Integration of lignite drying systems in power plant cycles and economics of pre-dried lignite production

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♦ Dryer integration
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♦ Pre-dried lignite economics
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♦ Conclusions
Drying technologies (1/4)

- Three drying technologies integrated to a lignite fired power plant
- Lignite fired power plant for dry lignite production
- Pre-dried lignite as supportive fuel for power plant and as commodity
- Feasible operation at 35% technical minimum load with pre-dried lignite co-firing
Drying technologies (2/4)

- quite mature technology with complexity due to the fluidized bed operation
- predesigned and all components provided by one provider
- malfunctions have no impact on the power plant and are limited within the drying unit
- mature technology for wood and food industry no references for lignite drying
- FGD unit necessary for dryer operation
- Special type corrosion resistant heat exchanger before the FGD
- malfunctions affect the FGD operating temperature
mature technology and long used in lignite drying.
- most simple implementation, is predesigned and all components from single provider
- malfunctions have no impact on the power plant and are limited within the drying unit
# Dryer integration: drying technologies

<table>
<thead>
<tr>
<th>Drying technologies investigated and operational data used</th>
<th>WTA dryer</th>
<th>Tube dryer</th>
<th>Drum dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Capacity</td>
<td>60 t/h dry</td>
<td>60 t/h dry</td>
<td>60 t/h dry</td>
</tr>
<tr>
<td>Type of drying</td>
<td>Indirect heating</td>
<td>Indirect heating</td>
<td>Direct heating</td>
</tr>
<tr>
<td>Raw material temperature</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Heating medium</td>
<td>Bleed steam</td>
<td>Bleed steam</td>
<td>Flue gas</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-consumption</td>
<td>MW_e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry material temperature</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condensate temperature</td>
<td>°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Assumes based on the experience gained through contacting with technology providers.
Dryer integration: reference plant

Agios Dimitrios V

Power plant characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross power output</td>
<td>374.2 MWe</td>
</tr>
<tr>
<td>Net power output</td>
<td>330.0 MWe</td>
</tr>
<tr>
<td>HP steam production</td>
<td>912.5 t/h</td>
</tr>
<tr>
<td>HP steam characteristics</td>
<td>538 °C/194 bar</td>
</tr>
<tr>
<td>HRH steam characteristics</td>
<td>538 °C/33 bar</td>
</tr>
</tbody>
</table>

Recent modifications in boiler configuration for low-NOx operation

Fuel characteristics

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Ash</th>
<th>Volatiles</th>
<th>Fixed carbon</th>
<th>LHV (d.b.) (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw lignite</td>
<td>49.7</td>
<td>18.47</td>
<td>22.32</td>
<td>9.51</td>
<td>12698.3</td>
</tr>
</tbody>
</table>
Dryer integration: results (1/3)

- WTA dryer concept – impact on power plant operation

60 t/h dry lignite production

- Rotary-tube dryer concept - impact on power plant operation

60 t/h dry lignite production

- Rotary dryer concept - impact on power plant operation

60 t/h dry lignite production

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Dryer integration: 35% load (1/3)

Loads within operating range

- Measurements for three loads
- Steam turbine with Gate Cycle
- Boiler with Aspen Plus & CFD
- Two loads feed boundary conditions to CFD
- Three loads for UA values & exponential curves
Dryer integration: 35% load (2/3)

- Initial UA value for 35% load for all cross-flow heat exchangers

- Steam turbine: in Gate Cycle based Stodola law

- Steam temperature & RH spraywater mass flow from parametric investigation

- Definition of steam mass flow and temperature for HP & LP turbine

35% load: process configuration initialization

- Measurements 100%, 80% & 60%
- Aspen Plus boiler model
- Water-wall inlet-outlet temperature & fuel consumption
- Boundary Conditions
- CFD 100% & 60% furnace model

Gate Cycle ST model

Parametric Investigation 35% load

HP & LP steam parameters

UA initial values

Aspen Plus boiler model 35%

Water-wall inlet-outlet Temperature & heat transfer

Boundary Conditions

CFD 35% furnace model

Heat flow to water-wall

Match?

NO

Update fuel consumption

YES

Results

Research Fund for Coal & Steel
Dryer integration: 35% load (3/3)

- Boiler model initial simulation
- $\varepsilon$-NTU code iterative method for UA values
- Boundary conditions to CFD
- Iterative loop with fuel mass flow update

35% load: iteration method before final case

Diagram:
- Gate Cycle ST model
- Measurements 100%, 80% & 60%
- Aspen Plus boiler model
- Water-wall inlet-outlet temperature & fuel consumption
- Boundary Conditions
- CFD 100% & 60% furnace model

- $\varepsilon$-NTU code iterative method for UA values
- Boundary conditions to CFD
- Iterative loop with fuel mass flow update

Research Fund for Coal & Steel

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Dryer integration: results

35% load

- Pre-dried lignite use beneficiary for boiler efficiency
- Retain gross efficiency
- Improved net efficiency

<table>
<thead>
<tr>
<th>Load</th>
<th>100%</th>
<th>80%</th>
<th>60%</th>
<th>35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross power output, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>366.9</td>
<td>296.6</td>
<td>216.7</td>
<td>128.4</td>
</tr>
<tr>
<td>Air to fuel equivalence ratio</td>
<td>1.15</td>
<td>1.31</td>
<td>1.31</td>
<td>1.41</td>
</tr>
<tr>
<td>Fuel consumption (raw), t/h</td>
<td>639.9</td>
<td>524.3</td>
<td>391.7</td>
<td>238.1</td>
</tr>
<tr>
<td>Fuel consumption (pre-dried), t/h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21.8</td>
</tr>
<tr>
<td>Total electric consumptions, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>26.4</td>
<td>21.5</td>
<td>16.1</td>
<td>10.8</td>
</tr>
<tr>
<td>HP steam production, t/h</td>
<td>936.0</td>
<td>770.0</td>
<td>585.0</td>
<td>419.8</td>
</tr>
<tr>
<td>RH steam production, t/h</td>
<td>994.5</td>
<td>760.5</td>
<td>534.6</td>
<td>405.0</td>
</tr>
<tr>
<td>SH steam characteristics, °C/bar</td>
<td>538/194</td>
<td>538/192</td>
<td>535/191</td>
<td>420/180</td>
</tr>
<tr>
<td>RH steam characteristics, °C/bar</td>
<td>538/33.4</td>
<td>538/24.1</td>
<td>538/19.0</td>
<td>420/11.0</td>
</tr>
<tr>
<td>Flue gas temperature outlet, °C</td>
<td>157.0</td>
<td>162.4</td>
<td>160.2</td>
<td>153.1</td>
</tr>
<tr>
<td>Gross efficiency, %</td>
<td>37.4</td>
<td>36.9</td>
<td>36.1</td>
<td><strong>36.4</strong></td>
</tr>
<tr>
<td>Boiler efficiency, %</td>
<td>84.9</td>
<td>84.4</td>
<td>84.2</td>
<td><strong>88.9</strong></td>
</tr>
<tr>
<td>Net efficiency, %</td>
<td>34.7</td>
<td>34.3</td>
<td>32.4</td>
<td><strong>33.3</strong></td>
</tr>
</tbody>
</table>
Pre-dried lignite economics

(DL Cost) =

+ (RL₁ Cost)
+ (Economic loss from net power reduction due to dryer)
+ (Dryer O&M Cost)
+ (Dryer annualized CAPEX)

Conventional power plant

Integrated drying power plant

DRYLIG: (RFCR-CT-2014-00009)
### Pre-dried lignite economics

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dryer capacity</strong></td>
<td>dry t/h</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hours of operation,</strong></td>
<td>h/a</td>
<td>8,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Annual capacity</strong></td>
<td>dry t/a</td>
<td>480,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Moisture</strong></td>
<td>w/w (%)</td>
<td>49.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Initial, w1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Final, w2</strong></td>
<td>w/w (%)</td>
<td>12.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Raw lignite</strong></td>
<td>raw kg/h</td>
<td>104,970</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>requirements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Greece</th>
<th>Romania</th>
<th>Poland</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw lignite</strong></td>
<td>kJ/kg</td>
<td>5,020.8</td>
<td>7,519.59</td>
<td>11,990</td>
</tr>
<tr>
<td><strong>LHV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dry lignite</strong></td>
<td>kJ/kg</td>
<td>11,264.9</td>
<td>12,476.2</td>
<td>14543.0</td>
</tr>
<tr>
<td><strong>LHV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Raw lignite</strong></td>
<td>EUR/GJ</td>
<td>2.95</td>
<td>3.08</td>
<td>2.01</td>
</tr>
<tr>
<td><strong>production cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Economic assumptions**
- **Discount rate, i**: 5%
- **Life time, t**: 25 years
Pre-dried lignite economics: CAPEX Income loss-Average electricity price

<table>
<thead>
<tr>
<th>Units</th>
<th>CAPEX</th>
<th>Drum dryer</th>
<th>WTA</th>
<th>Tube dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td>M EUR</td>
<td>21,5</td>
<td></td>
<td>37,3</td>
<td>21,3</td>
</tr>
</tbody>
</table>

Electricity price

<table>
<thead>
<tr>
<th>Quarter 2016</th>
<th>Units</th>
<th>Greece</th>
<th>Romania</th>
<th>Poland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>EUR/MWh</td>
<td>44.5</td>
<td>30.8</td>
<td>35.1</td>
</tr>
<tr>
<td>Q2</td>
<td>EUR/MWh</td>
<td>40.5</td>
<td>28.6</td>
<td>39.9</td>
</tr>
<tr>
<td>Q3</td>
<td>EUR/MWh</td>
<td>40.5</td>
<td>32.7</td>
<td>34.4</td>
</tr>
<tr>
<td>Q4</td>
<td>EUR/MWh</td>
<td>45.8</td>
<td>40.9</td>
<td>37.1</td>
</tr>
<tr>
<td>Average</td>
<td>EUR/MWh</td>
<td>42.825</td>
<td>33.25</td>
<td>36.625</td>
</tr>
</tbody>
</table>

- Greece has the highest electricity price, followed by Poland and Romania
- Income loss \[\text{EUR/a}=(P_{el1}-P_{el2})[\text{MW}_{el}] \times H [\text{h/a}] \times p_{el} [\text{EUR/MWh}_{el}]\]
Pre-dried lignite economics: Greece

| Raw lignite production cost | EUR/GJ | 2.95 | 3.08 | 2.01 |

<table>
<thead>
<tr>
<th>Drying technologies</th>
<th>Drum dryer</th>
<th>WTA dryer</th>
<th>Tube dryer</th>
<th>Drum dryer</th>
<th>WTA dryer</th>
<th>Tube dryer</th>
<th>Drum dryer</th>
<th>WTA dryer</th>
<th>Tube dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cost (€/GJ) 100%</td>
<td>3.54</td>
<td>3.39</td>
<td>3.43</td>
<td>3.37</td>
<td>3.40</td>
<td>3.45</td>
<td>3.00</td>
<td>3.36</td>
<td>3.46</td>
</tr>
<tr>
<td>Income loss 100%</td>
<td>0.84</td>
<td>0.39</td>
<td>0.73</td>
<td>0.66</td>
<td>0.40</td>
<td>0.75</td>
<td>0.30</td>
<td>0.36</td>
<td>0.76</td>
</tr>
<tr>
<td>OPEX 100%</td>
<td>0.12</td>
<td>0.49</td>
<td>0.28</td>
<td>0.12</td>
<td>0.49</td>
<td>0.28</td>
<td>0.12</td>
<td>0.49</td>
<td>0.28</td>
</tr>
<tr>
<td>CAPEX 100%</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
</tr>
<tr>
<td>Raw lignite cost 100%</td>
<td>3.54</td>
<td>3.39</td>
<td>3.43</td>
<td>3.37</td>
<td>3.40</td>
<td>3.45</td>
<td>3.00</td>
<td>3.36</td>
<td>3.46</td>
</tr>
</tbody>
</table>

DRYLIG: (RFCR-CT-2014-00009)
Pre-dried lignite economics: Romania

| Raw lignite production cost | EUR/GJ | 2.95 | 3.08 | 2.01 |

**Drying technologies**

<table>
<thead>
<tr>
<th>Fuel Cost (€/GJ)</th>
<th>100%</th>
<th>80%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum dryer</td>
<td>4.34</td>
<td>4.20</td>
<td>3.91</td>
</tr>
<tr>
<td>WTA dryer</td>
<td>4.21</td>
<td>4.24</td>
<td>4.21</td>
</tr>
<tr>
<td>Tube dryer</td>
<td>4.22</td>
<td>4.24</td>
<td>4.36</td>
</tr>
</tbody>
</table>

- **Income loss**
- **OPEX**
- **CAPEX**
- **Raw lignite cost**

DRYLIG: (RFCD-CT-2014-00009)
# Pre-dried lignite economics: Poland

<table>
<thead>
<tr>
<th>Raw lignite production cost</th>
<th>EUR/GJ</th>
<th>2.95</th>
<th>3.08</th>
<th>2.01</th>
</tr>
</thead>
</table>

## Drying technologies

<table>
<thead>
<tr>
<th>Fuel Cost (€/GJ)</th>
<th>Drum dryer</th>
<th>WTA dryer</th>
<th>Tube dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>2.87</td>
<td>2.82</td>
<td>2.79</td>
</tr>
<tr>
<td>80%</td>
<td>2.83</td>
<td>2.88</td>
<td>2.86</td>
</tr>
<tr>
<td>60%</td>
<td>2.58</td>
<td>2.83</td>
<td>2.90</td>
</tr>
</tbody>
</table>

- Income loss
- OPEX
- CAPEX
- Raw lignite cost

DRYLIG: (RFCR-CT-2014-00009)
Pre-dried lignite economics: Results (1/3)

• 100% load:
  • Dry lignite cost is lower with the WTA technology for Greece and Romania and with the Tube dryer technology for Poland
  • Highest cost with the Drum dryer technology for all countries

• 80% load:
  • Dry lignite cost is lower with the Drum dryer technology for all countries
  • Highest cost with Tube dryer technology for Greece and Romania and with WTA technology for Poland

• 60% load:
  • Dry lignite cost is lower with the Drum dryer technology for all countries
  • Highest cost with Tube dryer technology for all countries
## Pre-dried lignite economics: Results (2/3)

### Greece:
- **100% load:**
  - Lowest dry lignite cost: WTA technology
  - Highest cost: Drum dryer technology
- **80% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: Tube dryer technology
- **60% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: Tube dryer technology

### Romania:
- **100% load:**
  - Lowest dry lignite cost: WTA technology
  - Highest cost: Drum dryer technology
- **80% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: Tube dryer technology
- **60% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: Tube dryer technology

### Poland:
- **100% load:**
  - Lowest dry lignite cost: Tube dryer technology
  - Highest cost: Drum dryer technology
- **80% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: WTA technology
- **60% load:**
  - Lowest dry lignite cost: Drum dryer technology
  - Highest cost: Tube dryer technology
Pre-dried lignite economics: Results (3/3)

Comparison with Natural gas & fuel oil as commodity

Pre-dried lignite cost with ETS: 5 €/ton

Greece:  
- Drum dryer: 3.83 €/GJ  
- WTA: 3.91 €/GJ  
- Tube: 3.98 €/GJ  
- Emissions: 106.3 kgCO2/GJ

Romania:  
- Drum dryer: 4.63 €/GJ  
- WTA: 4.70 €/GJ  
- Tube: 4.75 €/GJ  
- Emissions: 95.9 kgCO2/GJ

Poland:  
- Drum dryer: 3.30 €/GJ  
- WTA: 3.38 €/GJ  
- Tube: 3.39 €/GJ  
- Emissions: 107.0 kgCO2/GJ

Pre-dried lignite cost with ETS: 25 €/ton

Greece:  
- Drum dryer: 5.96 €/GJ  
- WTA: 6.04 €/GJ  
- Tube: 6.10 €/GJ  
- Emissions: 106.3 kgCO2/GJ

Romania:  
- Drum dryer: 6.55 €/GJ  
- WTA: 6.62 €/GJ  
- Tube: 6.67 €/GJ  
- Emissions: 95.9 kgCO2/GJ

Poland:  
- Drum dryer: 5.44 €/GJ  
- WTA: 5.52 €/GJ  
- Tube: 5.53 €/GJ  
- Emissions: 107.0 kgCO2/GJ

- Natural gas  
  - Price: 8.37 €/GJ  
  - Emissions: 56.1 kgCO2/GJ  
  - Total cost: 8.65 €/GJ

- Fuel oil  
  - Price: 5.31 €/GJ  
  - Emissions: 77.4 kgCO2/GJ  
  - Total cost: 5.70 €/GJ

- Natural gas  
  - Price: 8.37 €/GJ  
  - Emissions: 56.1 kgCO2/GJ  
  - Total cost: 9.77 €/GJ

- Fuel oil  
  - Price: 5.31 €/GJ  
  - Emissions: 77.4 kgCO2/GJ  
  - Total cost: 7.24 €/GJ
Pre-dried lignite economics: Conclusions

- Feasibility of new technical minimum load with pre-dried lignite co-firing
- Powerful simulation tools predicting power plant and pre-dried lignite production
- Electricity cost highly affects the pre-dried lignite cost
- Minor cost fluctuation across load for WTA and tube drying technologies
- Competitive cost with current CO$_2$ emissions cost
Thank you for your attention!