Toledo, 21st November 2013

Gasification: Sustainable power production – The Puertollano IGCC plant
Francisco García Peña – ELCOGAS Puertollano IGCC plant
1. The Elcogas plant

2. Production of $H_2$ through gasification

3. Capture and storage of $CO_2$

4. Real experience in ELCOGAS: Pilot Plant

5. Costs and competitiveness
   5.1 $CO_2$
   5.2 $H_2$
1. The Elcogas plant

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   5.1 CO₂
   5.2 H₂
ELCOGAS is an Spanish company established in April 1992 to undertake the planning, construction, management and operation of a 335 MWe_{ISO} IGCC plant located in Puertollano (Spain).

**Shareholders**

- **Endesa Generación, S.A.**: 40.99%
- **Electricité de France International, S.A.**: 31.48%
- **Iberdrola Generación, S.A.**: 12.00%
- **Hidroeléctrica del Cantábrico, S.A.**: 4.32%
- **Siemens Project Ventures GmbH**: 2.53%
- **Hidroeléctrica de Centrales SAU**: 4.32%
- **Krupp Koppers GmbH**: 0.04%
- **Hidrocantábrico Explotación de Centrales SAU**: 4.32%
- **Enel SpA**: 4.32%
- **ENCASUR (open cast coal mine)**
- **REPSOL refinery**
- **Puertollano IGCC Plant**
The Elcogas plant (II)

- Fuel Preparation
- Gasifier
- Cleaning of gases
- Combined cycle
- Air separation unit
- Laboratory and water treatment
- CO₂ capture
The Elcogas plant (III)
Fuel design values

Fuel design is a mixture 50/50 of coal/coke which now is 45/55. Moreover some tests with biomass were undertaken (meat bone meal, grape seed meal, olive oil waste).

<table>
<thead>
<tr>
<th></th>
<th>COAL</th>
<th>PET COKE</th>
<th>FUEL MIX (50:50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>11.8</td>
<td>7.00</td>
<td>9.40</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>41.10</td>
<td>0.26</td>
<td>20.68</td>
</tr>
<tr>
<td>C (%)</td>
<td>46.27</td>
<td>82.21</td>
<td>59.21</td>
</tr>
<tr>
<td>H (%)</td>
<td>2.48</td>
<td>3.11</td>
<td>2.80</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.81</td>
<td>1.90</td>
<td>1.36</td>
</tr>
<tr>
<td>O (%)</td>
<td>6.62</td>
<td>0.02</td>
<td>3.32</td>
</tr>
<tr>
<td>S (%)</td>
<td>0.93</td>
<td>5.50</td>
<td>3.21</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>13.10</td>
<td>11.90</td>
<td>22.55</td>
</tr>
</tbody>
</table>

With those fuels at 50:50, the whole plant demonstrated a gross efficiency of 47.2% and a net efficiency of 42%, under acceptance tests in 2000 year.

Syngas composition

<table>
<thead>
<tr>
<th></th>
<th>RAW GAS</th>
<th></th>
<th>CLEAN GAS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real average</td>
<td>Design</td>
<td>Real average</td>
<td>Design</td>
</tr>
<tr>
<td>CO (%)</td>
<td>59.26</td>
<td>61.25</td>
<td>59.30</td>
<td>60.51</td>
</tr>
<tr>
<td>H₂ (%)</td>
<td>21.44</td>
<td>22.33</td>
<td>21.95</td>
<td>22.08</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td>2.84</td>
<td>3.70</td>
<td>2.41</td>
<td>3.87</td>
</tr>
<tr>
<td>N₂ (%)</td>
<td>13.32</td>
<td>10.50</td>
<td>14.76</td>
<td>12.5</td>
</tr>
<tr>
<td>Ar (%)</td>
<td>0.90</td>
<td>1.02</td>
<td>1.18</td>
<td>1.03</td>
</tr>
<tr>
<td>H₂S (%)</td>
<td>0.81</td>
<td>1.01</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>COS (%)</td>
<td>0.19</td>
<td>0.17</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>HCN (ppmv)</td>
<td>23</td>
<td>38</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>
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
2012: 1,498 hours in stand-by due to regulatory restrictions. (3,969 in 2013)
The Elcogas plant (VI)

ELCOGAS power plant emissions in NGCC & IGCC modes

Natural gas (mg/Nm³ at 6% O₂ dry)

Coal gas (mg/Nm³ at 6% O₂ dry)

SO2  NOx  Particles

Natural gas (NGCC)

Coal gas (IGCC)
The Elcogas plant (VII)

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>59.987</td>
<td>2,891</td>
<td>20.748</td>
<td>10.46</td>
<td></td>
<td>216.98</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural gas</td>
<td>249.495</td>
<td>22,154</td>
<td>11.262</td>
<td>10.46</td>
<td></td>
<td>117.77</td>
</tr>
<tr>
<td>NGCC + ASU</td>
<td>Natural gas</td>
<td>1.854.675</td>
<td>155,148</td>
<td>11.954</td>
<td>10.46</td>
<td></td>
<td>125.01</td>
</tr>
<tr>
<td>NGCC + ASU + Gasifier (by flare)</td>
<td>Natural gas</td>
<td>351.147</td>
<td>33,373</td>
<td>10.522</td>
<td>10.46</td>
<td>110.03</td>
<td>128.69</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>67.459</td>
<td></td>
<td>2.021</td>
<td>3.49</td>
<td>7.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Petocke</td>
<td>195.947</td>
<td></td>
<td>5.871</td>
<td>1.98</td>
<td>11.61</td>
<td></td>
</tr>
<tr>
<td>IGCC</td>
<td>NG auxiliar consumption</td>
<td>257.700</td>
<td>992,811</td>
<td>260</td>
<td>10.46</td>
<td>2.71</td>
<td>26.30</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>2.536.891</td>
<td></td>
<td>2.555</td>
<td>3.49</td>
<td>8.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Petocke</td>
<td>7.368.734</td>
<td></td>
<td>7.422</td>
<td>1.98</td>
<td>14.67</td>
<td></td>
</tr>
</tbody>
</table>

Note: Net energy variable costs (average 2012)
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 results report of that R&D Plan to Spanish government for evaluation.

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

- $\text{CO}_2$ EMISSION REDUCTION IN UTILIZATION OF FOSSIL FUELS
- $\text{H}_2$ PRODUCTION BY GASIFICATION OF FOSSIL FUELS
- DIVERSIFICATION OF RAW FUELS AND PRODUCTS
- OTHER ENVIRONMENTAL IMPROVEMENTS
- IGCC PROCESSES OPTIMIZATION
- DISSEMINATION OF RESULTS
1. The Elcogas plant

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   5.1 CO$_2$
   5.2 H$_2$
Worldwide production of H₂

Approximately, half of the worldwide production of hydrogen is produced through natural gas reforming.

Gasification of fossil fuels is increasing its contribution in a significant way during the last decade (the majority of the existents plants through the world produced H₂ for fertilizers).

Worldwide production of H₂ by technology

- Oil-based: 30%
- Coal gasification: 18%
- Natural Gas Steam Reforming: 48%
- Electrolysis: 4%


Worldwide accumulative capacity of gasitifacion

Source: Higman Consulting, 2012
Production of $H_2$ through gasification (II)

**General process**

1. **Gasification**
   - Carbonaceous component $+$ $O_2$ $+$ $H_2O \xrightarrow{400-1600ºC/10-40$ bar} CO $+$ $H_2$ $+$ Impurities

2. **Conditioning** → removing ashes, particles and sulphur compounds.

3. **Reaction gas-water** or “shifting”
   - $CO + H_2O \rightarrow CO_2 + H_2$

4. **Separation** of $H_2$ and $CO_2$

$H_2$ production from fossil fuels carries with the $CO_2$ generation $\Rightarrow$ in order to talk about “clean” hydrogen it is has to be considered the CCS.
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**2DS**

(2°C average increase of the atmosphere temperature)

Vision of sustainable energetic system of GHG and CO$_2$ emissions

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**4DS**

(4°C average increase of the atmosphere temperature)

Reflects countries commitments in order to reduce emissions and to increase energetic efficiency

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**6DS**

(6°C average increase of the atmosphere temperature)

Towards devastating results for the Earth
Capture and storage of CO₂ (II)

Technologies

Emissions (GtCO₂)

2009 2020 2030 2040 2050

- End-use fuel and electricity efficiency 31%
- End-use fuel switching 9%
- Power generation efficiency and fuel switching 3%
- CCS 22%
- Renewables 28%
- Nuclear 9%

Source: International Agency of the Energy, Energy Technology Perspective, 2012
Capture and storage of CO$_2$ (III)

Classification by technology

Source: ZEP WG1Report (August 2006)
Capture and storage of CO₂ (IV)
Worldwide integrated projects of CCS (2013)

Source: www.globalccsinstitute.com, Last updated Oct 2013
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Objectives:

- Viability demonstration of the CO$_2$ capture and H$_2$ production in a IGCC that uses solid fossil fuels and wastes as main.
- To obtain enough economical data to scale the project to the total capacity of syngas production of the Puertollano IGCC.

Participants: ELCOGAS – UCLM – CIEMAT – INCAR CSIC

In operation since October 2010. The first worldwide installation of this type (14 MWt)

- Construction costs (equipments and externals): 13.5 Millions €
- 1,121 working hours accumulated until September 2013
- 3,500 tones of CO$_2$ captured
- 6 tones of pure H$_2$ produced
- Intermittent operation associated to official projects/internal research development
Pilot plant process. Block diagram

Real experience in ELCOGAS: Pilot plant (II)

coal + coke

GASIFICATION

Raw gas

FILTRATION

Conversion unit
FeCr / CoMo

CO + H₂O → CO₂ + H₂

MP steam

Purification unit (PSA)

Raw H₂ (80% of purity)

100 t/d

Separation unit
CO₂ & H₂
(Chemical absorption, aMDEA)

MP steam

CO₂ + H₂S

CO₂ product

Recycle compressor

Tail gas @ 1.3 bar

H₂ product

99.99% H₂ @ 15 bar

CO₂ + H₂S

Recycled gas

Clean syngas

40%
Real experience in ELCOGAS: Pilot plant (III)

Pilot plant. Main equipments and suppliers

Engeneering: Empresarios Agrupados
CO2 unit: Linde-Caloric
PSA unit: Linde
Control: Zeus Control
Reactors: Técnicas Reunidas
Catalysts: Johnson Matthey
Construction: local companies
Real experience in ELCOGAS: Pilot plant (IV)

Conversion unit. Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design (sweet)</th>
<th>Alternative (sour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molar ratio steam/CO</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Conversion CO</td>
<td>92.5</td>
<td>93.1</td>
</tr>
<tr>
<td>ηthermal</td>
<td>75.0</td>
<td>74.9</td>
</tr>
<tr>
<td>H₂S (e/s)</td>
<td>0/0</td>
<td>0.78/0.75</td>
</tr>
<tr>
<td>COS (e/s)</td>
<td>0/0</td>
<td>0.12/0</td>
</tr>
</tbody>
</table>

Composition of gas during reaction

Feed syngas: 2.7% CO, 60.6% CO₂, 22.0% H₂
Between reactors: 46.3% H₂, 33.0% CO₂, 10.6% CO
Unit outlet: 50.0% H₂, 37.6% CO₂, 2.9% CO
Real experience in ELCOGAS: Pilot plant (V)

Separation: design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design (sweet)</th>
<th>Alternative (sour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2.4 GJ/t</td>
<td>2.4 GJ/t</td>
</tr>
<tr>
<td>$\eta$ thermal</td>
<td>78.1%</td>
<td>77.9%</td>
</tr>
</tbody>
</table>

**Design compositions (sweet) (%)**

- Gas shifted:
  - CO$_2$: 37.6%
  - CO: 2.9%
  - H$_2$: 50.1%

- CO$_2$ product:
  - CO: 0.0%
  - H$_2$: 0.2%
  - CO$_2$: 4.7%

- Raw H$_2$:
  - CO$_2$: 99.8%
  - H$_2$: 79.8%

**Alternative compositions (sour) (%)**

- Gas shifted:
  - CO$_2$: 37.8%
  - CO: 2.6%
  - H$_2$: 49.7%

- CO$_2$ product:
  - CO: 0.0%
  - H$_2$: 0.2%
  - CO$_2$: 4.3%

- Raw H$_2$:
  - CO$_2$: 98.2%
  - H$_2$: 80.4%

Tdes: 92.6 °C
Pdes: 1.8 bar
Real experience in ELCOGAS: Pilot plant (VI)

Purification unit

Gas composition (sweet design)

Results of real tests (sweet mode)

<table>
<thead>
<tr>
<th>Comp. (%vol.)</th>
<th>Pure H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0</td>
</tr>
<tr>
<td>CO₂</td>
<td>0</td>
</tr>
<tr>
<td>H₂</td>
<td>99.959 – 99.995</td>
</tr>
<tr>
<td>N₂</td>
<td>0.003 – 0.04</td>
</tr>
<tr>
<td>Ar</td>
<td>0.002 - 0.01</td>
</tr>
</tbody>
</table>
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   5.1 \( \text{CO}_2 \)

   5.2 \( \text{H}_2 \)
Comparison between costs of CO₂ capture technologies

With acid CO₂ capture & current status of technology ~125

~25

Source: DOE/NETL CCS RD&D ROADMAP (December 2010) + ELCOGAS own data

30 for ELCOGAS retrofitting
Costs and competitiveness: CO₂ (II)

CO₂ capture in IGCC plants

- With SWEET catalyst
  - Fuel preparation → Gasification → Filtration and wet scrubbing → Desulphurization and sulphur recovery → Unit of CO₂ capture → Combined cycle

- With SOUR catalyst
  - Fuel preparation → Gasification → Filtration and wet scrubbing → Unit of CO₂ capture → Combined cycle

Based on our CO₂ capture pilot plant, we have scaled the cost of a CO₂ capture unit at scale 1:1 about 350 M€. Approximately, it represents the cost of the desulphurization and sulphur recovery units in an IGCC w/o CO₂ capture.

By installing an IGCC with CO₂ acid capture to store or use CO₂ together with ~1.5% H₂S, the investment costs are similar to those w/o CO₂ capture. And the only penalty is the decreasing efficiency:

- From 42% currently
- and from 50% near future
Costs and competitiveness: H$_2$ (I)

H$_2$ co-production and electricity

IGCC Puertollano net production

**Decision of co-production depending on market prices**

Only Production electricity

- **284.5 MWe**

H$_2$ co-production with 40% of CO$_2$ capture in pilot plant

- **282.1 MWe**

Impact of 2.4 MWe in the generated power due to the production of 2 t/d of H$_2$ with capture of 40 t/d of CO$_2$

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**Electricity price (€/MWh)**

**H$_2$ price (€/MWh)**

- Better sell hydrogen
- Better sell electricity

Marginal price ELCOGAS

Current price

---

30
Costs and competitiveness: H₂ (II)

Applications of produced H₂ in the pilot plant

Possible applications of the H₂ produced in the ELCOGAS pilot plant, which illustrates its capacity of 2 t/d.

Ariane 5 rocket

On its launching it was consumed 24 tones of liquid hydrogen. This amount is produced during 12 days in the pilot plant.

Hyundai ix35 FCEV

- 165 HP, maximum speed 160 km/h
- Tank of 5.64 kg of H₂ at 700 bar. 3 minutes of recharge.
- Autonomy of 560 km: consumption of 1.01 kg/100 km
- With 1 day production of the pilot plant 354 cars like this one could be recharged, or could be travelling for 200,000 km
- It is on sale for 125,000 €.
Comparative on transport costs

Comparison of existent vehicles for different technologies only on fuel costs

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Model</th>
<th>Power (HP)</th>
<th>Consumption given by producer</th>
<th>Fuel cost</th>
<th>Cost (€/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>Hyundai x35</td>
<td>184</td>
<td>5.9 l/100km</td>
<td>1.4 €/l [1]</td>
<td>8.26</td>
</tr>
<tr>
<td>Electricity</td>
<td>BMWi3</td>
<td>170</td>
<td>9.89 kWh/100km</td>
<td>0.31 €/kWh [2]</td>
<td>3.07</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Hyundai ix35 FCEV</td>
<td>165</td>
<td>1.01 kg/100km</td>
<td>1.95 €/kg [3]</td>
<td>1.97</td>
</tr>
</tbody>
</table>

[1] Current electricity price for a particular consumer (taxes included)
[2] Current price for the public at service stations (taxes included)
[3] Hydrogen production marginal price given from results of Elcogas Pilot Plant (taxes excluded). 1.25 €/kg has to be added because of installation and compression unit operation, storage and filling (2 t/d) costs. (Source: NREL)

Despite the comparison of fuel cost is not completely exact, it is valid to give a future perspective:

- $H_2$ cost equivalent to the cost per km with diesel is 8.2 €/kg. The difference (around 6€) seems to be enough to think that $H_2$ could be competitive with diesel.
- Current prices on hydrogenerator varies between 8 and 15 €/kg.
- Production $H_2$ technology through gasification is commercial with a gap for the optimization. According to EPRI, the production cost in the future could be reduced 30% of the actual cost.
1) The carbon capture and H₂ production pilot project has been a **success**: first of its kind in the world, >90% capture rate achieved, and CO₂ capture cost can be <20-30 €/t

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

3) Carbon capture cost and hydrogen production costs estimations come from **figures of a real project** at industrial size, and show a clear **room for improvement**.

**ELCOGAS** offers both the Puertollano IGCC and the Pilot Plant for CO₂ capture and H₂ production as technical platforms to develop of process, equipments, components, or even pre-engineering of new plants with CCS and Zero emissions.
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THANK YOU FOR YOUR ATTENTION