Optimal Operation Strategy of Cogeneration System with Auxiliary Heat Facilities under Electricity Market Environments

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Outlines

- **Optimal operational strategy determination** to maximize the profit of a district heating company with CHP, PLB, and thermal storage.

- Each operational mode of CCGT-based CHP is defined and modeled mathematically.

- Optimal operating points of CHP are determined under (Korean) electricity market rules and other environments such as thermal load, fuel prices, heat price, etc.

- Thermal storage and peak load boiler (PLB) are considered when determining the thermal/electrical output of CHPs.

- Operation software is developed for practical applications.
Cogeneration System Optimization Process (1)

- Day/Week-ahead Hourly Heat and Electricity Demand Forecasting
- Day-ahead Power Market Forecasting & Analysis
  - Electricity Prices, CHP Outputs (Unconstrained and Constrained Output)
- CCGT CHP, PLB and Thermal Storage Optimization

Results
- Electricity Profit
- Heat Profit
- Electrical/Thermal output of CHP considering heat storage and PLB
Cogeneration System Optimization Process (2)

<Electrical Demand> → MODE_t, P_t, H_t

Electricity/Heat Market Forecasting

<Heat Demand> → TS^c_t, TS^d_t

<CHP>

<Peak Load Boiler>

<Thermal Storage>
LNG CCGT-based Cogeneration System (1)

CCGT-CHP

District Heat

HRSG

Steam Turbine

Gas Turbine

Boiler

District Heater

District Heat

Thermal Storage
LNG CCGT-based Cogeneration System (2)

- Gas turbine(s) + HRSG + High/Low pressure steam turbine(s)
  - CCGT CHP with various operational modes and characteristics
  - High efficiency can be maintained by separating steam turbine

- Multiple District Heaters
  - Increasing electrical output by optimizing extraction pressure
  - Temperature of district heating water: 65℃/ 90℃/ 115℃

- Optimize Seasonal Operation Mode
  - Optimize heat/power efficiency by not-operating at low pressure turbine and condenser during high thermal load season
  - Optimize heat/power efficiency by operating at low pressure turbine and condenser during low thermal load season
Operation Modes of CCGT-CHP System (1)

- **MODE I**: Heat-generation mode (winter)
  - Operation facilities: gas turbine, HRSG, high pressure steam turbine, district heater
  - Not operating facilities: Low pressure steam turbine, condenser

- **MODE II**: Gas turbine operation mode (uncommon operation)
  - Operating facilities: gas turbine (electricity only, no thermal output)
  - Not operating facilities: HRSG, high/low pressure steam turbine, condenser, district heater

- **MODE III**: Electricity-generation mode (summer)
  - Operating facilities: gas turbine, HRSG, high/low pressure steam turbine, condenser
  - Not operating facilities: district heater
  - CCGT operation only for electricity generation

- **MODE IV**: Maximum Heat Following Mode (High Heat Demand)
  - Operating facilities: gas turbine, HRSG, district heater
  - Not operating facilities: high/low pressure steam turbine, condenser
  - Uses all heat recovery to supply thermal load (not electricity)

- **MODE V**: Mixed-match mode (spring/fall, Low Heat Demand)
  - Operating facilities: gas turbine, HRSG, high/low pressure steam turbine, district heater
Operation Modes of CCGT-CHP System (2)
Operation Modes of CCGT-CHP System (3)

- Operation Zone in Each Mode

![Graph showing operation zones for different modes](image-url)

- Mode I
- Mode V
- Mode III

Heat [Gcal/h] vs. Power [MW]
Operation Modes of CCGT-CHP System (4)

- **Mode Physical Characteristics**

  - **Mode I**
    - Start-up: 4h
    - Shut-down: 10min
    - Mode Change Time: 2h 35min

  - **Mode III**
    - Start-up: 2h 35min
    - Shut-down: 30min
    - Mode Change Time: 10min

  - **Mode V**
    - Start-up: 4h
    - Shut-down: 30min
    - Mode Change Time: 10min
Mathematical Formulation (1)

- **Objective Function (Profit Maximization of a District Heating Co.)**

\[
\begin{align*}
\max & \quad \sum_{i} \sum_{j} \sum_{t} (SEP_{i,j,t} + GSCON_{i,j,t} + SCON_{i,j,t} + COFF_{i,j,t}) \\
& \quad + HL_t \times HP_t - FC_{i,j,t}^{CHP} \times FP_{i,t}^{CHP} - FC_{t}^{PLB} \times FP_{t}^{PLB} \\
\end{align*}
\]

- **Heat Supply/Demand Balance**

\[
\sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{t=1}^{T} H_{i,j,t} + H_{t}^{PLB} + H_{t}^{D} - H_{t}^{C} \geq HL_t
\]

- **Generator Output Constraints**

\[
P_{i,j,\text{min}} \times U_{i,j,t} \leq MGO_{i,j,t} \leq P_{i,j,\text{max}} \times U_{i,j,t}
\]
Mathematical Formulation (2)

Operational Modes of CHP

\[ H_{i,j,t} = \alpha_1 \times MGO_{i,j,t} + \beta_1 \times U_{i,j,t} \]

\[ H_{i,j,t} \geq \alpha_{2,1} \times MGO_{i,j,t} + \beta_{2,1} \times U_{i,j,t} \]

\[ H_{i,j,t} \leq \alpha_{2,2} \times MGO_{i,j,t} + \beta_{2,2} \times U_{i,j,t} \]

\[ H_{i,j,t} \leq \alpha_{2,3} \times MGO_{i,j,t} + \beta_{2,3} \times U_{i,j,t} \]

\[ H_{i,j,t} \geq 0 \]
Mathematical Formulation (3)

[Minimum Mode Change Time, MMCT]

\[ \sum_{t=1}^{G_{i,j}} [1 - U_{i,j,t}] = 0 \]

\[ \sum_{k=t}^{t+UT_{i,j} - 1} U_{i,j,k} \geq MMCT_{i,j} [U_{i,j,t} - U_{i,j,t-1}] \]

\( t = G_{i,j} + 1, \ldots, T - UT_{i,j} + 1 \)

\[ \sum_{k=t}^{T} \{ U_{i,j,k} - (U_{i,j,t} - U_{i,j,t-1}) \} \geq 0 \]

\( t = T - UT_{i,j} + 2, \ldots, T \)
Mathematical Formulation (4)

- **Charging, Discharging Limits of Thermal Storage**

\[
0 \leq H^C_t \leq H^C_{\text{max}} \times U^C_t \\
0 \leq H^D_t \leq H^D_{\text{max}} \times U^D_t
\]

- **Charging, Discharging State Variables**

\[
U^C_t + U^D_t \leq 1
\]

- **Storage Thermal Limits**

\[
ACC_t = H^C_t - H^D_t + ACC_{t-1} \\
0 \leq ACC_t \leq ACC_{\text{max}}
\]
# Numerical Studies for Sample System (1)

## CHP Input Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Mode I</td>
<td>100%</td>
<td>338.06</td>
<td>199.56</td>
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<tr>
<td></td>
<td>90%</td>
<td>351.31</td>
<td>179.47</td>
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<tr>
<td></td>
<td>40%</td>
<td>188.25</td>
<td>90.26</td>
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<tr>
<td></td>
<td>30%</td>
<td>165.01</td>
<td>77.13</td>
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<tr>
<td>Mode V</td>
<td>100%</td>
<td>431.18</td>
<td>180.80</td>
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<tr>
<td></td>
<td>90%</td>
<td>390.34</td>
<td>163.15</td>
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<tr>
<td></td>
<td>40%</td>
<td>209.17</td>
<td>82.05</td>
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<tr>
<td></td>
<td>30%</td>
<td>183.34</td>
<td>70.12</td>
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<tr>
<td>Mode III</td>
<td>100%</td>
<td>485.89</td>
<td>-</td>
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<tr>
<td></td>
<td>90%</td>
<td>439.80</td>
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<td></td>
<td>40%</td>
<td>233.14</td>
<td>-</td>
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<tr>
<td></td>
<td>30%</td>
<td>203.49</td>
<td>-</td>
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</tbody>
</table>
Numerical Studies for Sample System (2)

- **Hourly Heat Demand**
  - Min 78 [Gcal], Max 223 [Gcal] (24 Hrs Heat Demand 3,447 [Gcal])

- **Heat Sales**

<table>
<thead>
<tr>
<th></th>
<th>Residential</th>
<th>Commercial</th>
<th>Public</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Price [KRW/Gcal]</td>
<td>63,070</td>
<td>81,900</td>
<td>71,520</td>
<td>72,163</td>
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</tbody>
</table>
Day-ahead Electricity Market Forecasting

[Hourly SMP Forecasting]

[Hourly Generation Forecasting (PSE, MGO)]
## Numerical Studies for Sample System (4)

### Comparisons of Results

- HS Capacity 2000Gcal, Hourly Max C/D: 200Gcal/h, MMCT: 3Hrs,
- Heat Storage MUT/MDT: 10Hrs
- Case 1: without HS, Case 2: with HS (CHP, PLB, HS) without considering HS technical Constraints, Case 3: Considering all resources and constraints

<table>
<thead>
<tr>
<th>Revenue [MKRW]</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Sales</td>
<td>SEP</td>
<td>804.70</td>
<td>804.10</td>
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<tr>
<td></td>
<td>GSCON</td>
<td>542.92</td>
<td>361.30</td>
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<tr>
<td></td>
<td>SCON</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td>COFF</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Heat Sales</td>
<td></td>
<td>248.74</td>
<td>248.74</td>
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<tr>
<td>Total Revenue</td>
<td></td>
<td>1,596.35</td>
<td>1,414.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost [MKRW]</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP</td>
<td>1,518.21</td>
<td>1,281.25</td>
<td>1,358.79</td>
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<tr>
<td>PLB</td>
<td>19.48</td>
<td>4.53</td>
<td>19.48</td>
</tr>
<tr>
<td>Total Cost</td>
<td>1,537.70</td>
<td>1,285.78</td>
<td>1,378.27</td>
</tr>
<tr>
<td>Net Profit [MKRW]</td>
<td>58.65</td>
<td>128.35</td>
<td>68.47</td>
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</tbody>
</table>
Numerical Studies for Sample System (5)

Example of Thermal Storage Effect

![Graph showing thermal storage effect](image)

- Heat [Gcal]
- Without TS
- With TS
- Heat Load

1 to 24 days
Example of Electricity Output of CHP

The chart illustrates the electricity output of a Combined Heat and Power (CHP) system. The blue bars represent output without time synchronization (TS), while the red bars show output with TS. The x-axis represents different time slots, and the y-axis shows the electricity output in MW (megawatts). The data indicates a higher output with TS across most time slots, with variations in output between 100 MW and 900 MW.
Hana Power is a district heating company in Korea with 1 CHP, thermal storage, and PLB.
Development of Optimization System for Practical Applications (2)

- MILP & Excel Based System with Simple and Robust Solution Capability
Development of Optimization System for Practical Applications (3)

Real Optimization Results (Winter)

![Graph showing real optimization results for Winter. The graph includes multiple lines representing different optimization models, such as CHP, and indicates data points for each day of the month.](image-url)
Development of Optimization System for Practical Applications (4)

- Real Optimization Results (Summer)
Conclusions

- **Optimizer Development and Analysis**
  - System configuration with 1 CCGT-based CHP(3/5 modes), 1 PLB, 1 thermal storage. Heat demand and electricity market forecasting capability.
  - Considering physical constraints of CHP and HS. Implementation in Excel Environment (MILP)

- **Future works**
  - Configuration expansion for heat network interconnection consideration between district heating companies. ESS(Electrical Energy Storage System) consideration for electricity storage and optimization.
  - Experience sharing and collaboration with Danish district optimization system.
  - Journal Paper(s) / Software Improvement for practical applications
Further Research

- Each mode's time conversion consideration
- Heat flow optimization at the end
- Consideration of multiple CHPs
- PLB inclusion
- If possible, consider ESS for thermal and electrical optimal operation (Operation side)

3. Objective Function

- To maximize the total profit of the micro-grid power producer for a given period

Objective Function =

- Total Revenue: Selling electric power and thermal heat to the residents in its micro-grid + selling out the surplus electric power and the surplus heat generated by the distributed generation CHPs and boilers

- Total Cost: The cost of fuel for generating the distributed generators + the cost of purchasing electric power from the external grid + the cost for purchasing heat from the external thermal system

Thank You