Short Course Gasification

Prenflo Gasification Technology
Experiences from Puertollano plant

Fernando Alarcón
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2. UNAVAILABILITY REASONS
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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 MWei 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

Coal preparation

Coal - N₂

HP Boiler

MP Boiler

Gasifier

Raw Gas

Filtration

Quench Gas

Sulfur Removal

Clean syngas

Water wash

Fly ash

Tail Gas

Sulfur Recovery

Claus gas

Sulfur (99.8%)

Air Separation Unit

Waste N₂

Compressed air

Heat Recovery Steam Generator

Condenser

GAS TURBINE

200 MW ISO

STEAM TURBINE

135 MW ISO

Flue gas to stack

Steam

Hot combustion gas

Cooling tower

Coal Petroleum Coke

Limestone

Coal - N₂

N₂

O₂
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 8% (10% planned)
- 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>
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<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

<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>182.3</td>
<td>135.4</td>
<td>317.7</td>
<td>282.7</td>
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</tbody>
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<table>
<thead>
<tr>
<th>EFFICIENCY (LHV)</th>
<th>GROSS</th>
<th>NET</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.12%</td>
<td>42.2%</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>EMISSIONS</th>
<th>g/kWh</th>
<th>mg/Nm$^3$ (6% Oxygen)</th>
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</thead>
<tbody>
<tr>
<td>SO$_2$</td>
<td>0.07</td>
<td>25</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>0.40</td>
<td>150</td>
</tr>
<tr>
<td>Particulate</td>
<td>0.02</td>
<td>7.5</td>
</tr>
</tbody>
</table>
### 1. THE PUERTOLLANO ELCOGAS PLANT

#### RAW AND CLEAN GAS DATA

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

MAIN EQUIPMENT. GASIFIER

[Diagram of the gasifier with labeled components such as HP evaporator, reversal chamber, quench gas, transfer lines, and raw gas flows.]

- HP EVAPORATOR 2 (972 m³)
- HP EVAPORATOR 1 (972 m³)
- REVERSAL CHAMBER (8 m³)
- HP MEmbrane WALL (387 m³)
- HP RAW GAS EXIT ELBOWS TO TRANSFER LINES
- BURNERS
- SLAG RUNOUT
- SLAG IMMERSION SHAFT
- Water level
- TOP CONE
- BOTTOM CONE
- Transfer lines
- Raw gas (113,770 m³/h)
- Raw gas to CANDLE FILTER (113,770 m³/h)
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
- Turbine
- Combustion chamber
- Air Compressor
- Generator

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>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)**

- **SO₂**: 29.2 (EEC 88/609), 12.5 (ELCOGAS Environmental Permit), 4.2 (ELCOGAS 2011 average)
- **Particles**: 8.6 (EEC 88/609), 4.2 (ELCOGAS Environmental Permit), 1.4 (ELCOGAS 2011 average)
- **NOₓ**: 291.7 (EEC 88/609), 250.0 (ELCOGAS 2011 average), 166.0 (ELCOGAS Environmental Permit)

**Coal gas (mg/Nm³ at 6% O₂ dry)**

- **SO₂**: 500 (EEC 88/609), 200 (EU Directive 2001/80/EEC), 200 (ELCOGAS Environmental Permit), 400 (ELCOGAS 2011 average)
- **NOₓ**: 650 (EEC 88/609), 500 (EU Directive 2001/80/EEC), 119 (ELCOGAS Environmental Permit), 50 (ELCOGAS 2011 average)
- **Particles**: 0.74 (EU Directive 2001/80/EEC), 50 (ELCOGAS Environmental Permit), 5 (ELCOGAS 2011 average)

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 WN\textsubscript{2} 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
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 (GJ_PCS)</th>
<th>Production (GWh)</th>
<th>Heat rate (GJ_PCS/GWh)</th>
<th>Fuel cost (€/GJ_PCS)</th>
<th>Partial cost (€/MWh)</th>
<th>Total cost (€/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GT</strong></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><strong>NGCC</strong></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><strong>NGCC + ASU</strong></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><strong>NGCC+ ASU+ Gasifier (by flare)</strong></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></td>
<td>3.098</td>
<td>3.35</td>
<td>10,39</td>
<td></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></td>
</tr>
<tr>
<td><strong>IGCC</strong></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>
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<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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2. UNAVAILABILITY REASONS
   a. First five years
   b. Last years

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

4. R&D INVESTMENT PLAN
2. UNAVAILABILITY REASONS

6 months accumulated gross IGCC production

50,000 EOH Major Overhaul + 4 weeks delay (inner casing)

GT main transformer bushing fault

75,000 EOH Major Overhaul

Air-WN compressor coupling breakdown

No operation. Non-profitable electricity price

100,000 EOH Major Overhaul
2. UNAVAILABILITY REASONS

a) First five years
2. UNAVAILABILITY REASONS.

a) First five years

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.

Transversal section in the leakage area
2. UNAVAILABILITY REASONS. a) First five years

Reason 2. Gasifier (II)

- Gas leakage due to piping corrosion. Proper selection of materials. To avoid “cold ends” and down time corrosion.
2. UNAVAILABILITY REASONS. a) First five years

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)
2. UNAVAILABILITY REASONS. a) First five years

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.
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.
2. UNAVAILABILITY REASONS. a) First five years

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
2. UNAVALABILITY REASONS. a) First five years

Reason 6. Fuel dust conveying and feeding systems

Pressure control and fluidization stability. Design of fluidization systems and preventive maintenance of components.
2. UNAVAILABILITY REASONS. a) First five years

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.
b) Last years
### 2. UNAVAILABILITY REASONS. b) Last years

#### 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>

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.
- **Gasifier.** Fly ash filters failure.
- **Gasifier.** High vibrations in quench gas compressor.
IGCC AVAILABILITY IN 2011

<table>
<thead>
<tr>
<th></th>
<th>Availability</th>
<th>Planned Outages</th>
<th>Unplanned Outages</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC</td>
<td>59.2%</td>
<td>21.5%</td>
<td>19.2%</td>
</tr>
<tr>
<td>Gasifier</td>
<td>74.9%</td>
<td>17.8%</td>
<td>9.1%</td>
</tr>
<tr>
<td>Power Block</td>
<td>85.3%</td>
<td>19.6%</td>
<td>5.5%</td>
</tr>
<tr>
<td>ASU</td>
<td>12.8%</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

2. UNAVAILABILITY REASONS. b) Last years
2. UNAVAILABILITY REASONS. b) Last years

IGCC UNAVAILABILITY 2011

- Combined cycle
  - GAS TURBINE: 93%
  - WATER-STEAM CYCLE: 3%

- Gasification
  - GAS OXYGEN PRODUCTION: 36%
  - WASTE NITROGEN PRODUCTION: 49%
  - PURE NITROGEN PRODUCTION: 15%

- ASU
  - 4%

- BOP
  - 5%

- Combined Cycle
  - 60%

- AUXILIARY SYSTEM
  - DCS: 41%
  - ELECTRICAL SYSTEM: 43%

- QUENCH GAS RECLAMATION
  - 12%

- MIXING & GRINDING PLANT
  - 1%

- DUST FUEL CONVEYING & FEEDING
  - 6%

- START-UP BURNER & FLAME MONITORS
  - 0%

- SLAGS
  - 35%

- GAS WET TREATMENT
  - 15%

- WATER STEAM SYSTEMS & BOILERS
  - 28%

- GAS SATURATOR
  - 4%

- SULPHUR RECOVERY & TAIL GAS RECYCLE
  - 31%

- Mix. & GRIND. PLANT
  - 1%

- DRY DEDUSTING & FLY ASH SYSTEMS
  - 3%

- WATER-STEAM CYCLE
  - 3%

- QUENCH ASH SYSTEMS
  - 3%

- MIXING & GRINDING PLANT
  - 1%

- DUST FUEL CONVEYING & FEEDING
  - 6%

- START-UP BURNER & FLAME MONITORS
  - 0%

- SLAGS
  - 35%

- GAS WET TREATMENT
  - 15%

- WATER STEAM SYSTEMS & BOILERS
  - 28%

- GAS SATURATOR
  - 4%

- SULPHUR RECOVERY & TAIL GAS RECYCLE
  - 31%

- MIX/GRIND PLANT
  - 1%

- DRY DEDUSTING & FLY ASH SYSTEMS
  - 3%
2. UNAVAILABILITY REASONS. b) Last years

100.000 eoh & Life Time Extension outage at Puertollano CC

<table>
<thead>
<tr>
<th>Summary of schedule and critical path</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>Site preparation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turning Gear off</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissassembly. Stator &amp; rotor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fact findings &amp; inspections</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Repairs</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Scheduled</strong> works after dissassembly checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reassembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turning gear on</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blow out and tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG Commercial operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGCC start up</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch over</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>Gasifier</th>
<th>Power Block</th>
<th>ASU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>60,7</td>
<td>81,2</td>
<td>85,5</td>
<td>83,3</td>
</tr>
<tr>
<td>Planned Outages</td>
<td>10,7</td>
<td>9,1</td>
<td>6,1</td>
<td>4,8</td>
</tr>
<tr>
<td>Unplanned Outages</td>
<td>28,7</td>
<td>9,8</td>
<td>85,5</td>
<td>83,3</td>
</tr>
</tbody>
</table>
2. UNAVAILABILITY REASONS. b) Last years

**STATICS MAINTENANCE CYCLE 2008-2011**

- GASIFICATION 40%
- ASU 30%
- BOP 4%
- COMBINED CYCLE 26%
- POWER 13.4%
- DCS 38.4%

- GAS TURBINE 81%
- WATER STEAM CYCLE 8%
- GAS SATURATOR 11%

- FUEL PREPARATION 4%
- WATER STEAM 17%
- QUENCH GAS 10%

- SLAGS 11%
- BURNERS FEEDING 9%
- SULPHUR RECOVERY 8%

- GAS TREATMENT 8%
- FLY ASH 28%

- OXYGEN PRODUCTION 16%
- PURE NITROGEN 3%
- WASTE NITROGEN 81%
2. UNAVAILABILITY REASONS. b) Last years

**ASU. WN$_2$ 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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1. THE PUERTOLLANO ELCOGAS PLANT

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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>
<thead>
<tr>
<th>Recommendations</th>
<th>Av</th>
<th>Vc</th>
<th>Fc</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>Av</th>
<th>Vc</th>
<th>Fc</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>
### 3. OTHER LESSONS LEARNT. a) Carnot Project

#### 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 $H_2S$</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 ) ( \mathrm{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>( \mathrm{Av} ) &amp; ( \mathrm{Vc} ) would be improved by using a 50% air compressor, and the other 50% coming from 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 )</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 )</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>
3. OTHER LESSONS LEARNT. a) Carnot Project

**Highlighted conclusions:**

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

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

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

**Elcogas operating experiences**

Investment cost saving around 30%
Availability increase (up to 90%)
### 3. OTHER LESSONS LEARNT. a) Carnot Project

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ELCOGAS design</th>
<th>CARNOT design</th>
<th>CARNOT design with CO₂ capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal and petcoke (50% wt)</td>
<td>Coal and petcoke (50% wt)</td>
<td>Coal and petcoke (50% wt)</td>
</tr>
<tr>
<td>LHVₚₙₑᵤ (MJ/kg)</td>
<td>22.55</td>
<td>24.41</td>
<td>24.41</td>
</tr>
<tr>
<td>Gas Turbine (MW)</td>
<td>200</td>
<td>291.0</td>
<td>281.1</td>
</tr>
<tr>
<td>Steam Turbine (MW)</td>
<td>135</td>
<td>193.6</td>
<td>186.8</td>
</tr>
<tr>
<td>Total Gross (MW)</td>
<td>335</td>
<td>484.6</td>
<td>467.9</td>
</tr>
<tr>
<td>Total Net (MW)</td>
<td>300</td>
<td>414.2</td>
<td>399.8</td>
</tr>
<tr>
<td>Efficiency{sub}_LHV (%)</td>
<td>47.12</td>
<td>52.1</td>
<td>45.2</td>
</tr>
<tr>
<td>Heat Rate{sub}_LHV (kJ/kWh)</td>
<td>7,647</td>
<td>6,908</td>
<td>7,959</td>
</tr>
</tbody>
</table>
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>
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</thead>
<tbody>
<tr>
<td>Basic Engineering</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Detailed engineering</td>
<td></td>
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<tr>
<td>Supply main equipment</td>
<td></td>
<td></td>
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<tr>
<td>Erection Power Block</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Commissioning PB with NG</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Erection ASU &amp; Gasification</td>
<td></td>
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<tr>
<td>Commissioning ASU &amp; Gasification</td>
<td></td>
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</tr>
</tbody>
</table>

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

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

### 3. OTHER LESSONS LEARNT.

b) Organisation
3. OTHER LESSONS LEARNT. b) Organisation

<table>
<thead>
<tr>
<th>MECHANICAL</th>
<th>ELECTRICAL</th>
<th>I&amp;C</th>
<th>DCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps</td>
<td>Transformer</td>
<td>Local instrument</td>
<td>Signals</td>
</tr>
<tr>
<td>Compressors &amp; fans</td>
<td>High voltage</td>
<td></td>
<td>BOP</td>
</tr>
<tr>
<td>Conveyors &amp; Screw</td>
<td>6/0.4 KV</td>
<td></td>
<td>ASU</td>
</tr>
<tr>
<td>transporters</td>
<td></td>
<td></td>
<td>Gasification</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td></td>
<td></td>
<td>TOTAL</td>
</tr>
<tr>
<td>Tanks</td>
<td>CCM 400V</td>
<td>Local PLC</td>
<td></td>
</tr>
<tr>
<td>VALVES</td>
<td>Motors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td>10.5 KV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic</td>
<td>6 KV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Act. Motorised</td>
<td>400 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Act. Pneumatic</td>
<td>km cabling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Act. Hydraulic</td>
<td>Power &amp; control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Auxiliaries</td>
<td></td>
<td></td>
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</tbody>
</table>

|                     |                     |                   |               |

**MECHANICAL**

- Pumps: 363
- Compressors & fans: 201
- Conveyors & Screw transporters: 32
- Heat exchangers: 351
- Tanks: 248
- VALVES: 13414
- Manual: 12052
- Automatic: 1362
- Act. Motorised: 116
- Act. Pneumatic: 1162
- Act. Hydraulic: 84

**ELECTRICAL**

- Transformers: 20
- High voltage: 6
- 6/0.4 KV: 14
- CCM 400V: 23
- Motors: 715
- 10.5 KV: 1
- 6 KV: 27
- 400 V: 687
- km cabling: 1290
- Power & control: 920
- Auxiliaries: 370

**I&C**

- Local instrument: 6807
- Local PLC: 40

**DCS**

<table>
<thead>
<tr>
<th></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>
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   a. Carnot Project
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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:**

- **CO₂** EMISSION REDUCTION IN UTILIZATION OF FOSSIL FUELS
- **H₂** PRODUCTION BY GASIFICATION OF FOSSIL FUELS
- **DIVERSIFICATION** OF RAW FUELS AND PRODUCTS
- OTHER **ENVIRONMENTAL** IMPROVEMENTS
- **IGCC PROCESSES** **OPTIMIZATION**
- **DISSEMINATION** OF RESULTS
4. R&D INVESTMENT PLAN

Dissemination of results

• **Forum** participations. CO₂, H₂, 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.
Optimisation of IGCC processes: Oriented to improve availability & costs

Test materials

Gasifier materials/Syngas corrosion processes

Elimination of membrane water leakages at reaction chamber

Ceramic filters
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.
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 H$_2$ by gasification of fuels

H$_2$ production in IGCC. Project HYDROSEEP (RFCS, to study IGCC adaptation to H$_2$ production)

Study and tests of new processes of H$_2$ purification. Project SPHERA (ESP-CENIT)

Available to collaborate with new H$_2$ & Fuel Cells Experimental National Centre of Puertollano
### 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><strong>3.661.42</strong></td>
<td><strong>1.126.7</strong></td>
</tr>
</tbody>
</table>

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

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

**Load during 8% orujillo co-gasification test**

**Olive oil waste storage area**

**Diversification of raw fuels and products. Biomass co-gasification**
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**
4. R&D INVESTMENT PLAN. PSE-CO$_2$: CO$_2$ Capture Pilot Plant

**TARGETS**

- 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.

**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-CO$_2$: CO$_2$ Capture Pilot Plant
4. R&D INVESTMENT PLAN. PSE-CO₂: CO₂ Capture Pilot Plant

COAL + COKE

GASIFICATION

FILTRATION SYSTEM

PURIFICATION & DESULPHURATION

CO₂ Capture Pilot Plant

COMBINED CYCLE

Recycle compressor

Raw gas

H₂ rich gas

37.5 % CO₂
50.0 % H₂
3.0 % CO

100 t/d

CO₂ + H₂S (1.44%)

Raw H₂ (80% of purity)

Tail gas

1.3 bar

CO₂ & H₂ separation

(Chemical, aMDEA)

CO + H₂O → CO₂ + H₂

IP STEAM

SYNGAS PURIFICATION & DESULPHURATION

Tail gas

1.3 bar

H₂O

37.5 % CO₂
50.0 % H₂
3.0 % CO

Flow (Nm³/h)

3,610

4,006

P (bar)

19.8

23.6

T (ºC)

126

138

% CO₂

60.45

53.72

% H₂

21.95

19.57

% H₂O

0.29

10.40

% H₂S

0

0.70

% COS

0

0.11

99.99% H₂ @ 15 bar

100 t/d

40%
4. R&D INVESTMENT PLAN. PSE-CO$_2$: CO$_2$ Capture Pilot Plant

First CO$_2$ tonne captured in 13th September 2010

1000 tonnes of CO$_2$ captured

6 tonnes of H$_2$ produced

MILESTONES

Engineering
- CO$_2$ Unit
- PSA Unit
- Control
- Reactors
- Catalysts
- Construction

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

Analysis shelter

PSA Unit

Electric & Control Building

CO$_2$ Wash Unit

Shifting Unit
### 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>
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<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>
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<td>0.0</td>
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<tr>
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<td>138</td>
<td>53.72</td>
<td>19.57</td>
<td>2.70</td>
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<td>0.70</td>
<td>0.11</td>
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<tr>
<td><strong>Shifted gas to separation unit</strong></td>
<td></td>
<td></td>
<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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<td>21.1</td>
<td>277</td>
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<td>28.39</td>
<td>21.53</td>
<td>42.73</td>
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<td><strong>IP saturated steam to feed</strong></td>
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<tr>
<td>Sweet</td>
<td>5,055</td>
<td>34.0</td>
<td>243</td>
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<tr>
<td>Sour</td>
<td>4,706</td>
<td>34.0</td>
<td>243</td>
<td>0.0</td>
<td>0.0</td>
<td>100</td>
<td>0.0</td>
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</tbody>
</table>

General view of Shifting Unit
4. R&D INVESTMENT PLAN. PSE-CO$_2$: CO$_2$ Capture Pilot Plant

**Separation unit**

**General view of Separation Unit**

<table>
<thead>
<tr>
<th></th>
<th>Flow kg/h</th>
<th>P bar</th>
<th>T ºC</th>
<th>CO %</th>
<th>H$_2$ %</th>
<th>CO$_2$ %</th>
<th>H$_2$O %</th>
<th>H$_2$S %</th>
<th>COS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shifted gas to absorber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<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>
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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>
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<tr>
<td>Process condensated</td>
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<tr>
<td>Sweet</td>
<td>3,414</td>
<td>15.9</td>
<td>45</td>
<td>0.0</td>
<td>0.0</td>
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<td>100</td>
<td>0.0</td>
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<td>3,387</td>
<td>19.7</td>
<td>45</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>
<tr>
<td>CO$_2$ product</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sweet</td>
<td>4,185</td>
<td>1.5</td>
<td>40</td>
<td>0.18</td>
<td>95.32</td>
<td>4.47</td>
<td>0.0</td>
<td>0.0</td>
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<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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<td>H$_2$ to PSA</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>
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<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>
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<td>Rich H$_2$ gas</td>
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<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>
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<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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<td>LP Steam to reboiler</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>
<td>100</td>
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<tr>
<td>Sour</td>
<td>4,797</td>
<td>4.1</td>
<td>144</td>
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<td>100</td>
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</tbody>
</table>
4. R&D INVESTMENT PLAN. PSE-CO₂: CO₂ Capture Pilot Plant

**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>H₂ from</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>
<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>H₂ product</td>
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<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>Tail gas</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>
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</tbody>
</table>

**General view of PSA unit**
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)
4. R&D INVESTMENT PLAN. PSE-CO$_2$: CO$_2$ Capture Pilot Plant

**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 1$^{st}$ 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

  ↑ of 30% in steam consumption leads to ↑ 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-CO$_2$: CO$_2$ Capture Pilot Plant

**CO$_2$ Capture Pilot Plant. CO$_2$ 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-CO$_2$: CO$_2$ Capture Pilot Plant

**CO$_2$ 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 CO$_2$ capture</td>
<td>33 %</td>
</tr>
<tr>
<td>Treated gas</td>
<td>100 %</td>
</tr>
</tbody>
</table>
4. R&D INVESTMENT PLAN. PSE-CO$_2$: CO$_2$ Capture Pilot Plant

Relationship between electricity price and hydrogen price

Minimum H2 prices depending on electricity price

Better to sell H$_2$

Better to sell electricity

€/Kg. H$_2$ market price uncompressed

€/MWh. Electricity market price
Final Conclusions

1) The carbon capture pilot Project has been a success: first of its kind in the world, >90% capture rate achieved, and CO₂ 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** 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
Short Course Gasification

Prenflo Gasification Technology
Experiences from Puertollano plant

Fernando Alarcón