H₂ PRODUCTION FROM COAL AND BIOMASS CO-GASIFICATION.
ELCOGAS EXPERIENCE ON THE FIELD

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1. H₂ production through gasification

2. Puertollano IGCC Power Plant

3. Real experience at ELCOGAS: Pilot Plant for CO₂ capture and H₂ production

4. Costs and competitiveness
1. H₂ production through gasification

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4. Costs and competitiveness
About half of the global H₂ production is done via natural gas steam reforming.

Fossil fuel gasification is increasing its contribution intensively in the last decade (most existing plants in the world are engaged in H₂ production for fertilizers).

Worldwide H₂ production by technology

Coal gasification: 18% (Now ~30%)
Electrolysis: 4%
Oil-based: 29%
Natural Gas Reforming: 49%

Acumulated wordlwide gasification capacity

Source: Industrial Gases by the Chemical Economics Handbook, SRI (Oct 2007)
Source: Higman Consulting, 2013
1. **H₂ production through gasification (II)**

**General process**

1. **Step 1:** Syngas production through Gasification
   
   Carbonaceous component + O₂ + H₂O → CO + H₂ + Impurities

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

3. **Step 3:** Water-gas-shift reaction
   
   CO + H₂O → CO₂ + H₂

4. **Step 4:** Separation of H₂ and CO₂
   
   **H₂** & **CO₂**

- **H₂** production from fossil fuels involves CO₂ generation → To talk about “clean” H₂ it is required to consider CCS.
1. H₂ production through gasification (III)
   Existing and emerging technologies for each step

Existing technologies

<table>
<thead>
<tr>
<th>Syngas production</th>
<th>CO to CO₂ conversion</th>
<th>CO₂ &amp; H₂ separation</th>
<th>H₂ purification</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG SMR</td>
<td>WGS reaction</td>
<td>Chemical absorption</td>
<td>Adsorption</td>
</tr>
<tr>
<td>SMR</td>
<td></td>
<td>Physical absorption</td>
<td>Permeation</td>
</tr>
<tr>
<td>POX</td>
<td></td>
<td>Physico-chemical</td>
<td>Cryogenics</td>
</tr>
<tr>
<td>ATR</td>
<td></td>
<td>absorption</td>
<td></td>
</tr>
<tr>
<td>Gasification</td>
<td></td>
<td>Adsorption</td>
<td></td>
</tr>
<tr>
<td>(IGCC)</td>
<td></td>
<td>Membranes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cryogenics</td>
<td></td>
</tr>
</tbody>
</table>

Emerging technologies

- Combinations from existing ones:
  - SEWGS (sorbent enhanced water-gas-shift): reaction + adsorption.

- Improvement of existing ones: better catalysts and solvents, more efficient processes, separation at higher temperatures, ...
1. H$_2$ production through gasification

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4. Costs and competitiveness
2. Puertollano IGCC Power Plant (I)

ELCOGAS IGCC process description
Alternative fuels adequate for co-gasification with common fuel at ELCOGAS:

- **Without investment (real tests done):** MBM (Meat and Bone Meal), Orujillo (Olive residue), GSM (Grape Seed Meal). Accumulated total: 4987 t of biomass in 1647 h of operation.

- **With investment (feasibility assessment):** industrial residues (aluminum manufacture, activated carbon, refinery sludge, paper sludge, cotton dust), used tyres, municipal solid wastes, sewage sludge, olive mill sludge.

Conclusions (<10%wt):

- Technically viable without any investment in the plant.
- IGCC cleaner than incineration to eliminate organic wastes, regarding dioxins and furans emissions.
- No influence in the gasification process.
- No influence neither in the CO$_2$ capture nor in the H$_2$ production.

With investment, up to 70%wt is possible.
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Aims:

- To demonstrate the viability of the CO₂ capture and H₂ production in an IGCC that uses fossil fuels and residues as main feed-stock.
- To obtain economic data enough to scale the project to the total capacity of syngas production of the Puertollano IGCC.

Participants: ELCOGAS – UCLM – CIEMAT – INCAR CSIC

✓ In operación since October 2010. First installation of its kind in the world (14 MWt)
✓ Capital cost (service and equipments): 13.5 M€
✓ 1,121 accumulated hours up to December 2013.
✓ 3,500 tonnes of CO₂ captured.
✓ 6 tonnes of pure H₂ produced.
✓ Current intermittent operation in official projects and internal research.
Pilot Plant Process. Block Diagram

coal + coke

GASIFICATION → FILTRATION → PURIFICATION AND DESULPHURIZATION → COMBINED CYCLE

<table>
<thead>
<tr>
<th>Design</th>
<th>Sweet</th>
<th>Sour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nm³/h</td>
<td>3,610</td>
<td>4,006</td>
</tr>
<tr>
<td>P (Bar)</td>
<td>19.8</td>
<td>23.6</td>
</tr>
<tr>
<td>T (°C)</td>
<td>126</td>
<td>138</td>
</tr>
<tr>
<td>CO₂ %</td>
<td>60.45</td>
<td>53.72</td>
</tr>
<tr>
<td>H₂ %</td>
<td>21.95</td>
<td>19.57</td>
</tr>
<tr>
<td>H₂O %</td>
<td>0.29</td>
<td>10.40</td>
</tr>
<tr>
<td>H₂S %</td>
<td>0</td>
<td>0.70</td>
</tr>
<tr>
<td>COS %</td>
<td>0</td>
<td>0.11</td>
</tr>
</tbody>
</table>

FeCr / CoMo

CO + H₂O → CO₂ + H₂

Shifted gas
37.5 % CO₂
50.0 % H₂
3.0 % CO

Conversion unit

IP steam

100 t/d

Raw H₂ (80% of purity)

CO₂ & H₂ Separation unit
(Chemical absorption, aMDEA)

Purification unit (PSA)

2 t/d

Tail gas @ 1.3 bar

H₂ product

99.99% H₂ @ 15 bar

CO₂ + H₂S

CO₂ product

Recycle compressor

Clean syngas
3. ELCOGAS real experience: pilot plant for CO₂ capture and H₂ production (III)

Engineering: Empresarios Agrupados
Separation Unit: Linde-Caloric
PSA Unit: Linde
Control: Zeus Control
Reactors: Técnicas Reunidas
Catalysts: Johnson Matthey
Construction: Local companies
3. ELCOGAS real experience: pilot plant for CO₂ capture and H₂ production (IV)

**Conversion unit**

**Gas composition during reaction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design (Sweet)</th>
<th>Alternative (Sour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed syngas</td>
<td>kg/h</td>
<td>3,677</td>
</tr>
<tr>
<td>IP steam</td>
<td>kg/h</td>
<td>5,055</td>
</tr>
<tr>
<td>Steam/CO molar ratio</td>
<td></td>
<td>2.9</td>
</tr>
<tr>
<td>CO conversion</td>
<td>%</td>
<td>92.5</td>
</tr>
<tr>
<td>Thermal Efficiency</td>
<td>%</td>
<td>75.0</td>
</tr>
<tr>
<td>Gas condensate</td>
<td>kg/h</td>
<td>3,414</td>
</tr>
<tr>
<td>H₂S (in/out)</td>
<td>vol%</td>
<td>0/0</td>
</tr>
<tr>
<td>COS (in/out)</td>
<td>vol%</td>
<td>0/0</td>
</tr>
</tbody>
</table>
### Design compositions (sweet) (%)

- **CO2**: 37.6
- **H2**: 50.1
- **CO**: 2.9
- **H2**: 99.8
- **CO2**: 97.6
- **H2**: 79.8

<table>
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<tr>
<th>Parameter</th>
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<tr>
<td>CO2 leak</td>
<td>%</td>
<td>0.8</td>
</tr>
<tr>
<td>CO2 product</td>
<td>kg/h</td>
<td>4,185</td>
</tr>
<tr>
<td>Energy</td>
<td>GJ/t</td>
<td>2.4</td>
</tr>
<tr>
<td>Thermal eff.</td>
<td>%</td>
<td>78.1</td>
</tr>
</tbody>
</table>

### Alternative compositions (sour) (%)

- **CO2**: 37.8
- **H2**: 49.7
- **CO**: 2.6
- **H2S**: 0.8
- **CO2**: 98.2
- **H2**: 80.4

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</tr>
<tr>
<td>Energy</td>
<td>GJ/t</td>
<td>2.4</td>
</tr>
<tr>
<td>Thermal eff.</td>
<td>%</td>
<td>77.9</td>
</tr>
</tbody>
</table>
3. ELCOGAS real experience: pilot plant for CO₂ capture and H₂ production (VI)

**PSA unit**

**Gas composition (sweet design)**

- **Raw H₂**
  - CO₂: 0.5%
  - CO: 4.6%
  - H₂: 79.7%

- **H₂ product**
  - CO₂: 1.1%
  - CO: 10.5%
  - H₂: 99.99%

- **Tail gas**
  - CO₂: 54.2%
  - CO: 1 ppm
  - H₂: 4.6%

**Real tests results (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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Co-production decision according to market price

Puertollano IGCC net production (MW)

Production of electricity only

284.5 MWe

H₂ co-production in Pilot Plant

282.1 MWe

2.4 MWe impact on power output due to the production of 2 t/d of H₂ with 40 t/d of CO₂ captured

44.26 €/MWh (Spain 2013 market price) → 1.28 €/kg H₂
21.18 €/MWh (ELCOGAS 2013 marginal price) → 0.61 €/kg H₂
4. Costs and competitiveness (II)

Competitiveness in the H₂ production

**Coal gasification vs NG reforming**

Cost of production for a given technology depends on: cost of the fuel used, process efficiency and scale of production (central or distributed).

H₂ production from natural gas (Steam-Methane-Reforming or SMR) is the most extended way where natural gas is available.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Production cost ($/kg H₂)</th>
<th>Emissions (kg C/kg H₂)</th>
<th>USA fuel price ($/GJ HHV)</th>
<th>USA average 2013 fuel price ($/GJ HHV)</th>
<th>EU28 average 2013 fuel price ($/GJ HHV)</th>
<th>ELCOGAS average 2013 fuel price ($/GJ HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG SMR</td>
<td>1.03</td>
<td>2.50</td>
<td>4.27</td>
<td>4.10</td>
<td>13.76</td>
<td>13.95</td>
</tr>
<tr>
<td>Coal gasification</td>
<td>0.96</td>
<td>5.12</td>
<td>1.16</td>
<td>2.50</td>
<td>2.42</td>
<td>2.34</td>
</tr>
</tbody>
</table>


Central production, 1.2 tonnes H₂/day. Carbon tax: 50 $/mton.

Coal is more competitive when differential price with NG is > 3.80 $/GJ (EPRI-2012). This can be currently found in Europe and Asia but it is not usual in US.

If CCS is added, estimations also show competitiveness of coal gasification.

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<thead>
<tr>
<th>Technology</th>
<th>Production cost ($/kg H₂)</th>
<th>Emissions (kg C/kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG SMR with CCS</td>
<td>1.22</td>
<td>0.42</td>
</tr>
<tr>
<td>Coal gasification with CCS</td>
<td>1.03</td>
<td>0.82</td>
</tr>
</tbody>
</table>

As a case study using commercial technology, a \( \text{H}_2 \) filling station can be:

- Adjacent to existing \( \text{H}_2 \) Production Unit (therefore central production, no transport required).
- Standard capacity of 100 kg/d (able to fill 20 FCEVs per day).
- \( \text{H}_2 \) purity fulfils quality standards for FCEVs

This \( \text{H}_2 \) station would ease the interconnection between active stations in Spain.
4. Costs and competitiveness (III)

Case study: H₂ station at Puertollano IGCC plant

H₂ production (coal gasification)

Marginal: 0,6 €/kg
As market: 1,3 €/kg

Installation already built (capital cost excluded)

Compression, Storage, Dispensing (CSD)

Total: 4 €/kg
Capital cost: 60%
Fixed O&M: 30%
Other variable cost: 10%

Source: NREL.

H₂ at the pump

4,6 – 5,3 €/kg

Selling price in stations uses to be fixed case-by-case. It can vary in the range of 8 – 15 €/kg
1) H₂ production via coal gasification is a commercial technology, available at any scale.

2) At IGCC Puertollano there is a unique installation in the world that produces a high purity hydrogen, integrated in an operative plant.

3) Gasification is considered as the most developed technology for zero-emissions plants. Sustainability comes from two sources: CCS and co-use of biomass:
   - During H₂ production, CO₂ is captured and could be eventually stored underground or used as feedstock in other sustainable processes.
   - IGCC process easily allows the partial substitution of fossil fuel by biomass up to amounts over 70 %wt.

4) Marginal H₂ production costs at ELCOGAS pilot plant show that H₂ as fuel in transport can be competitive.
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