<td>21.44</td>
<td>22.33</td>
<td>21.95</td>
<td>22.08</td>
</tr>
<tr>
<td><strong>CO₂ (%)</strong></td>
<td>2.84</td>
<td>3.70</td>
<td>2.41</td>
<td>3.87</td>
</tr>
<tr>
<td><strong>N₂ (%)</strong></td>
<td>13.32</td>
<td>10.50</td>
<td>14.76</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>Ar (%)</strong></td>
<td>0.90</td>
<td>1.02</td>
<td>1.18</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>H₂S (%)</strong></td>
<td>0.81</td>
<td>1.01</td>
<td><strong>H₂S (ppmv)</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>COS (%)</strong></td>
<td>0.19</td>
<td>0.17</td>
<td><strong>COS (ppmv)</strong></td>
<td>9</td>
</tr>
<tr>
<td><strong>HCN (ppmv)</strong></td>
<td>23</td>
<td>38</td>
<td><strong>HCN (ppmv)</strong></td>
<td>-</td>
</tr>
</tbody>
</table>
1. THE PUERTOLLANO ELCOGAS PLANT

MAIN EQUIPMENT: GASIFIER
1. THE PUERTOLLANO ELCOGAS PLANT

SIMPLIFIED BURNERS ARRANGEMENT

- Burner Type 1
- Burner Type 2
- Start-up Burner
- Igniter
1. THE PUERTOLLANO ELCOGAS PLANT

MAIN EQUIPMENT. GAS TURBINE

Air intake

Combustion chamber

Air Compressor

Generator

Turbine

Model V94.3
1. THE PUERTOLLANO ELCOGAS PLANT

PROJECT MILESTONES

1992  
Main contracts award

Jun 1996  
First synchronization of gas turbine

Oct 1996  
Commercial operation with natural gas

Jun 1997  
Performance test of the Air Separation Unit

Mar 1998  
First switch over from natural gas to coal gas

Nov 2000  
First 1,000 GWh produced with coal gas as IGCC

Dec 2011  
Total: 22,675 GWh
IGCC: 15,795 GWh

<table>
<thead>
<tr>
<th>BEST RESULTS</th>
<th>IGCC</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>Maximum continuous operating hours</td>
<td>953.70 h</td>
<td>1,513 h</td>
</tr>
<tr>
<td>Maximum annual production</td>
<td>1,595 GWh</td>
<td>1,938 GWh</td>
</tr>
<tr>
<td>Cumulative operating hours</td>
<td>57,106 h</td>
<td>91,944 h</td>
</tr>
</tbody>
</table>
1. THE PUERTOLLANO ELCOGAS PLANT

OPERATIONAL DATA. EMISSIONS 2011

Natural gas (mg/Nm³ at 6% O₂ dry)

- EEC 88/609
- ELCOGAS Environmental Permit
- ELCOGAS 2011 average

Coal gas (mg/Nm³ at 6% O₂ dry)

ELCOGAS power plant emissions in NGCC & IGCC modes
1. THE PUERTOLLANO ELCOGAS PLANT

OPERATIONAL DATA. Annual Energy Production

1st 5 years: Learning curve
2003: Major overhaul Gas Turbine findings
2004 & 2005: Gas turbine main generation transformer isolation fault
2006: Gas turbine major overhaul & candle fly ash filters crisis
2007 & 2008: ASU WN₂ compressor coupling fault and repair MAN TURBO
2010: No operation due to non-profitable electricity price (30-40 days).
2011: 100,000 EOH Major Overhaul
1. THE PUERTOLLANO ELCOGAS PLANT

ACCUMULATED INVESTMENT COSTS:

2008 OPERATING COSTS, WITHOUT FINANCIAL COSTS:

- **Fixed costs:**
  - Total: 29,441 K€ (20.39 €/MWh)

- **Variable costs:**
  - Fuels: 54,276 K€ (37.59 €/MWh)
  - Total: 83,602 K€ (57.90 €/MWh)
## 1. THE PUERTOLLANO ELCOGAS PLANT

### OPERATIONAL DATA. VARIABLE COSTS

<table>
<thead>
<tr>
<th>Fuel mode</th>
<th>Fuel</th>
<th>Consume (GJPCS)</th>
<th>Production (GWh)</th>
<th>Heat rate (GJPCS/GWh)</th>
<th>Fuel cost (€/GJPCS)</th>
<th>Partial cost (€/MWh)</th>
<th>Total cost (€/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT</td>
<td>Natural gas</td>
<td>73.574</td>
<td>4,253</td>
<td>17.299</td>
<td>9.60</td>
<td>166,08</td>
<td>166,08</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural gas</td>
<td>193.062</td>
<td>19,861</td>
<td>9.721</td>
<td>9.60</td>
<td>93,32</td>
<td>93,32</td>
</tr>
<tr>
<td>NGCC + ASU</td>
<td>Natural gas</td>
<td>1.913.372</td>
<td>174,993</td>
<td>10.934</td>
<td>9.60</td>
<td>104,97</td>
<td>104,97</td>
</tr>
<tr>
<td>NGCC + ASU + Gasifier (by flare)</td>
<td>Natural gas</td>
<td>339.750</td>
<td>33,057</td>
<td>10.278</td>
<td>9.60</td>
<td>98,67</td>
<td>98,67</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>102.412</td>
<td>3,35</td>
<td>3.098</td>
<td>3.35</td>
<td>10,39</td>
<td>10,39</td>
</tr>
<tr>
<td></td>
<td>Pet coke</td>
<td>255.477</td>
<td></td>
<td>7.728</td>
<td>2.70</td>
<td>20.91</td>
<td>20.91</td>
</tr>
<tr>
<td>IGCC</td>
<td>NG auxiliar consumption</td>
<td>221.057</td>
<td>1.160,901</td>
<td>190</td>
<td>9.60</td>
<td>1,83</td>
<td>32,23</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>3.493.829</td>
<td></td>
<td>3.010</td>
<td>3.35</td>
<td>10,09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pet coke</td>
<td>8.716.378</td>
<td></td>
<td>7.508</td>
<td>2.70</td>
<td>20,31</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Net energy variable costs (average 2011)
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4. R&D INVESTMENT PLAN
2. UNAVAILABILITY REASONS

1. THE PUERTOLLANO ELCOGAS PLANT

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4. R&D INVESTMENT PLAN
Reason 1. Gas Turbine

- Model V94.3 prototype abandoned by Siemens after 5 equipment fabrication

- Optimization of syngas burners to prevent overheating / humming and to accomplish more stability and remaining life of the hot components.

- Up to last design of syngas burner was installed in 2003 preventive inspections of hot gas path every 500 – 1000 syngas operating hours. High rate of ceramic tiles change.
2. UNAVAILABILITY REASONS. a) First five years

Reason 2. Gasifier

- Water leakage of membrane tubes due to flow blockages or local erosion. Design of distributors. Chemical control. Particle filtration.

![Reaction Chamber Diagram]

**REACTION CHAMBER**

- 4 x DN 200
  - (+36,200)
- 4 x DN 250
  - (+37,500)

Transversal section in the leakage area
Reason 2. Gasifier (II)

- Gas leakage due to piping corrosion. Proper selection of materials. To avoid “cold ends” and down time corrosion.
Reason 2. Gasifier (III)

- Fouling of Waste Heat boilers:
  - Sticky fly ash (reduced by decreasing gas inlet temperature to cooling surfaces. More quench flow)
  - Fluffy fly ash (reduced by increasing the velocity of the gas)
Reason 3. Grinding and mixing systems
Clogging in mills feeding and mixing conveyors. Two trains of 60%. Lack of robustness of equipment.
2. UNAVAILABILITY REASONS. a) First five years

Reason 4. Solids handling (slag and fly ash)

Erosion of components by local high velocities. Substitution of parts for abrasion resistant materials. Revision of design and operating procedures.
2. UNAVAILABILITY REASONS. a) First five years

Reason 5. Ceramic filters
Life time of filtrating elements is half of expected (4000 h). Very expensive cost. To improve by changing supporting design of elements.
Reason 5. Ceramic filters (II)

Wrong design, fly ash bypass, movement of candles during operation.

Change of system to Pall-Schumaker system during 2011 Overhaul
Reason 6. Fuel dust conveying and feeding systems

Pressure control and fluidization stability. Design of fluidization systems and preventive maintenance of components.
Reason 7. COS catalyst

2 – 3 changes by year of alumina based catalyst. Water carryover. Change to Titanium oxide catalyst (3 – 4 years) and pre-heater installation.
2. UNAVAILABILITY REASONS

1. THE PUERTOLLANO ELCOGAS PLANT

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4. R&D INVESTMENT PLAN
Main reasons for unavailability:

- IGCC. Product not required by System Operator during one month.
- Gasifier. COS hydrolysis catalyst deactivation.
- Gasifier. Water leaks in IP WHB and damage of candle filters and quench gas compressor.

### STATISTICS 2012 (up to August 28th)

<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>Gasifier</th>
<th>Power Block</th>
<th>ASU</th>
</tr>
</thead>
<tbody>
<tr>
<td>On stream (%)</td>
<td>48.5</td>
<td>51.2</td>
<td>67.4</td>
<td>60.2</td>
</tr>
<tr>
<td>Planned Outages (%)</td>
<td>3.6</td>
<td>3.9</td>
<td>3.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Unplanned Outages (%)</td>
<td>31.9</td>
<td>21.8</td>
<td>5.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Product not required (%)</td>
<td>13.0</td>
<td>16.0</td>
<td>23.0</td>
<td>32.4</td>
</tr>
<tr>
<td>Start up (%)</td>
<td>3.0</td>
<td>7.2</td>
<td>0.9</td>
<td>5.2</td>
</tr>
</tbody>
</table>
2. UNAVAILABILITY REASONS. b) Last years

IGCC AVAILABILITY IN 2011

- IGCC: Availability 21.5%, Planned Outages 19.2%, Unplanned Outages 1.8%
- Gasifier: Availability 73.1%, Planned Outages 9.1%, Unplanned Outages 5.5%
- Power Block: Availability 74.9%, Planned Outages 19.6%, Unplanned Outages 12.8%
- ASU: Availability 85.3%, Planned Outages 17.8%, Unplanned Outages 19.6%
2. UNAVAILABILITY REASONS. b) Last years

**IGCC UNAVAILABILITY 2011**

**Combined cycle**
- Gas Turbine: 93%
- Water-steam cycle: 3%
- GAS SATURATOR: 4%

**Gasification**
- Combined cycle water-steam cycle: 3%
- Gas saturator: 4%
- Sulfur recovery: 31%
- Gasification: 31%
- ASU: 4%
- BOP: 5%
- DCS: 41%
- Electrical system: 43%

**Gas Wet Treatment**
- Sulfur recovery: 15%

**Dry Deducing & Fly Ash Systems**
- Drying: 3%

**Quench Gas Recirculation**
- Quench gas recirculation: 12%

**Mixing & Grinding Plant**
- Mixing & grinding plant: 1%

**Start-Up Burner & Flame Monitors**
- Start-up burner & flame monitors: 0%

**MIXING & GRINDING PLANT**
- Mixing & grinding plant: 1%

**Dust Fuel Conveying & Feeding**
- Dust fuel conveying & feeding: 6%

**SULPHUR RECOVERY & TAIL GAS RECYCLE**
- Sulfur recovery & tail gas recycle: 0%

**Dry Deducing & Fly Ash Systems**
- Dry deducing & fly ash systems: 3%

**Quench Gas Recirculation**
- Quench gas recirculation: 12%

**Gasification**
- Gasification: 31%

**ASU**
- ASU: 4%

**BOP**
- BOP: 5%

**Combined Cycle**
- Combined cycle: 60%

**Unavailability Reasons**
- DUST FUEL CONVEYING & FEEDING: 0%
- MIXING & GRINDING PLANT: 1%
- SULPHUR RECOVERY & TAIL GAS RECYCLE: 0%
- DRY DEDUSTR & FLY ASH SYSTEMS: 3%
- QUENCH GAS RECIRCULATION: 12%
- GAS SATURATOR: 4%
- GAS WET TREATMENT: 15%
- SLAGS: 35%
- WATER-STEAM CYCLE: 3%
- GAS TURBINE: 93%
- PURS NITROGEN PRODUCTION: 15%
- WASTE NITROGEN PRODUCTION: 49%
- GAS OXYGEN PRODUCTION: 36%
- AUXILIARY SYSTEM: 16%
- DCS: 41%
- ELECTRICAL SYSTEM: 43%
- WATER STEAM SYSTEMS & BOILERS: 28%
- SULPHUR RECOVERY & TAIL GAS RECYCLE: 0%
- DRY DEDUSTR & FLY ASH SYSTEMS: 3%
- QUENCH GAS RECIRCULATION: 12%
- GAS SATURATOR: 4%
- GAS WET TREATMENT: 15%
- SLAGS: 35%
- WATER-STEAM CYCLE: 3%
- GAS TURBINE: 93%
- PURS NITROGEN PRODUCTION: 15%
- WASTE NITROGEN PRODUCTION: 49%
- GAS OXYGEN PRODUCTION: 36%
- AUXILIARY SYSTEM: 16%
- DCS: 41%
- ELECTRICAL SYSTEM: 43%
2. UNAVAILABILITY REASONS. b) Last years

100,000 eoh & Life Time Extension outage at Puertollano CC

Accumulated delay: 26 days by Siemens management. And 10 days by balancing and equipment faults along commissioning.
2. UNAVAILABILITY REASONS. b) Last years

STATISTICS MAINTENANCE CYCLE 2008-2011

- IGCC: Availability 28.7%, Planned Outages 10.7%, Unplanned Outages 60.7%
- Gasifier: Availability 9.1%, Planned Outages 9.8%, Unplanned Outages 81.2%
- Power Block: Availability 6.1%, Planned Outages 8.4%, Unplanned Outages 85.5%
- ASU: Availability 11.9%, Planned Outages 4.8%, Unplanned Outages 83.3%
2. UNAVAILABILITY REASONS. b) Last years

STATICS MAINTENANCE CYCLE 2008-2011

- GASIFICATION 40%
  - ASU 30%
  - BOP 4%
  - Combined Cycle 26%
- GAS TURBINE 81%
- DCS 38.4%
- POWER 13.4%
- AUXILIARY 48.3%
- OXYGEN PRODUCTION 16%
- PURE NITROGEN 3%
- WASTE NITROGEN 81%
- GAS SATURATOR 11%
- WATER STEAM CYCLE 8%
- WATER STEAM 17%
- FLY ASH 28%
- GAS TREATMENT 8%
- SULPHUR RECOVERY 8%
- SLAGS 11%
- BURNERS FEEDING 9%
- FUEL PREPARATION 4%
- START UP BURNER 5%
2. UNAVAILABILITY REASONS. b) Last years

**ASU. WN₂ compressor.**
Major overhaul of compressor, gear, coupling was done 10 months before incident. MAN TURBO
Coupling was found broken after a vibration trip during compressor start up

Root cause has not been determined by Man Turbo, nor Flender (coupling manufacturer). But very probable is due to bolt fatigue
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4. R&D INVESTMENT PLAN
3. OTHER LESSONS LEARNT. a) Carnot Project

European Commission CARNOT project  4.1004/D/02-002/2002

Pre-Engineering Studies for a New IGCC Plant Based on Puertollano ELCOGAS Plant Experience

Targets

- Definition of a Second Generation IGCC plant concept
- Assessment of optional pre-combustion CO₂ removal
- Dissemination of IGCC technology capability for clean and efficient power generation

Scope

Analysis of relevant plant operation data - definition of improvement potential - evaluation of technical, environmental and other general boundary conditions - definition of main process units - assessment of CO₂ capture and H₂ co-production - market potential emphasizing Russia - dissemination

Partners

- ELCOGAS S.A. (Coordinator, E)
- UHDE GmbH (D)
- Siemens AG PG (D)

Duration

08/2003 – 01/2005
**Fuel preparation**

<table>
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<tr>
<th>Recommendations</th>
<th>$A_v$</th>
<th>$V_c$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>To install a dual drying circuit using natural gas and syngas</td>
<td>≈</td>
<td>↓↓</td>
<td>↑</td>
</tr>
<tr>
<td>Current configuration is 2 mills x 60% → the best option should be 3 mills x 50%</td>
<td>↑</td>
<td>≈</td>
<td>↑↑</td>
</tr>
<tr>
<td>The fuel mixing does not require an extremely high precision → the fuel can be mixed in the coal yard</td>
<td>↑↑</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>To use a more robust system, maintaining the entrance plate of the mills hot enough to prevent the material to stick</td>
<td>↑↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>To take account of the future use of “green fuels”</td>
<td>≈</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>

**Coal dust feeding system**

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>$A_v$</th>
<th>$V_c$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>New LH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>To increase the outlet diameter of the lock hoppers</td>
<td>↑↑</td>
<td>≈</td>
<td>≈</td>
</tr>
<tr>
<td>To install a greater feed bin (100 t) and reduce the number of lock hoppers</td>
<td>↑</td>
<td>≈</td>
<td>↓↓</td>
</tr>
<tr>
<td>Pump system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New pneumatic pumping system: The pumps should have to work at high density and pressure conditions</td>
<td>↑</td>
<td>↑</td>
<td>↓↓↓</td>
</tr>
</tbody>
</table>
## Gasifier

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>$A_v$</th>
<th>$V_c$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>The design pressure is 40 bar, but the operation pressure is 25 bar → design pressure of most components could be reduced</td>
<td>≈</td>
<td>≈</td>
<td>↓↓</td>
</tr>
<tr>
<td>To develop a new start-up system with a igniter able to work at high pressure</td>
<td>↑</td>
<td>≈</td>
<td>≈</td>
</tr>
<tr>
<td>There are parts of the gasifier with low temperature → To change tube materials to avoid corrosion</td>
<td>↑</td>
<td>≈</td>
<td>↑</td>
</tr>
</tbody>
</table>

## Waste Heat Boilers

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>$A_v$</th>
<th>$V_c$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fouling can be mitigated with higher velocities of the gas → a new design should consider the reduction of HP heat exchanger surface and size</td>
<td>↑↑</td>
<td>≈</td>
<td>↑↑</td>
</tr>
<tr>
<td>The cleaning of the system is performed by rappers, that are changed every year → To change the rapper and plate materials</td>
<td>↑</td>
<td>↓</td>
<td>≈</td>
</tr>
</tbody>
</table>

## Slag handling

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>$A_v$</th>
<th>$V_c$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>To install a decanters system instead the bag filters system</td>
<td>↑</td>
<td>≈</td>
<td>↓</td>
</tr>
<tr>
<td>One of the slag lock hoppers and one of the slag extractors could be removed</td>
<td>≈</td>
<td>≈</td>
<td>↓</td>
</tr>
<tr>
<td>To replace pump and component material for a more resistant one</td>
<td>↑</td>
<td>≈</td>
<td>↑</td>
</tr>
</tbody>
</table>
## Dedusting, Quench & Fly ash systems

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</th>
</tr>
</thead>
<tbody>
<tr>
<td>To install a new type of candle filter</td>
<td>↑</td>
<td>↑</td>
<td>≈</td>
</tr>
<tr>
<td>Safe and reliable filtration elements support system</td>
<td>↑↑</td>
<td>↓↓</td>
<td>≈</td>
</tr>
<tr>
<td>The fly-ash recycling system is not necessary</td>
<td>≈</td>
<td>↓</td>
<td>↓↓</td>
</tr>
<tr>
<td>To remove the wet discharge system</td>
<td>≈</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

## Gas cleaning-up (Scrubbing and Desulphurization)

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</th>
</tr>
</thead>
<tbody>
<tr>
<td>To install a higher quality material (S.S.) in the main raw gas pipe to avoid corrosion</td>
<td>↑</td>
<td>≈</td>
<td>↑</td>
</tr>
<tr>
<td>To install a new catalyst type to improve COS hydrolysis to H₂S</td>
<td>↑↑</td>
<td>↓↓</td>
<td>↑</td>
</tr>
<tr>
<td>To use new solvents with COS removing capacity</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>To install a desalting pilot plant to remove MDEA formiates</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>

## Clean Gas Conditioning System

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing waste nitrogen with clean gas before saturation would improve controllability</td>
<td>↑↑</td>
<td>≈</td>
<td>≈</td>
</tr>
<tr>
<td>Syngas fuel feeding system should be designed and operated to prevent condensation</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>
## Air Separation Unit

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</th>
</tr>
</thead>
<tbody>
<tr>
<td>To consider $\uparrow$ $\text{O}_2$ purity ( $&gt; 95%$ instead of $85%$) $\rightarrow$ makes ASU control more stable, and % plant load change can be improved</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow \downarrow$</td>
</tr>
<tr>
<td>Oxygen storage and LOX system are not necessary</td>
<td>$\approx$</td>
<td>$\downarrow$</td>
<td>$\downarrow \downarrow$</td>
</tr>
<tr>
<td>$\text{Av}$ &amp; $\text{Vc}$ would be improved by using a $50%$ air compressor, and the other $50%$ coming from $\text{GT}$ compressor $\rightarrow$ the time required for IGCC commissioning is also reduced</td>
<td>$\uparrow \uparrow \uparrow$</td>
<td>$\downarrow \downarrow \downarrow$</td>
<td>$\uparrow \uparrow$</td>
</tr>
</tbody>
</table>

## Gas Turbine

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</th>
</tr>
</thead>
<tbody>
<tr>
<td>New models with more robust combustors. General line should be increasing resistance of components to high temperature.</td>
<td>$\uparrow \uparrow$</td>
<td>$\downarrow \downarrow$</td>
<td>$\uparrow$</td>
</tr>
<tr>
<td>Fogging system with a proper drain system should be installed.</td>
<td>$\uparrow \uparrow$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
</tr>
<tr>
<td>Increasing power and efficiency with last proven models. The effect of scale will increase economical figures of the project.</td>
<td>$\uparrow$</td>
<td>$\downarrow \downarrow \downarrow$</td>
<td>$\uparrow$</td>
</tr>
<tr>
<td>Start-up directly with syngas instead NG, and offering NG as an alternative fuel to attend gasification unavailability</td>
<td>$\approx$</td>
<td>$\downarrow \downarrow$</td>
<td>$\approx$</td>
</tr>
</tbody>
</table>
In a new design for Puertollano IGCC plant with the reported improvements:

- **Investment cost saving around 30%**
- **Availability increase (up to 90%)**

Elcogas operating experiences → Highlighted conclusions:

1. **Inflexibility of the operation due to design**
   - The total integration ASU-CC implies a long and costly start-up sequence

2. **Causes of limitation in availability**
   - Availability not affected by gasification process, but by low reliability of conventional units

3. **Improvements to initial design**
   - Satisfactory solutions have been found to the problems identified during last years → more than 4450 modifications executed
INDEX

1. THE PUERTOLLANO ELCOGAS PLANT

2. UNAVAILABILITY REASONS
   a. First five years
   b. Last years

3. OTHER LESSONS LEARNT
   a. Carnot Project
   b. Organisation

4. R&D INVESTMENT PLAN
## ELCOGAS IGCC Project General Schedule

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td><strong>Basic Engineering</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Detailed engineering</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Supply main equipment</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Erection Power Block</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commissioning PB with NG</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Erection ASU &amp; Gasification</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commissioning ASU &amp; Gasification</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Scheduled**
- **As was**

- **Cabling, 37 vs 1290**
- **Auxiliaries, GT**
- **Coal prep., KU**

### 3. OTHER LESSONS LEARNT.

#### b) Organisation
### MECHANICAL

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps</td>
<td>363</td>
</tr>
<tr>
<td>Compressors &amp; fans</td>
<td>201</td>
</tr>
<tr>
<td>Conveyors &amp; Screw transporters</td>
<td>32</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>351</td>
</tr>
<tr>
<td>Tanks</td>
<td>248</td>
</tr>
<tr>
<td>VALVES</td>
<td>13414</td>
</tr>
<tr>
<td>Manual</td>
<td>12052</td>
</tr>
<tr>
<td>Automatic</td>
<td>1362</td>
</tr>
<tr>
<td>Act. Motorised</td>
<td>116</td>
</tr>
<tr>
<td>Act. Pneumatic</td>
<td>1162</td>
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<tr>
<td>Act. Hydraulic</td>
<td>84</td>
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</table>

### ELECTRICAL

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformers</td>
<td>20</td>
</tr>
<tr>
<td>High voltage</td>
<td>6</td>
</tr>
<tr>
<td>6/0.4 KV</td>
<td>14</td>
</tr>
<tr>
<td>CCM 400V</td>
<td>23</td>
</tr>
<tr>
<td>Motors</td>
<td>715</td>
</tr>
<tr>
<td>10.5 KV</td>
<td>1</td>
</tr>
<tr>
<td>6 KV</td>
<td>27</td>
</tr>
<tr>
<td>400 V</td>
<td>687</td>
</tr>
<tr>
<td>km cabling</td>
<td>1290</td>
</tr>
<tr>
<td>Power &amp; control</td>
<td>920</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>370</td>
</tr>
</tbody>
</table>

### I&C

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local instrument</td>
<td>6807</td>
</tr>
<tr>
<td>Local PLC</td>
<td>40</td>
</tr>
</tbody>
</table>

### DCS

<table>
<thead>
<tr>
<th>Category</th>
<th>CC &amp; PB</th>
<th>BOP</th>
<th>ASU</th>
<th>Gasification</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signals</td>
<td>8547</td>
<td>4385</td>
<td>4774</td>
<td>17648</td>
<td>35354</td>
</tr>
<tr>
<td>Functionals</td>
<td>6390</td>
<td>1220</td>
<td>2501</td>
<td>11273</td>
<td>21384</td>
</tr>
<tr>
<td>Alarms</td>
<td>2666</td>
<td>1135</td>
<td>882</td>
<td>3089</td>
<td>7772</td>
</tr>
<tr>
<td>Electronic boxes</td>
<td>35</td>
<td>9</td>
<td>6</td>
<td>33</td>
<td>83</td>
</tr>
</tbody>
</table>
3. LESSONS LEARNT - SUMMARY

✓ **High efficiency.** Higher than other coal-based technologies & great potential of improvement: net 42% → 50%

✓ **Flexible feeding**

✓ Coal (several qualities)

✓ Alternative fuels (pet-coke, USW, biomass, etc.)

✓ Availability of second fuel for combined cycle

Reliability of energy supply

✓ **Product flexibility** → power, H₂, CO₂, methanol, NH₃, gasolines, etc

Lower risk: Production as per market
3. LESSONS LEARNT - SUMMARY

✔ **Environment:**

- Lower CO$_2$ emissions compared to other coal-based technologies. Higher potential to zero emission plants
- Low acid gas emission (SO$_2$, NO$_x$) and particles. Similar or best than NGCC plants
- Lower wastes. Slag, fly ash, sulphur and salts are by-products
- Lower water consumption than other coal-based technologies
- No dioxins/furans using organic fuels
- Lower Hg emissions and best method to remove it

✔ **Economy:**

- Very competitive fuel compared to natural gas. Variable cost per kWh with coal is very low compared to natural gas
- Lower cost of CO$_2$ capture (pre-combustion)
- Wastes are marketable products

✔ **Sustainability:**

- Coal reserves for more than 200 years and best geographical distribution
- Almost any fuel with enough carbon can be gasified
3. LESSONS LEARNT - SUMARY

✗ Technology at demonstration state
   ✓ First coal-based plants (USA & EU, 1994 - 1998) show 60-80% of IGCC availability (> 90 % considering auxiliary fuel)
   ✓ Main unavailability causes related with its maturity lack in the past:
     ✗ Auxiliary system design: solid handling, downtime corrosion, ceramic filters, materials and suitable procedures
     ✗ Performance of last generation turbines with syngas or natural gas
     ✗ Excessive integration between units. High dependence and start-up delay
     ✗ More complex process compared to other coal-based plants. Learning is necessary. IGCC power plants using petroleum wastes show higher availability than 92%

✗ High inversion cost
   ✓ Investment costs of existing plants varies 1,500-2,000 €/kW installed (1990-1998)
   ✓ Currently, its estimation varies 2,500-5,000 €/kW installed
3. LESSONS LEARNT - SUMARY

Technology at demonstration state. IGCC availability at 2010

Source: 2010 Gasification report. EPRI
3. LESSONS LEARNT - SUMMARY

REGULATORY SUPPORT IS ESSENTIAL IN TECHNOLOGY DEMONSTRATION PROJECT AT COMMERCIAL SCALE

Total production cost
1. THE PUERTOLLANO ELCOGAS PLANT

2. UNAVAILABILITY REASONS
   a. First five years
   b. Last years

3. OTHER LESSONS LEARNED
   a. Carnot Project
   b. Organisation

4. R&D INVESTMENT PLAN
Since 2007 Elcogas has defined a R&D Investment Plan to develop IGCC technology in order to decrease the environmental impact of power production as main target.

Elcogas presents a yearly report of results of that R&D Plan to Spanish government for evaluation.

**MAIN LINES OF R&D PLAN ARE:**

- **CO\(_2\)** emission reduction in utilization of fossil fuels
- **H\(_2\)** production by gasification of fossil fuels
- **Diversification** of raw fuels and products
- Other environmental improvements
- IGCC processes optimization
- Dissemination of results
Dissemination of results

- **Forum** participations. $\text{CO}_2$, $\text{H}_2$, and sustainability associations and Technological Platforms. European and Spanish. **Coordinating working groups in Technological Spanish Platforms.**

- Participation in **conferences**, seminars, congresses.

- **Consulting** services. Germany, China, Chile

- Attending and promoting technical **visits**. Generally international visits.
4. R&D INVESTMENT PLAN

**Optimisation of IGCC processes:** Oriented to improve availability & costs

- **Gasifier materials/Syngas corrosion processes**
- **Test materials**
- **Elimination of membrane water leakages at reaction chamber**
- **Ceramic filters**
4. R&D INVESTMENT PLAN

**Other environmental improvements**

- Liquid *wastes* reduction. Change of waste water treatment plant
- Improvement of syngas **cleaning** systems. Currently participating in project AGAPUTE (RFCS, 2004-08, to study improvements in syngas cleaning). Hg task.
- Improvements in **Sulphur** Recovery plant. In progress several modifications to improve availability and to reduce S emissions.
- Operation and additives **parameters** optimization. Included in AGAPUTE to study dosing of limestone, oxygen, steam, vs. concentration of contaminants in slags, fly ash and washing water
- Emissions reduction during start up and other **transitory** situations.

Overview of the test rig for mercury and carbonyls analysis

Cross correlation between limestone content in the fuel and Se bulk fly ash content
4. R&D INVESTMENT PLAN

Diversification of raw fuels and products

Project PIIBE (ESP-CENIT). To impulse biofuels technologies in Spain. ELCOGAS coordinates the subproject about biodiesel from gasification by real co-gasification 10% of biomass and syngas characterization (F-T process in laboratory)

Agreement with a private European Company to install a pilot plant in IGCC of Puertollano to develop process to obtain gasoline from syngas

Project PEIXE VERDE. (ESP-PSE). Technical-economic study about uses of syngas as fuel for fishing ships in different scales of production

Co-gasification of car manufacture wastes (shredder fibres) was agreed with supplier.

Available to do tests of gasification of different fuels at large scale to help in design of new IGCC plants

Clean H₂ by gasification of fuels

H₂ production in IGCC. Project HYDROSEP (RFCS, to study IGCC adaptation to H₂ production)

Study and tests of new processes of H₂ purification. Project SPHERA (ESP-CENIT)

Available to collaborate with new H₂ & Fuel Cells Experimental National Centre of Puertollano
### Diversification of raw fuels and products. Biomass co-gasification

**Biomass selection criteria:**

- **Size**: < 25 mm
- **Humidity**: < 12%
- **Price**: < 150 €/t
- **Availability in large quantities**

**Battery of co-gasification tests undertaken with olive oil waste (orujillo)**

<table>
<thead>
<tr>
<th>Test Month/Year</th>
<th>orujillo dosage ratio in weight%</th>
<th>orujillo tonnes (t)</th>
<th>Test duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007-2009</td>
<td>1-2 %</td>
<td>1.572,84</td>
<td>800,3</td>
</tr>
<tr>
<td>2008</td>
<td>4 %</td>
<td>652,14</td>
<td>154</td>
</tr>
<tr>
<td>March 2009</td>
<td>6 %</td>
<td>395,86</td>
<td>64,4</td>
</tr>
<tr>
<td>June 2009</td>
<td>8 %</td>
<td>383,90</td>
<td>46</td>
</tr>
<tr>
<td>Sept. 2009</td>
<td>10 %</td>
<td>656,68</td>
<td>62</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>3.661,42</td>
<td>1.126,7</td>
</tr>
</tbody>
</table>

**Critical parameter for the biomass selection was the behavior on the ELCOGAS grinding system.**

**Olive oil waste storage area**

---

**4. R&D INVESTMENT PLAN**

**Load during %8 olive oil waste co-gasification test**
4. R&D INVESTMENT PLAN

**CO₂ line**

**CO₂ EMISSION REDUCTION**

**IGCC Efficiency** Optimisation

- Analysis of viability to improve efficiency based on **Critical Assessment** of Puertollano IGCC design
- **Auxiliary** consumption optimization. New revision
- Development of **tools** to improve efficiency. Supervision on line of main (120) equipment efficiency. Installed and in tests
- Integration optimization. Improvement of **controls** to adjust heat & mass balances in real operation

**CO₂ capture for CCS with IGCC**
To demonstrate the **feasibility of capture of CO$_2$ and production of H$_2$** in an IGCC that uses solid fossil fuels and wastes as main feedstock.

To obtain **economic data** enough to **scale** it to the full Puertollano IGCC capacity in synthetic gas production.

**TARGETS**

**PARTICIPANTS & BUDGET**

- ELCOGAS – UCLM – Ciemat – INCAR CSIC

14.5 M€ (initially 18.5 M€)

**COORDINATION**

- Project of pilot plant in an existing IGCC of Puertollano (pre-combustion technology) is part of a **Spanish national initiative, “Advanced technologies of CO$_2$ conversion, capture and storage”** and it is coordinated with other related projects:

  - Project # 2 **is to explore** oxyfuel combustion **to be applied in the construction of a pilot plant (20-30 MW) to be built in El Bierzo, NW of Spain. CIUDEN**
  - Project # 3 **is to study and regulate** geological storage in Spain. **IGME**
  - Project # 4 **is to study** public awareness of CCS technologies. **CIEMAT**
Puertollano IGCC power plant and pilot plant location

Pilot plant general view (14 MWt)

IGCC power plant general view
**4. R&D INVESTMENT PLAN.**

PSE-CO₂: CO₂ Capture Pilot Plant

**COMBINED CYCLE**

**COAL + COKE**

- **GASIFICATION**
  - Raw gas

- **FILTRATION SYSTEM**
  - Syngas

- **PURIFICATION & DESULPHURATION**
  - 2%

- **SHIFT REACTOR**
  - H₂ rich gas
    - 37.5% CO₂
    - 50.0% H₂
    - 3.0% CO
  - CO + H₂O → CO₂ + H₂

- **CO₂ & H₂ separation**
  - (Chemical, aMDEA)
  - 100 t/d

- **HYDROGEN PURIFICATION (PSA)**
  - 40%
  - Pure H₂ (2 t/d)
  - Tail gas 1.3 bar
  - 99.99% H₂ @ 15 bar

- **Recycle compressor**

<table>
<thead>
<tr>
<th>Flow (Nm³/h)</th>
<th>SWEET</th>
<th>SOUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,610</td>
<td>60.45</td>
<td>53.72</td>
</tr>
<tr>
<td>4,006</td>
<td>21.95</td>
<td>19.57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P (bar)</th>
<th>T (°C)</th>
<th>% CO₂</th>
<th>% H₂</th>
<th>% H₂O</th>
<th>% H₂S</th>
<th>% COS</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.8</td>
<td>126</td>
<td>60.45</td>
<td>21.95</td>
<td>0.29</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>23.6</td>
<td>138</td>
<td>53.72</td>
<td>19.57</td>
<td>10.40</td>
<td>0.70</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**R&D INVESTMENT PLAN.**
PSE-CO₂: CO₂ Capture Pilot Plant
4. R&D INVESTMENT PLAN.

PSE-CO₂: CO₂ Capture Pilot Plant

**Empresarios Agrupados**
Linde-Caloric
Linde
Zeus Control
Técnicas Reunidas
Johnson Matthey
Local companies

**Construction**

**MILESTONES**

- First CO₂ tonne captured in 13th September 2010
- 1000 tonnes of CO₂ captured
- 6 tonnes of H₂ produced
### Shifting unit

<table>
<thead>
<tr>
<th></th>
<th>Flow kg/h</th>
<th>P bar</th>
<th>T °C</th>
<th>CO %</th>
<th>H₂ %</th>
<th>CO₂ %</th>
<th>H₂O %</th>
<th>H₂S %</th>
<th>COS %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>3,677</td>
<td>19.8</td>
<td>126</td>
<td>60.45</td>
<td>21.95</td>
<td>2.66</td>
<td>0.29</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>3,999</td>
<td>23.6</td>
<td>138</td>
<td>53.72</td>
<td>19.57</td>
<td>2.70</td>
<td>10.40</td>
<td>0.70</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Shifted gas to</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>separation unit</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sweet</td>
<td>8,732</td>
<td>17.3</td>
<td>274</td>
<td>1.68</td>
<td>28.37</td>
<td>21.34</td>
<td>43.26</td>
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<tr>
<td>Sour</td>
<td>8,705</td>
<td>21.1</td>
<td>277</td>
<td>1.40</td>
<td>28.39</td>
<td>21.53</td>
<td>42.73</td>
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<tr>
<td><strong>IP saturated steam</strong></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>to feed</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>5,055</td>
<td>34.0</td>
<td>243</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100</td>
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<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>4,706</td>
<td>34.0</td>
<td>243</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**General view of Shifting Unit**
### General View of Separation Unit

#### Process Flow Table

<table>
<thead>
<tr>
<th></th>
<th>Flow kg/h</th>
<th>P bar</th>
<th>T °C</th>
<th>CO %</th>
<th>H₂ %</th>
<th>CO₂ %</th>
<th>H₂O %</th>
<th>H₂S %</th>
<th>COS %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shifted gas to absorber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sweet</td>
<td>5,318</td>
<td>15.9</td>
<td>45</td>
<td>2.9</td>
<td>49.7</td>
<td>37.3</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Sour</td>
<td>5,318</td>
<td>19.7</td>
<td>45</td>
<td>2.46</td>
<td>49.7</td>
<td>37.69</td>
<td>0.62</td>
<td>0.51</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Process condensed</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Sweet</td>
<td>3,414</td>
<td>15.9</td>
<td>45</td>
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<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Sour</td>
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<td>19.7</td>
<td>45</td>
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<td>0.0</td>
<td>0.0</td>
<td>100</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>CO₂ product</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>4,185</td>
<td>1.5</td>
<td>40</td>
<td>0</td>
<td>0.18</td>
<td>95.32</td>
<td>4.47</td>
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</tr>
<tr>
<td>Sour</td>
<td>4,295.5</td>
<td>1.55</td>
<td>40</td>
<td>0.01</td>
<td>0.21</td>
<td>94.02</td>
<td>4.47</td>
<td>1.27</td>
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<tr>
<td><strong>H₂ to PSA</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Sweet</td>
<td>481.7</td>
<td>15.2</td>
<td>40</td>
<td>4.63</td>
<td>79.37</td>
<td>0.5</td>
<td>0.48</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>457.3</td>
<td>19.1</td>
<td>40</td>
<td>4.02</td>
<td>80.44</td>
<td>0.5</td>
<td>0.39</td>
<td>0.0001</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Rich H₂ gas</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>1,190.1</td>
<td>15.6</td>
<td>40</td>
<td>4.63</td>
<td>79.37</td>
<td>0.5</td>
<td>0.48</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>1,135.2</td>
<td>19.4</td>
<td>40</td>
<td>4.02</td>
<td>80.44</td>
<td>0.5</td>
<td>0.39</td>
<td>0.0001</td>
<td>0.0</td>
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<tr>
<td><strong>LP Steam to reboiler</strong></td>
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<td></td>
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<tr>
<td>Sweet</td>
<td>4,763</td>
<td>4.1</td>
<td>144</td>
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<td>0.0</td>
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<tr>
<td>Sour</td>
<td>4,797</td>
<td>4.1</td>
<td>144</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100</td>
<td>0.0</td>
<td>0.0</td>
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</tbody>
</table>
### PSA Unit

<table>
<thead>
<tr>
<th></th>
<th>Flow Nm³/h</th>
<th>P bar</th>
<th>T °C</th>
<th>CO %</th>
<th>H₂ %</th>
<th>CO₂ %</th>
<th>H₂S %</th>
<th>COS %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H₂ from separation unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>1,431</td>
<td>15.2</td>
<td>40</td>
<td>4.63</td>
<td>79.37</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>1,412</td>
<td>19.1</td>
<td>40</td>
<td>4.02</td>
<td>80.44</td>
<td>0.5</td>
<td>0.0001</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>H₂ product</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>795</td>
<td>14.7</td>
<td>43</td>
<td>0.0004</td>
<td>99.99</td>
<td>0.0001</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>795.1</td>
<td>18.6</td>
<td>43</td>
<td>0.0004</td>
<td>99.99</td>
<td>0.0001</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Tail gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweet</td>
<td>636</td>
<td>1.3</td>
<td>35.9</td>
<td>10.42</td>
<td>53.58</td>
<td>1.13</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sour</td>
<td>616.9</td>
<td>1.3</td>
<td>35.7</td>
<td>9.2</td>
<td>55.23</td>
<td>1.14</td>
<td>0.0002</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**General view of PSA unit**

**H₂ product**

**Tail gas drum**

**Adsorbers**

**H₂ from separation unit**

**Rich H₂ gas (40 % flow)**

**Tail gas**
The main learning in project phase:

- **The finance delay**: MICINN (Spanish Science & Research Minister) and JCCM (Regional Government).

- **Delay in main equipment supply**: more than 12-14 months.

- **Detailed engineering**: conditioned by suppliers.

- **PP construction step**: delay due to safety permits since it is installed in an operating plant.

- **Delay of commissioning**: low availability of experimented personnel.
Characterization tests

- Completed tests with sweet and sour gas.
- **Objective**: Characterization of each unit.
- **Approach**: Starting from reference conditions, modify a parameter, stability, sample analysis and then, coming back to reference conditions and repeat with others parameters.
- Commitment of funding programme.
- Schedule:
  - **15-19 Nov 2010**. H₂ purification unit with *sweet gas*.
  - **17-20 Jan 2011**. CO₂ & H₂ separation unit with *sweet gas*.
  - **20-22 Jan 2011**. WGS reaction unit with *sweet gas*.
  - **6-10 Jun 2011**. WGS reaction unit and CO₂ & H₂ separation unit with *sour gas*.
- 1000 tonnes of CO₂ have been captured and 6 tonnes of H₂ have been produced.
- The PSA is quite stable and not affected by variation of the different parameters.

Further tests

**New tests** are being carried out to study alternative fuels influence in CO₂ capture and H₂ co-production (FECUNDUS project- RFCS Programme)
**Outcome**

- **Operation**: with sour catalyst found to be more stable than with sweet catalyst.
- **Number of reactors**: 95% of the total conversion takes place in the 1st reactor. Are necessary two stages?. Cost assessment: investment cost vs. capture rate.

<table>
<thead>
<tr>
<th>Number of reactors</th>
<th>CO outlet shifting unit</th>
<th>CO$_2$ capture (shifting + amines)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.9%</td>
<td>91%</td>
</tr>
<tr>
<td>1</td>
<td>10.6%</td>
<td>75%</td>
</tr>
</tbody>
</table>

*Design figures in sweet conditions*

- **Steam consumption**: key parameter for efficiency and capture rate. Cost assessment

  $\uparrow$ of 30% in steam consumption leads to $\uparrow$ 1% in CO conversion.

<table>
<thead>
<tr>
<th>Feed gas</th>
<th>Steam consumption</th>
<th>Thermal efficiency Shifting Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>sweet</td>
<td>5.055 kg/h</td>
<td>75.3%</td>
</tr>
<tr>
<td>sour</td>
<td>4.706 kg/h</td>
<td>77.1%</td>
</tr>
</tbody>
</table>

*Design figures*
4. R&D INVESTMENT PLAN.
PSE-CO₂: CO₂ Capture Pilot Plant. Shift converter unit

**WGS Operational window**

- **Inlet temperature to reactor 1 (ºC)**
- **Molar steam/CO ratio**
- **Out of operational limits**
- **Coking risk**
- **Areas of interest for future tests**
- **Real tests**
- **Minimum reaction temperature**
IGCC net efficiency penalty when adding (retrofit) a carbon capture unit
CO2 Capture Pilot Plant. CO2 capture cost estimation

- **Scenario.** To add a carbon capture unit to the Puertollano IGCC Plant based on Pilot Plant Retrofitting.

\[
\text{Cost of CO}_2\text{ not emitted} = \frac{\text{Cost derived from CO}_2\text{ Unit addition}}{\text{amount of non - emitted CO}_2}
\]

- **Investment costs.** Installation costs: \(349.800.000\) € (not PSA, scale factor, 25 years, IR: 3 %).

- **Fixed O&M Costs:** Spare, consumables, maintenance, external services, ...: based on in-house information: \(416.232\) €/y.

- **Variable O&M costs:** Efficiency loss => Production loss = f (operating hours: 6.500; load factor: 0.92; efficiency penalty: 9%; electricity price: 40 €/MWh).

- **Total of CO\(_2\) captured:** 90%

- **Cost of non-emitted CO\(_2\) (without compression):** \(26,35\) €/tCO\(_2\)

- Extensive sensitive analysis has been carried out (scale factor, operating hours, load factor, COE, \(\Delta\eta\), investment costs).
4. R&D INVESTMENT PLAN.

PSE-CO₂: CO₂ Capture Pilot Plant

CO₂ Capture Costs (SWEET).
As IGCC retrofit

<table>
<thead>
<tr>
<th>Variables</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected life</td>
<td>25</td>
</tr>
<tr>
<td>Bank interest</td>
<td>3.0 %</td>
</tr>
<tr>
<td>Bank fee</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Scale factor</td>
<td>0.75</td>
</tr>
<tr>
<td>Operating hours (IGCC mode)</td>
<td>6,500 h</td>
</tr>
<tr>
<td>Average load factor</td>
<td>0.92</td>
</tr>
<tr>
<td>Electricity price</td>
<td>40 €/MWh</td>
</tr>
<tr>
<td>Net efficiency of power plant with CO₂ capture</td>
<td>33 %</td>
</tr>
<tr>
<td>Treated gas</td>
<td>100 %</td>
</tr>
</tbody>
</table>
Relationship between electricity price and hydrogen price

Minimum H2 prices depending on electricity price

Better to sell H₂

Better to sell electricity

4. R&D INVESTMENT PLAN.
PSE-CO₂: CO₂ Capture Pilot Plant
1) The carbon capture pilot Project has been a **success**: first of its kind in the world, >90% capture rate achieved, and CO$_2$ capture cost can be <30 €/t

2) Commercial technology **at any scale** is available: the singularity comes from “integration in a existing IGCC plant”

3) Tests carried out show **room for improvement** in operating conditions and optimization of energy balance.

4) Carbon capture cost estimations come from **figures of a real project**.

5) From now on, the pilot is being used for **internal research**

6) But it is **also open** for international research projects and for other kinds of collaboration
4. R&D INVESTMENT PLAN.
PSE-CO$_2$: CO$_2$ Capture Pilot Plant

**Pilot Plant beyond PSE project**

*Pilot plant* for CO$_2$ capture and production of H$_2$ and electricity with IGCC technology

**Other** activities: To be done *after PSE* as R&D platform:

- Water shift reaction *catalyst* optimization. Tests of different catalyst
- **New processes** to separate CO$_2$-H$_2$
- CO$_2$ different *treatment* processes
- Improvement of *integration* efficiency between CO$_2$ separation processes and IGCC plant

ELCOGAS offers both the Puertollano IGCC and the Pilot Plant for CO$_2$ capture and H$_2$ production as technical platforms to develop of process, equipments, components, or even pre-engineering of new plants with CCS and Zero emissions.
International Training Programme on Clean Coal Technologies and Carbon Capture and Storage: Learning from the European CCT/CCS Experiences

IGCC Technology and CCS Demonstration – Spain Experience
Experiences from ELCOGAS IGCC plant

Francisco García Peña
gtecno@elcogas.es