An integrated market for electricity and natural gas systems with stochastic producers

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Objective

• Define **existing synergies** among energy systems.

• **Efficiently align** the existing synergies towards **optimal operation** of the energy system.

• New **market** structures that will provide incentives to market participants.

• Manage high **uncertainty** on both supply and demand sides.
System operation

Short-term planning (scheduling/dispatch)

Real-time operation (balancing)

Day d-1

Day d
Conventional market-clearing

Sequential clearing of two trading floors:
1) Day-ahead market is cleared based on deterministic description of uncertain wind power production.
2) A balancing market is cleared for real-time operation.
Stochastic market-clearing

Co-optimization of two trading floors:
1) Day-ahead dispatch is determined by co-optimizing day-ahead and real-time dispatch, where wind power uncertainty is probabilistically described.
2) A balancing market is cleared for real-time operation.
Electrical power and natural gas systems

Decoupled: 1) Economic dispatch (ED) of electricity system \(\rightarrow\) NG consumption for electricity.
2) ED of gas system.
Integrated: Simultaneously solve the ED of electricity and gas systems.
Market-clearing models for electricity and natural gas systems

**Stoch-Coup**: Stochastic market-clearing of coupled electricity and natural gas systems.

**Conv-Coup**: Sequential market-clearing of coupled electricity and natural gas systems.

**Conv-Dec**: Sequential market-clearing of decoupled electricity and natural gas systems.
Optimization problems – Stoch-Coup

Min. Day-ahead El and NG cost + Exp. {Balancing El and NG cost}

s.t.

Day-ahead El and NG system constraints

Balancing El and NG system constraints (for all wind power scenarios)

DA dispatch is determined
The following model is solved for a specific wind power realization

Min. Balancing El and NG cost

s.t.

Balancing El and NG system constraints
Optimization problems – Conv-Coup

Min. Day-ahead El and Gas cost
s.t.
Day-ahead El and Gas system constraints
Wind power is constrained by its expected value

The following model is solved for a specific wind power realization

Min. Balancing El and NG cost
s.t.
Balancing El and NG system constraints

DA dispatch is determined
Optimization problems – Conv-Dec

Min. Day-ahead El cost  
s.t.  
Day-ahead El constraints  
Wind power is constrained by its expected value  

GFPPs NG consumption is determined

Min. Day-ahead NG cost  
s.t.  
Day-ahead NG constraints

DA dispatch is determined

The following model is solved for a specific wind power realization

Min. Balancing El and NG cost  
s.t.  
Balancing El and NG system constraints
Model details

1) The optimization models recast as MILP problems.

2) Power flow is modelled by DC approximation.

3) A Taylor series expansion is used to linearize the constraints related to the natural gas network.

4) A dynamic gas system with line pack is considered.
Test case
## Test case data

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{max}}$ (MW)</th>
<th>$R^{(+/-)}$ (MW)</th>
<th>$\eta$ (km³/MW)</th>
<th>$C$ ($/\text{MWh}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>100</td>
<td>0</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>G2</td>
<td>80</td>
<td>0</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>G3</td>
<td>60</td>
<td>60</td>
<td>0.205</td>
<td>-</td>
</tr>
<tr>
<td>G4</td>
<td>60</td>
<td>60</td>
<td>0.264</td>
<td>-</td>
</tr>
<tr>
<td>WP</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$G_{\text{max}}$ (km³)</th>
<th>Initial storage level (km³)</th>
<th>Max in/outflow rate (km³/h)</th>
<th>$C$ ($/\text{km³}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW1</td>
<td>150</td>
<td>-</td>
<td>-</td>
<td>184</td>
</tr>
<tr>
<td>GW2</td>
<td>170</td>
<td>-</td>
<td>-</td>
<td>110</td>
</tr>
<tr>
<td>GS1</td>
<td>150</td>
<td>75</td>
<td>50</td>
<td>147</td>
</tr>
</tbody>
</table>
## Results

<table>
<thead>
<tr>
<th>Optimization model</th>
<th>Total cost ($) (35%)</th>
<th>Total cost ($) (53%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stoch-Coup</td>
<td>576 694</td>
<td>572 483</td>
</tr>
<tr>
<td>Conv-Coup</td>
<td>+ 6.25 %</td>
<td>+ 9.91 %</td>
</tr>
<tr>
<td>Conv-Dec (k=1.1)</td>
<td>+ 6.29 %</td>
<td>+ 9.97 %</td>
</tr>
<tr>
<td>Conv-Dec (k=0.9)</td>
<td>+ 6.92 %</td>
<td>+ 11.05 %</td>
</tr>
</tbody>
</table>
Towards the loose coupling of electric power and natural gas markets

Coordination parameters:
- Total natural gas availability (NGA) for electricity production.
- Natural gas consumption for each GFPP.
- Natural gas prices.

Reality: Conv-Dec

Ideal: Stoch-Coup
Towards the loose coupling of electric power and natural gas markets

Coordination parameters:

- Total natural gas availability (NGA) for electricity production.
- Natural gas consumption for each GFPP.
- Natural gas prices.

Reality: Conv-Dec

Ideal: Stoch-Coup
Coupling through proper flexibility price signals

- Increase the available flexibility to handle wind power variability.
- Respect merit-order principle in electricity market.
- Cost-neutral action for the day-ahead stage.

The problem is formulated as a bi-level model (Imp-Coup):

- **Upper-level**: The operator minimizes the expected system cost and decides how to optimally change the natural gas price available for power production.

- **Lower-level**: Sequential market clearing.
Coupling through proper flexibility price signals

<table>
<thead>
<tr>
<th>Optimization model</th>
<th>Stoch-Coup</th>
<th>Imp-Coup</th>
<th>Conv-Coup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Expected Cost ($)</td>
<td>194 665.27</td>
<td>195 245.57</td>
<td>196 156.30</td>
</tr>
</tbody>
</table>

- The expected cost is reduced by $910.73.
- The system operator is expected to pay $75.18.
- The proposed model can be seen as an alternative to capacity payments for power availability in real-time operation.
Future plans

• Evaluate the benefit of NG storage in pipelines.

• Examine cost recovery for market participants and revenue adequacy of the market design for the case of loose coupling the markets.

• Examine the case of NGA as a coordination parameter.
Thank you for your attention!

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