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

(CITIES Fourth General Consortium Meeting, Aarhus, Denmark)

May 31, 2017.

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Outlines

- <u>Optimal operational strategy determination</u> to maximize the profit of a district heating company with CHP, PLB, and thermal storage
- <u>Each operational mode of CCGT-based CHP</u> is defined and modeled mathematically
- <u>Optimal operating points of CHP</u> are determined under (Korean) electricity market rules and other environments such as thermal load, fuel prices, heat price, etc.
- <u>Thermal storage and peak load boiler (PLB)</u> are considered when determining the thermal/electrical output of CHPs
- <u>Operation software</u> is developed for practical applications

Cogeneration System Optimization Process (1)

- Day/Week-ahead Hourly Heat and Electricity Demand Forecasting

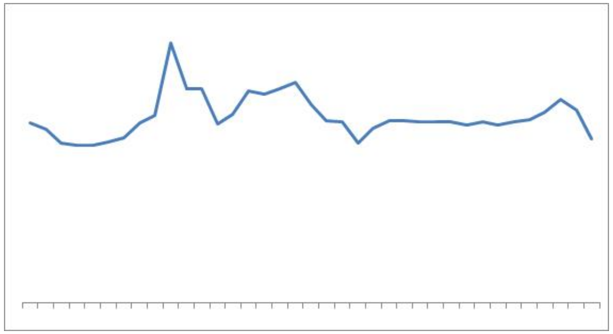
- Day-ahead Power Market Forecasting & Analysis
- Electricity Prices, CHP Outputs (Unconstrained and Constrained Output)

- **CCGT CHP, PLB and Thermal Storage Optimization**

Results

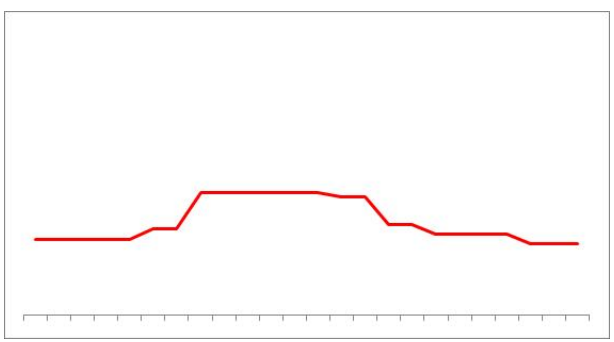
- Electricity Profit
- Heat Profit
- Electrical/Thermal output of CHP considering heat storage and PLB

Cogeneration System Optimization Process (2)



<Electrical Demand>

Electricity/Heat Market Forecasting



<Heat Demand>

<CHP>

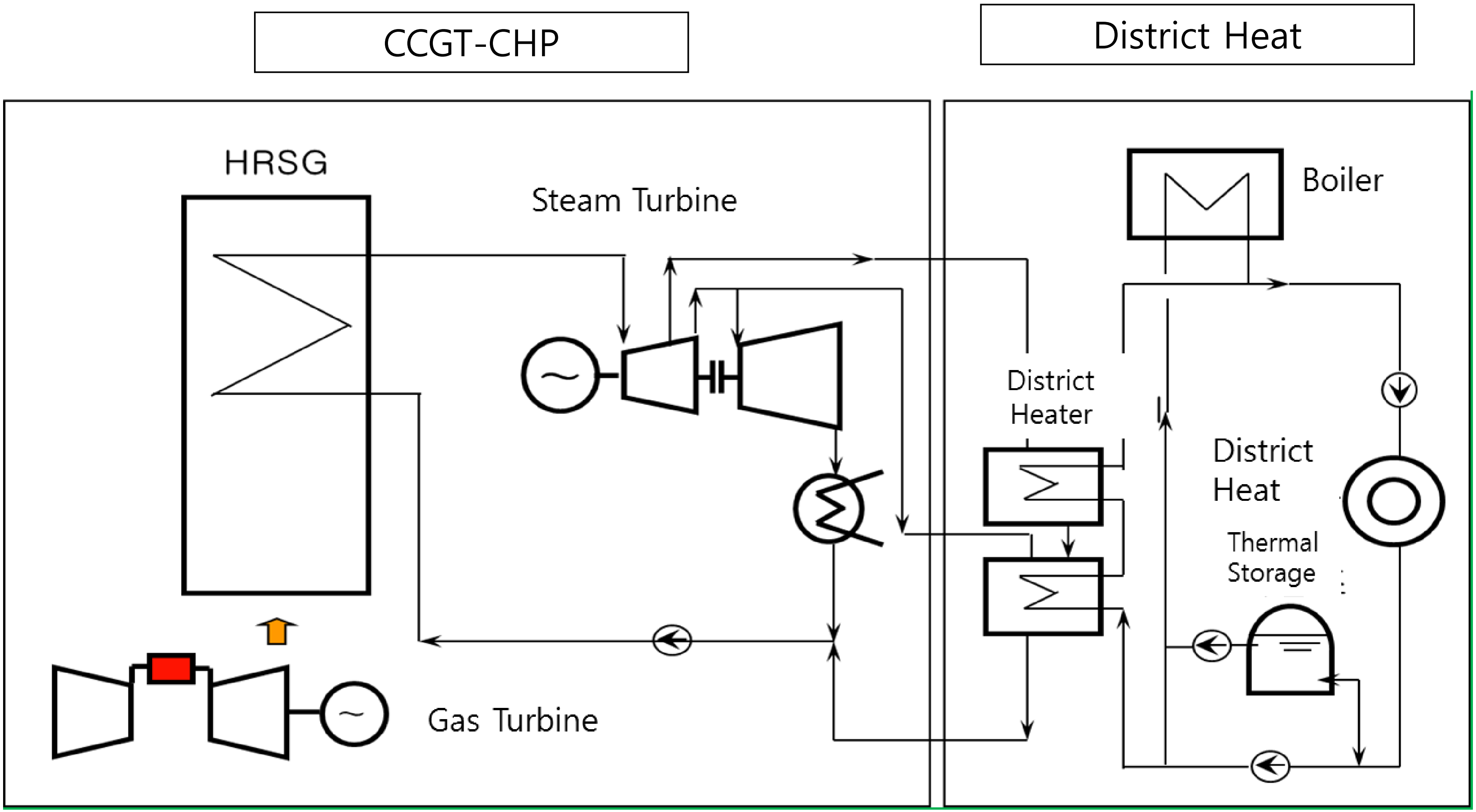
$\rightarrow$ $MODE_t, P_t, H_t$

<Peak Load Boiler>

<Thermal Storage>

$\rightarrow$ TS_t^C, TS_t^D

LNG CCGT-based Cogeneration System (1)



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℃

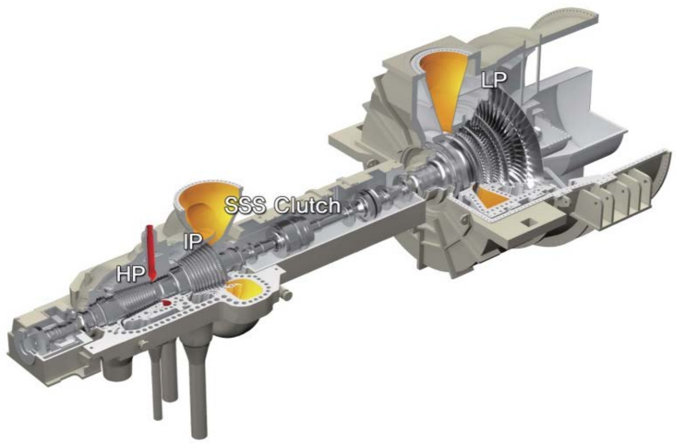
Optimize Seasonal Operation Mode

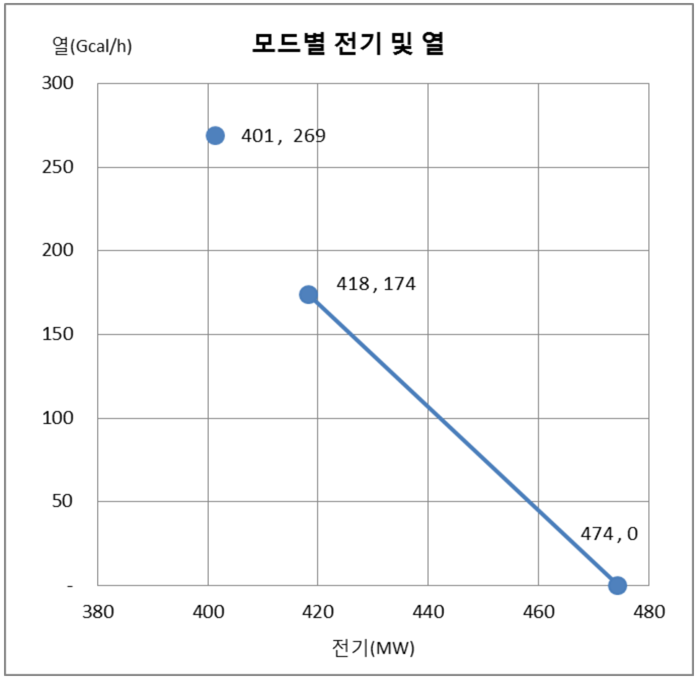
- Optimize heat/power efficiency by not-operating at low pressure turbine and condenser during high thermal load season
- Optimize heat/power efficiency by operating at low pressure turbine and condenser during low thermal load season

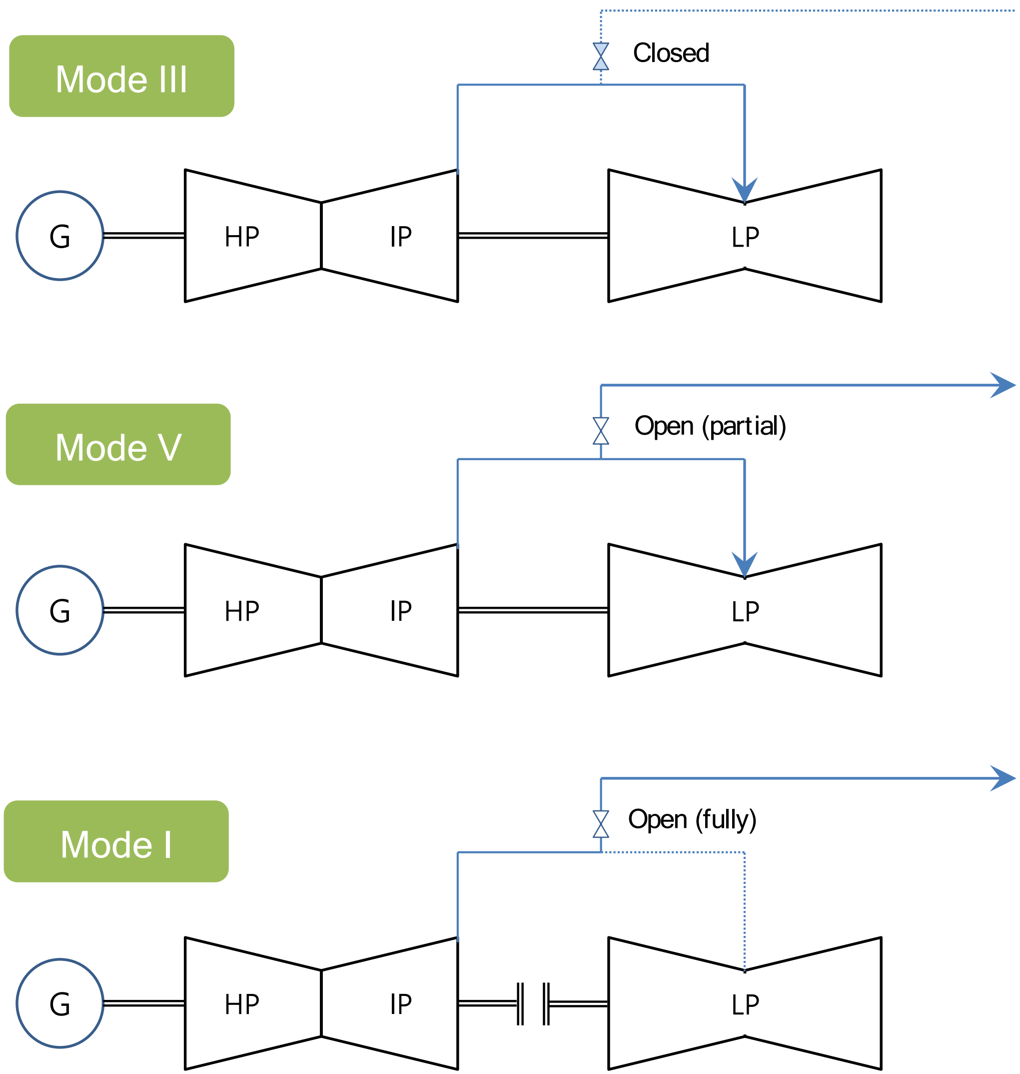
Operation Modes of CCGT-CHP System (1)

- <u>MODE Ⅰ</u> **: 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
- <u>MODE Ⅲ</u> **: 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)
- <u>MODE Ⅴ</u> **: 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)

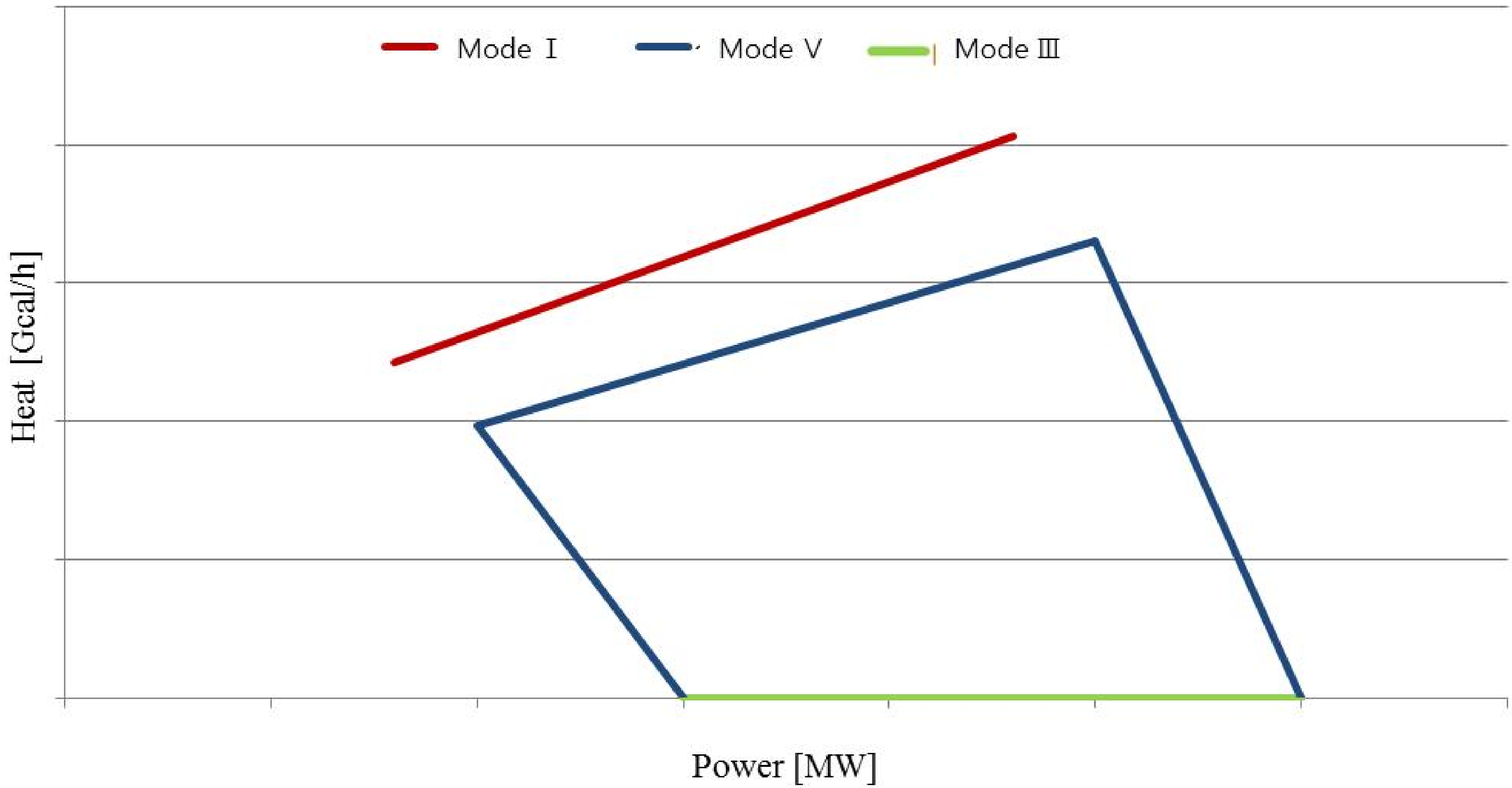






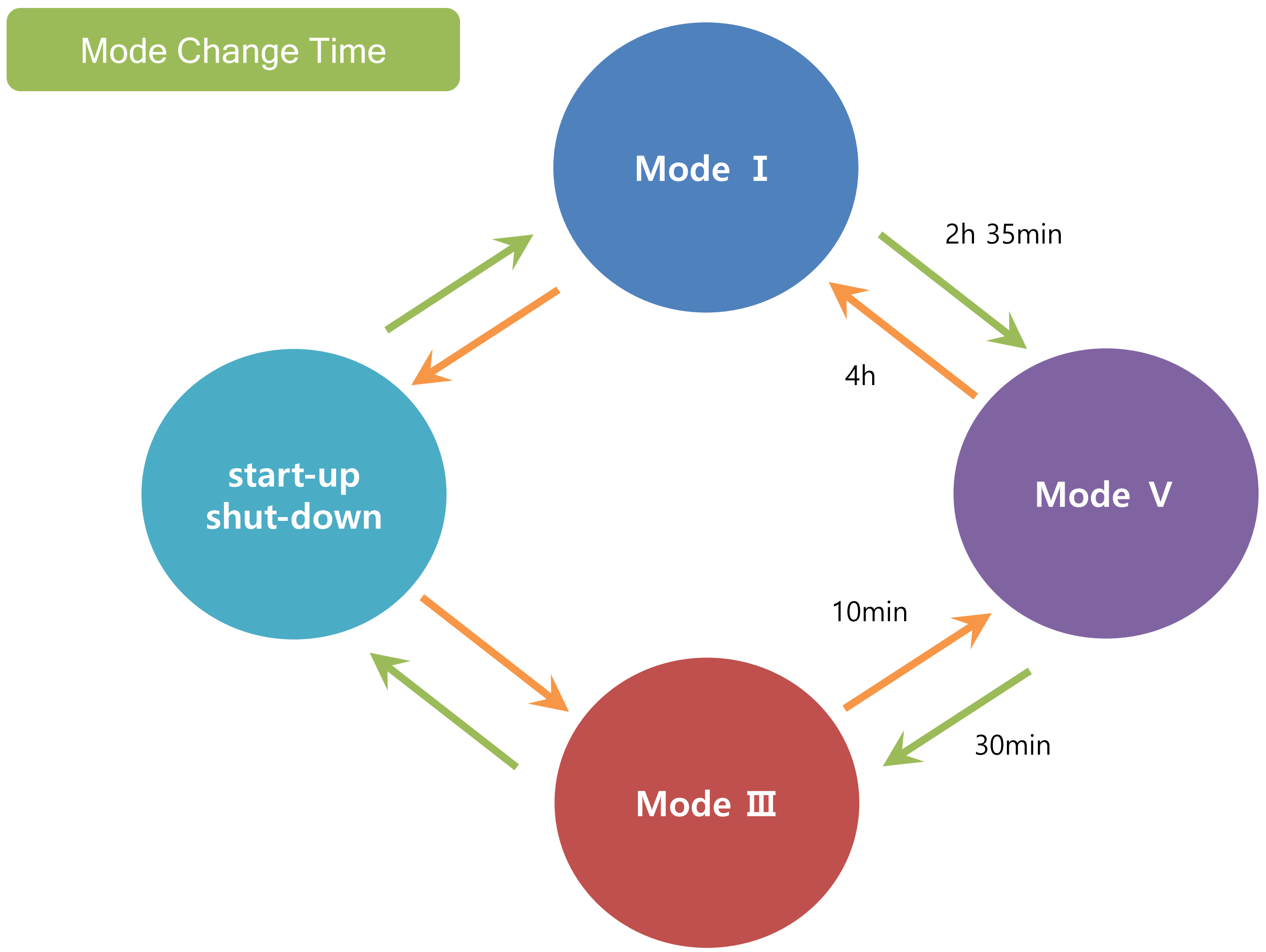
Operation Modes of CCGT-CHP System (3)

Operation Zone in Each Mode



Operation Modes of CCGT-CHP System (4)

Mode Physical Characteristics



Mathematical Formulation (1)

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

$$\max \sum_{i}^{N}\sum_{j}^{M}\sum_{t}^{T}\overbrace{(SEP_{i,j,t} + GSCON_{i,j,t} + SCON_{i,j,t} + COFF_{i,j,t})}^{\text{Revenue of Electricity Sales}}$$

$$+\underbrace{HL_t \times HP_t}_{\text{Heat Sales Revenue}} - \underbrace{FC_{i,j,t}^{CHP} \times FP_{i,t}^{CHP} - FC_t^{PLB} \times FP_t^{PLB}}_{\text{Fuel Cost}}$$

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

$$P_{i,j,\min} \times U_{i,j,t} \leq MGO_{i,j,t} \leq P_{i,j,\max} \times U_{i,j,t}$$

Mathematical Formulation (2)

Operational Modes of CHP

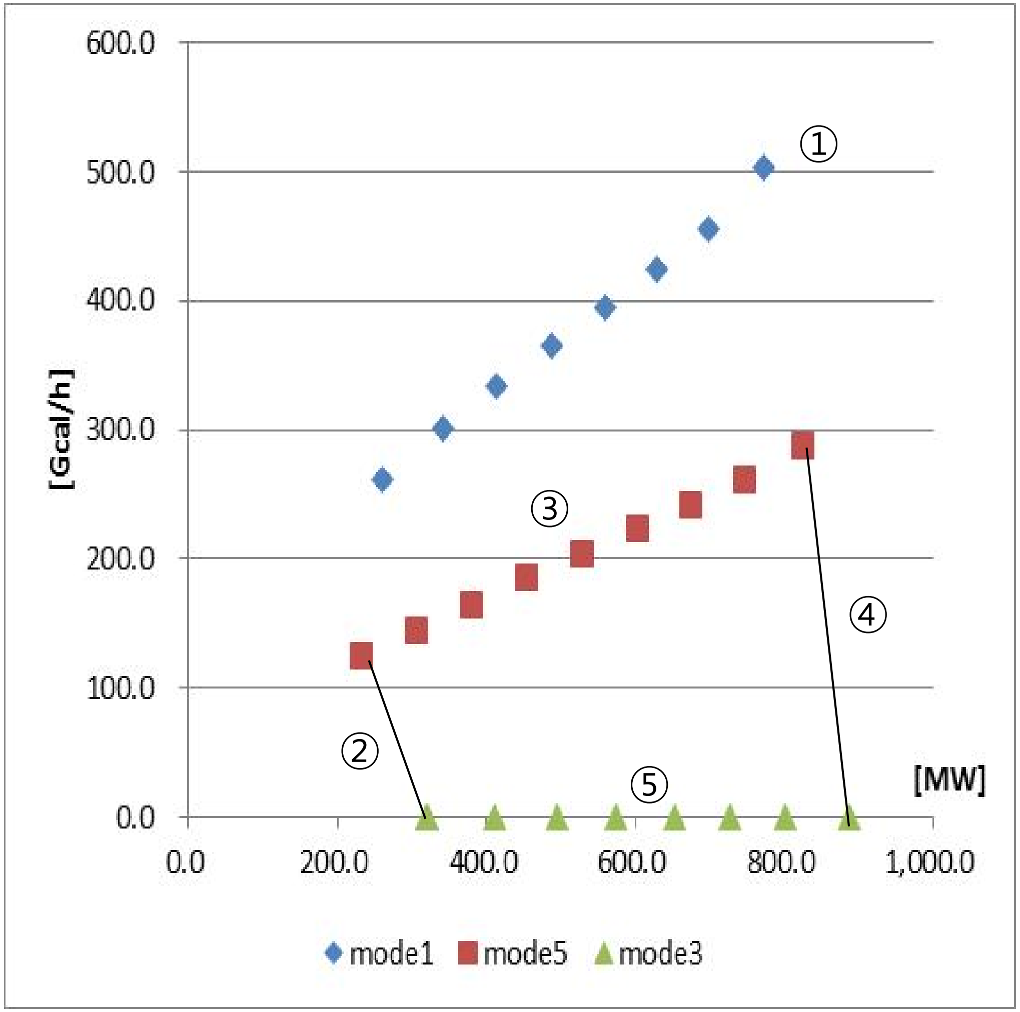
$$H_{i,j,t} = \alpha_1 \times MGO_{i,j,t} + \beta_1 \times U_{i,j,t}$$

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

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

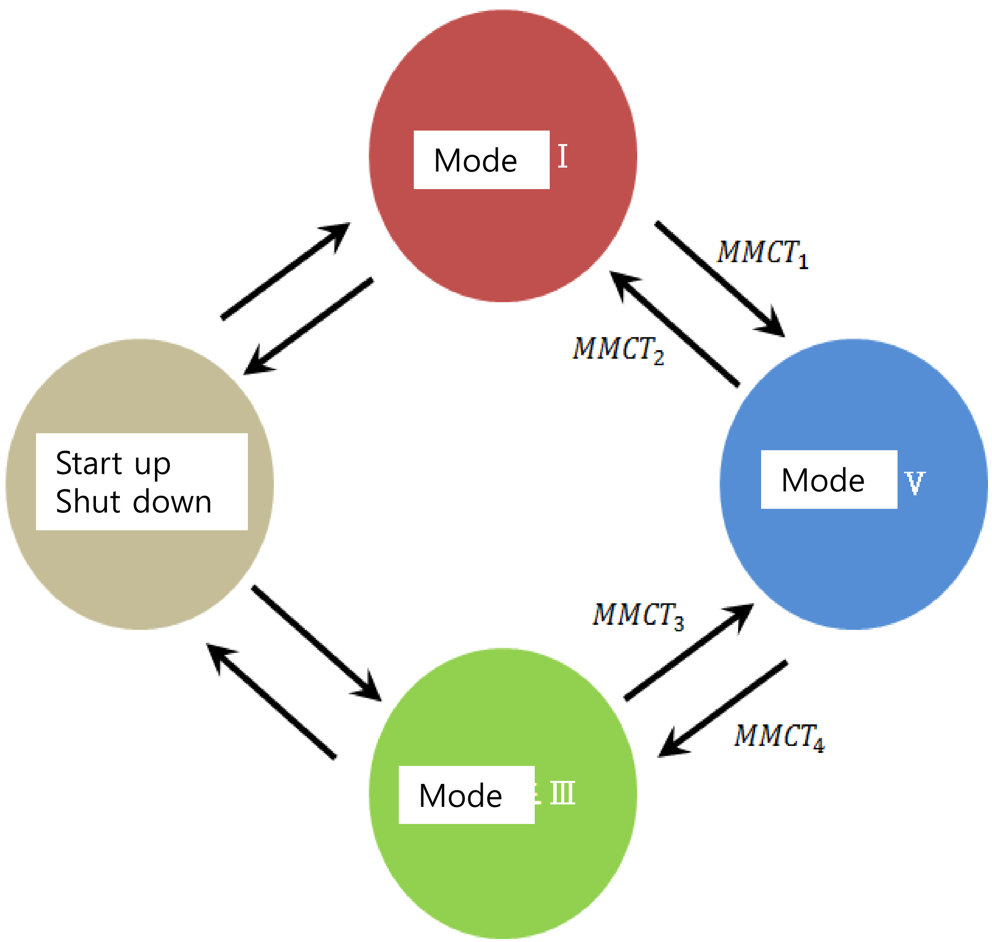
$$H_{i,j,t} \leq \alpha_{2,3} \times MGO_{i,j,t} + \beta_{2,3} \times U_{i,j,t}$$

$$H_{i,j,t} \geq 0$$



Mathematical Formulation (3)

[Minimum Mode Change Time, MMCT]



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

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

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

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

$$(t = T - UT_{i,j}+2, \cdots, T)$$

Mathematical Formulation (4)

Charging, Discharging Limits of Thermal Storage

$$0 \leq H^C{}_t \leq H^C{}_{max} \times U^C{}_t$$

$$0 \leq H^D{}_t \leq H^D{}_{max} \times U^D{}_t$$

Charging, Discharging State Variables

$$U^C{}_t + U^D{}_t \leq 1$$

Storage Thermal Limits

$$ACC_t = H^C{}_t - H^D{}_t + ACC_{t-1}$$

$$0 \leq ACC_t \leq ACC_{max}$$

Numerical Studies for Sample System (1)

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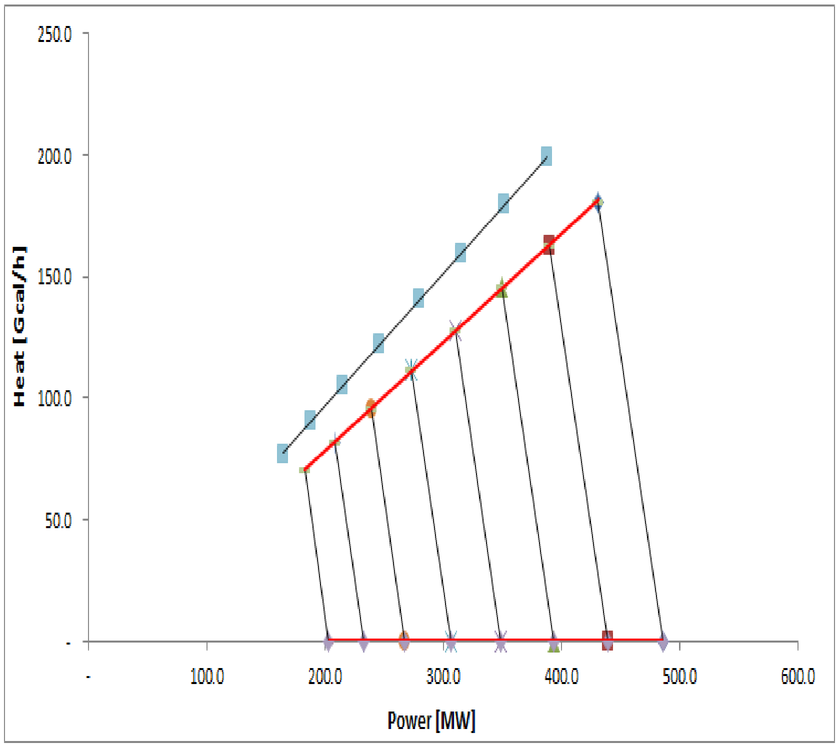
CHP Input Data

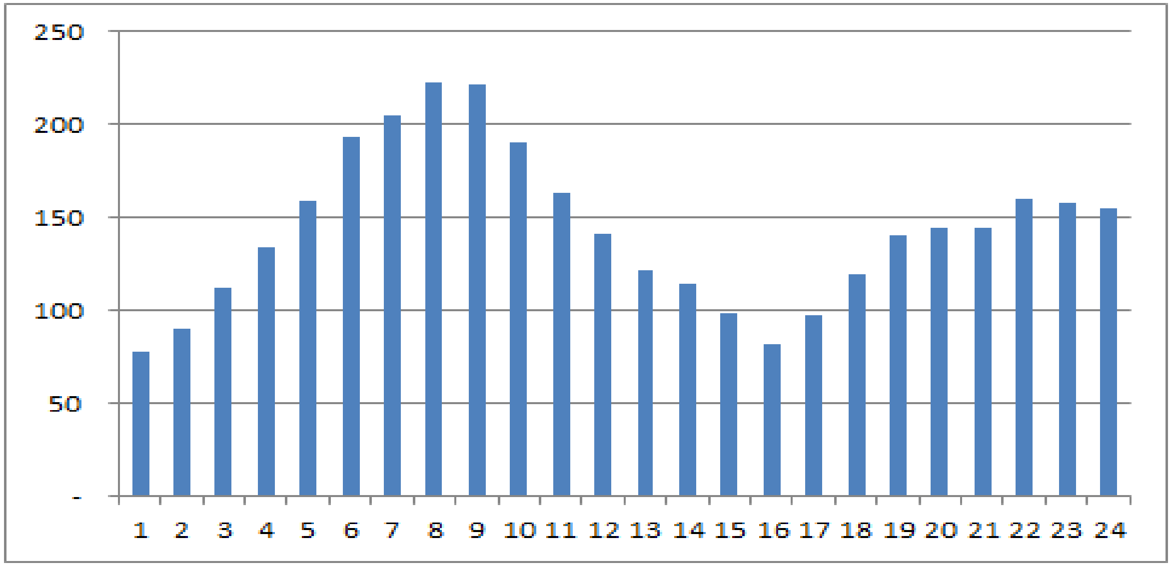


modes		Power [MW]	Heat [Gcal/h]	Fuel [Ton/h]
Mode Ⅰ	100%	338.06	199.56	54.83
	90%	351.31	179.47	50.33
	⋮	⋮	⋮	⋮
	40%	188.25	90.26	29.45
	30%	165.01	77.13	26.40
Mode Ⅴ	100%	431.18	180.80	58.95
	90%	390.34	163.15	54.12
	⋮	⋮	⋮	⋮
	40%	209.17	82.05	31.67
	30%	183.34	70.12	28.38
Mode Ⅲ	100%	485.89	-	58.95
	90%	439.80	-	54.12
	⋮	⋮	—	⋮
	40%	233.14	-	31.67
	30%	203.49	-	28.68

Numerical Studies for Sample System (2)

Hourly Heat Demand

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

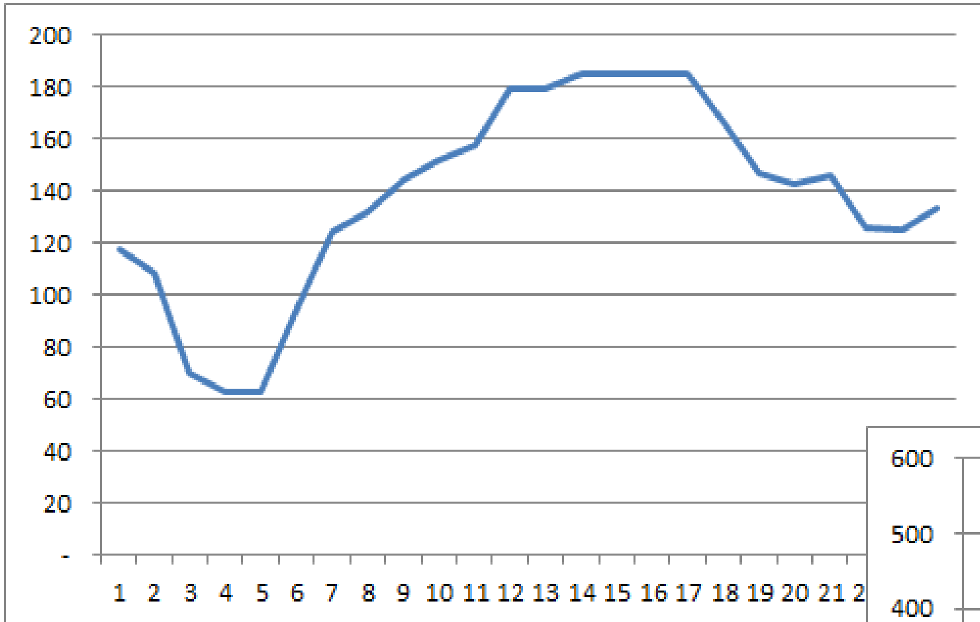


Heat Sales

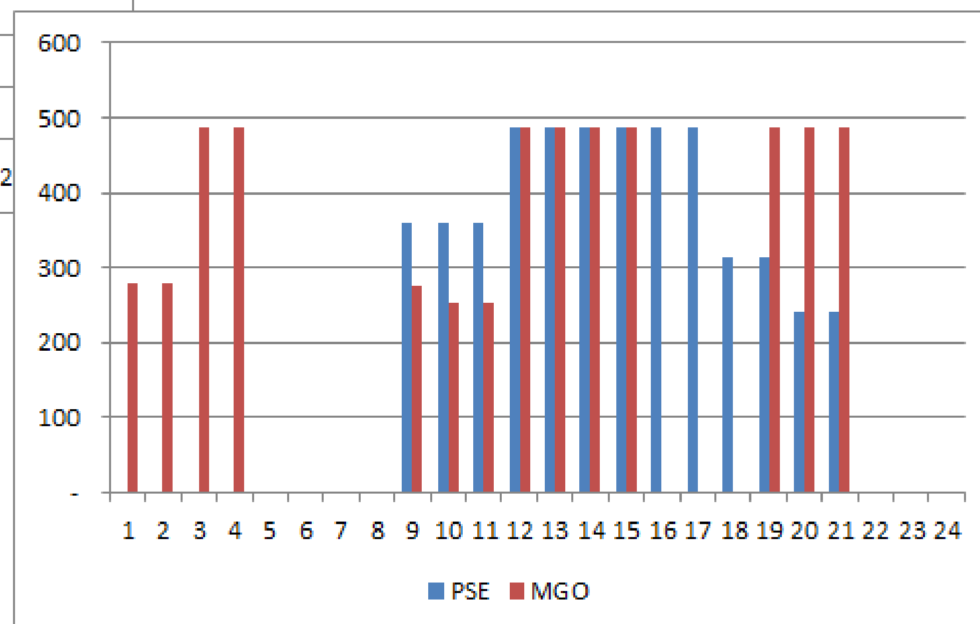
	Residential	Commercial	Public	Average
Heat Price [KRW/Gcal]	63,070	81,900	71,520	**72,163**

Numerical Studies for Sample System (3)

Day-ahead Electricity Market Forecasting



[Hourly SMP Forecasting]



[Hourly Genertion Forecasting(PSE, MGO)]

Numerical Studies for Sample System (4)

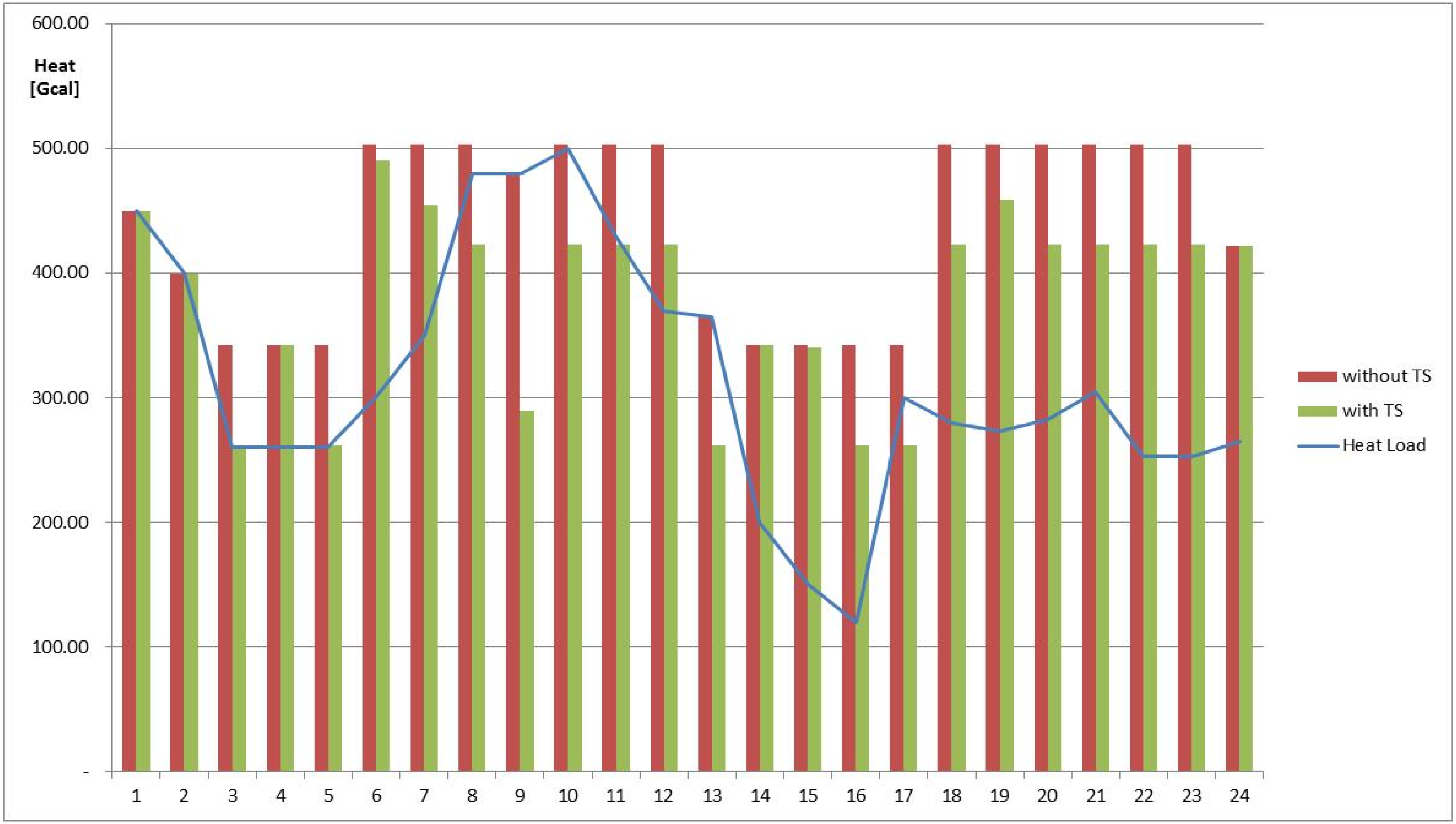
Comparisons of Results

- HS Capacity 2000Gcal, Houly 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

			Case 1	Case 2	Case 3
Revenue [MKRW]	Electricity Sales	SEP	804.70	804.10	804.70
		GSCON	542.92	361.30	393.31
		SCON	0	0	0
		COFF	0	0	0
	Heat Sales		248.74	248.74	248.74
	Total Revenue		1,596.35	1,414.13	1,446.74
Cost [MKRW]	CHP		1,518.21	1,281.25	1,358.79
	PLB		19.48	4.53	19.48
	Total Cost		1,537.70	1,285.78	1,378.27
Net Profit [MKRW]			**58.65**	**128.35**	**68.47**

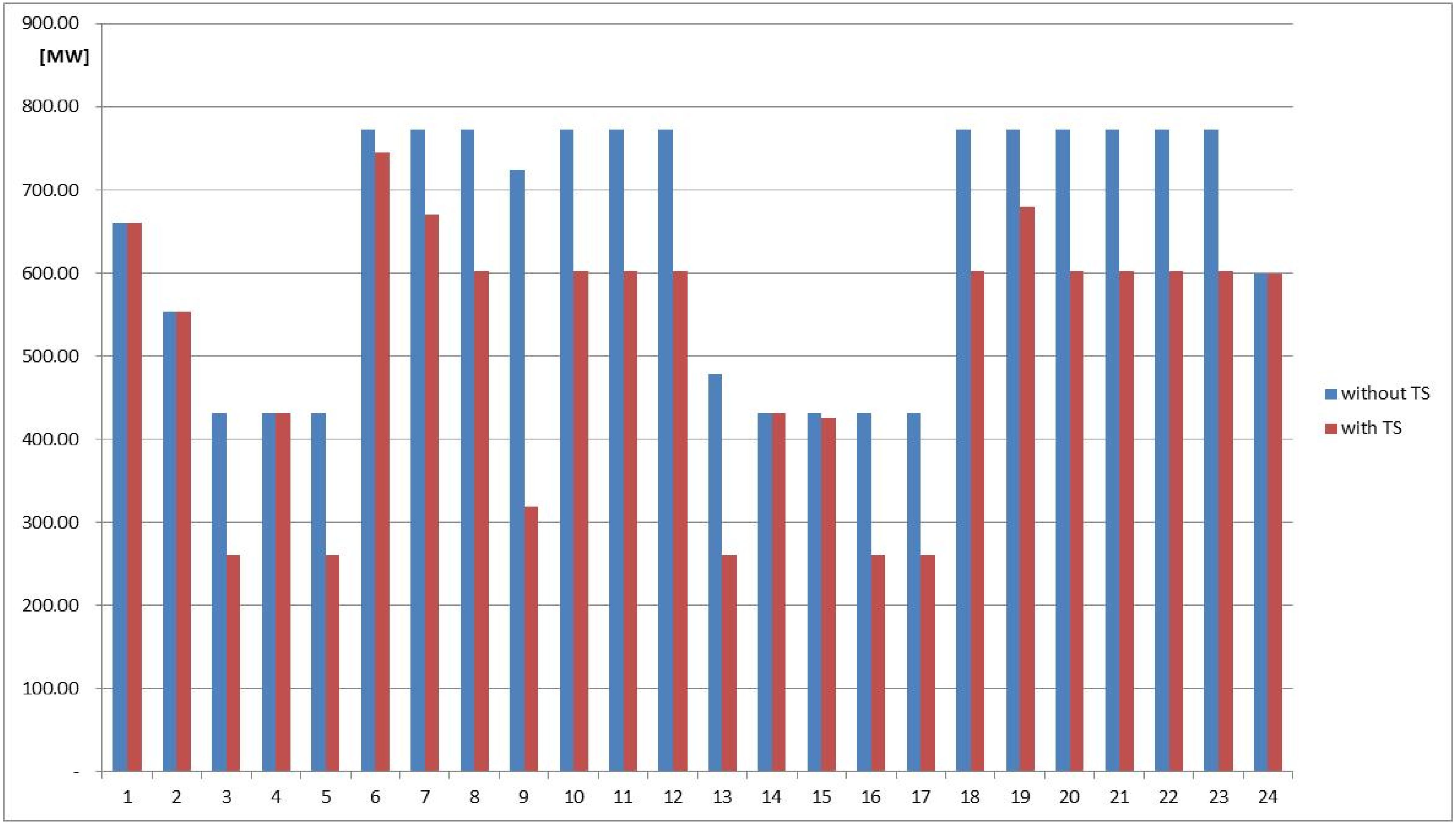
Numerical Studies for Sample System (5)

Example of Thermal Storage Effect



Numerical Studies for Sample System (6)

Example of Electricity Output of CHP



Development of Optimization System for Practical Applications (1)

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Optimal Operation Analysis Program (Start)

평택에너지서비스 | 하나파워

Optimal Operation Analysis Program
열병합 발전소 최적 운영 분석 프로그램

Private and Confidential
2017-05-22

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각 분석 Factor들은 일정한 가정조건 및 전제, 제공데이터를 기반으로 최적화를 수행합니다.

아래의 Start 버튼을 누르면 본 시트로 이동하게 됩니다.

START

Hana Power is a district heating company in Korea with 1 CHP, thermal storage, and PLB.

Development of Optimization System for Practical Applications (2)

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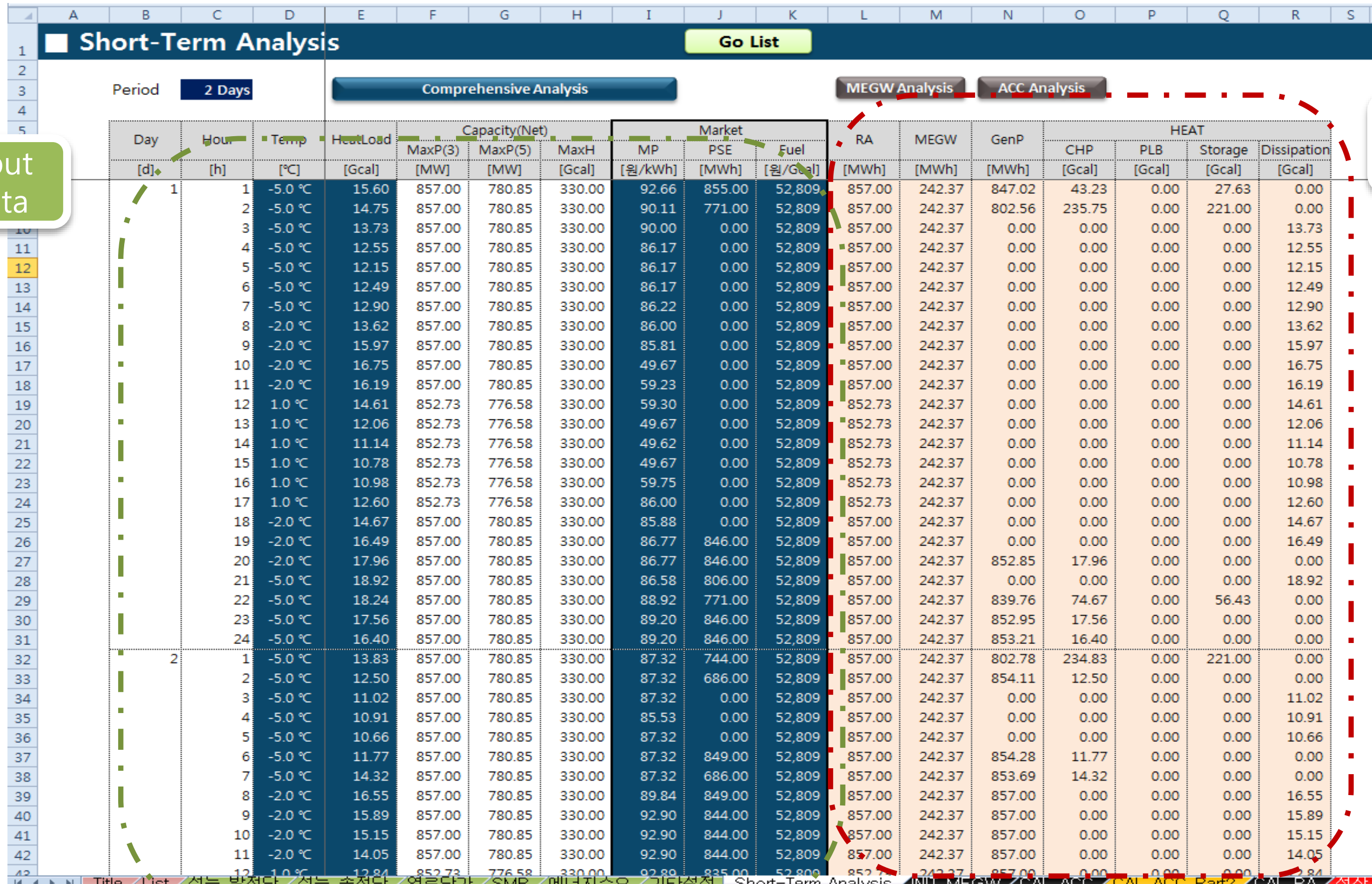
Optimal Operation Analysis Program (Main Page)

Input Data

Output Data



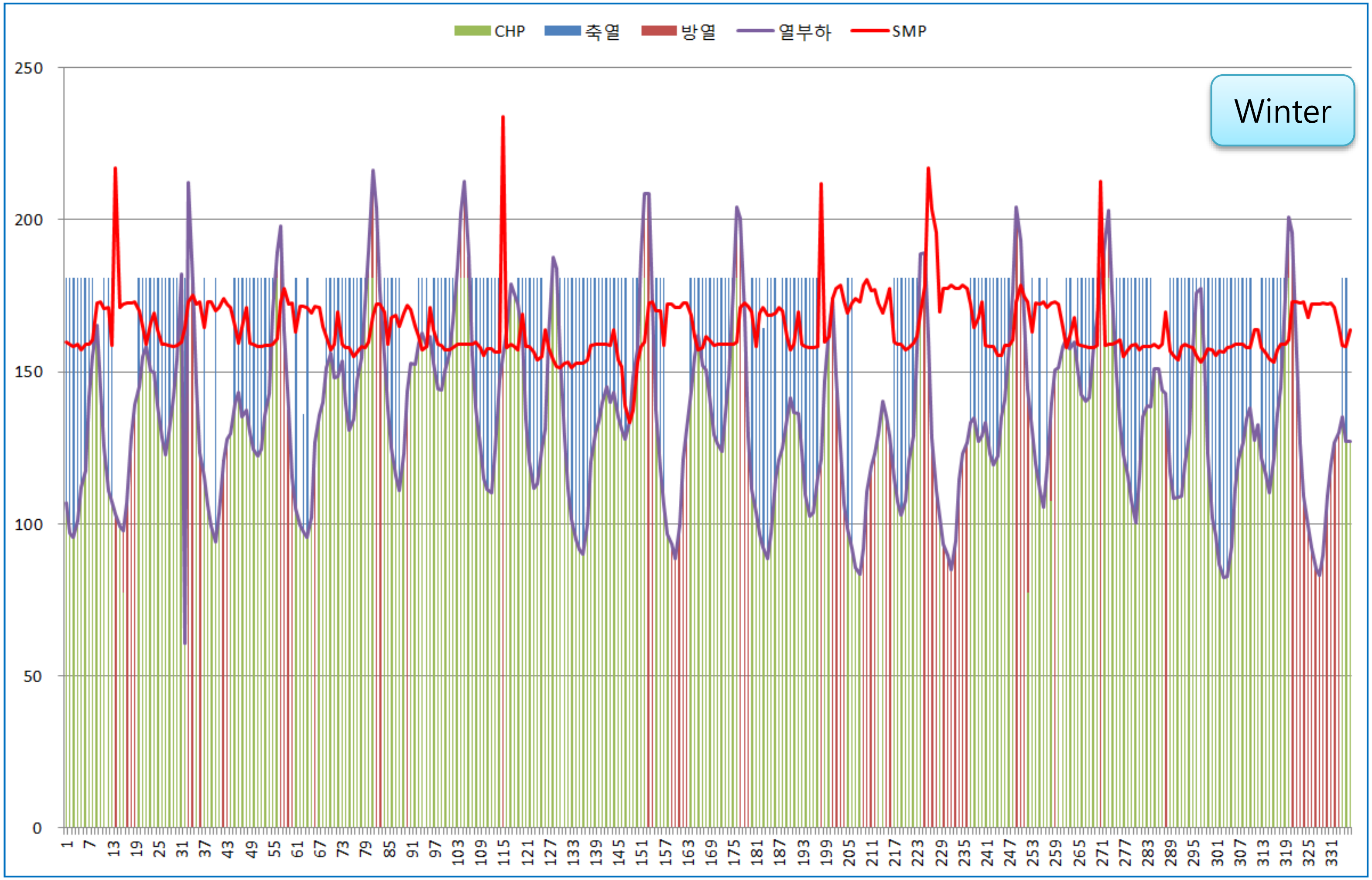
Day	Hour	Temp	HeatLoad	Capacity(Net)			Market			RA	MEGW	GenP	HEAT			
				MaxP(3)	MaxP(5)	MaxH	MP	PSE	Fuel				CHP	PLB	Storage	Dissipation
[d]	[h]	[℃]	[Gcal]	[MW]	[MW]	[Gcal]	[원/kWh]	[MWh]	[원/Gcal]	[MWh]	[MWh]	[MWh]	[Gcal]	[Gcal]	[Gcal]	[Gcal]
1	1	-5.0 ℃	15.60	857.00	780.85	330.00	92.66	855.00	52,809	857.00	242.37	847.02	43.23	0.00	27.63	0.00
	2	-5.0 ℃	14.75	857.00	780.85	330.00	90.11	771.00	52,809	857.00	242.37	802.56	235.75	0.00	221.00	0.00
	3	-5.0 ℃	13.73	857.00	780.85	330.00	90.00	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	13.73
	4	-5.0 ℃	12.55	857.00	780.85	330.00	86.17	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	12.55
	5	-5.0 ℃	12.15	857.00	780.85	330.00	86.17	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	12.15
	6	-5.0 ℃	12.49	857.00	780.85	330.00	86.17	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	12.49
	7	-5.0 ℃	12.90	857.00	780.85	330.00	86.22	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	12.90
	8	-2.0 ℃	13.62	857.00	780.85	330.00	86.00	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	13.62
	9	-2.0 ℃	15.97	857.00	780.85	330.00	85.81	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	15.97
	10	-2.0 ℃	16.75	857.00	780.85	330.00	49.67	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	16.75
	11	-2.0 ℃	16.19	857.00	780.85	330.00	59.23	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	16.19
	12	1.0 ℃	14.61	852.73	776.58	330.00	59.30	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	14.61
	13	1.0 ℃	12.06	852.73	776.58	330.00	49.67	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	12.06
	14	1.0 ℃	11.14	852.73	776.58	330.00	49.62	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	11.14
	15	1.0 ℃	10.78	852.73	776.58	330.00	49.67	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	10.78
	16	1.0 ℃	10.98	852.73	776.58	330.00	59.75	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	10.98
	17	1.0 ℃	12.60	852.73	776.58	330.00	86.00	0.00	52,809	852.73	242.37	0.00	0.00	0.00	0.00	12.60
	18	-2.0 ℃	14.67	857.00	780.85	330.00	85.88	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	14.67
	19	-2.0 ℃	16.49	857.00	780.85	330.00	86.77	846.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	16.49
	20	-2.0 ℃	17.96	857.00	780.85	330.00	86.77	846.00	52,809	857.00	242.37	852.85	17.96	0.00	0.00	0.00
	21	-5.0 ℃	18.92	857.00	780.85	330.00	86.58	806.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	18.92
	22	-5.0 ℃	18.24	857.00	780.85	330.00	88.92	771.00	52,809	857.00	242.37	839.76	74.67	0.00	56.43	0.00
	23	-5.0 ℃	17.56	857.00	780.85	330.00	89.20	846.00	52,809	857.00	242.37	852.95	17.56	0.00	0.00	0.00
	24	-5.0 ℃	16.40	857.00	780.85	330.00	89.20	846.00	52,809	857.00	242.37	853.21	16.40	0.00	0.00	0.00
2	1	-5.0 ℃	13.83	857.00	780.85	330.00	87.32	744.00	52,809	857.00	242.37	802.78	234.83	0.00	221.00	0.00
	2	-5.0 ℃	12.50	857.00	780.85	330.00	87.32	686.00	52,809	857.00	242.37	854.11	12.50	0.00	0.00	0.00
	3	-5.0 ℃	11.02	857.00	780.85	330.00	87.32	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	11.02
	4	-5.0 ℃	10.91	857.00	780.85	330.00	85.53	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	10.91
	5	-5.0 ℃	10.66	857.00	780.85	330.00	87.32	0.00	52,809	857.00	242.37	0.00	0.00	0.00	0.00	10.66
	6	-5.0 ℃	11.77	857.00	780.85	330.00	87.32	849.00	52,809	857.00	242.37	854.28	11.77	0.00	0.00	0.00
	7	-5.0 ℃	14.32	857.00	780.85	330.00	87.32	686.00	52,809	857.00	242.37	853.69	14.32	0.00	0.00	0.00
	8	-2.0 ℃	16.55	857.00	780.85	330.00	89.84	849.00	52,809	857.00	242.37	857.00	0.00	0.00	0.00	16.55
	9	-2.0 ℃	15.89	857.00	780.85	330.00	92.90	844.00	52,809	857.00	242.37	857.00	0.00	0.00	0.00	15.89
	10	-2.0 ℃	15.15	857.00	780.85	330.00	92.90	844.00	52,809	857.00	242.37	857.00	0.00	0.00	0.00	15.15
	11	-2.0 ℃	14.05	857.00	780.85	330.00	92.90	844.00	52,809	857.00	242.37	857.00	0.00	0.00	0.00	14.05

- MILP & Excel Based System with Simple and Robust Solution Capability

KUPOSYS Konkuk University Power System

Development of Optimization System for Practical Applications (3)

Real Optimization Results (Winter)



Development of Optimization System for Practical Applications (4)

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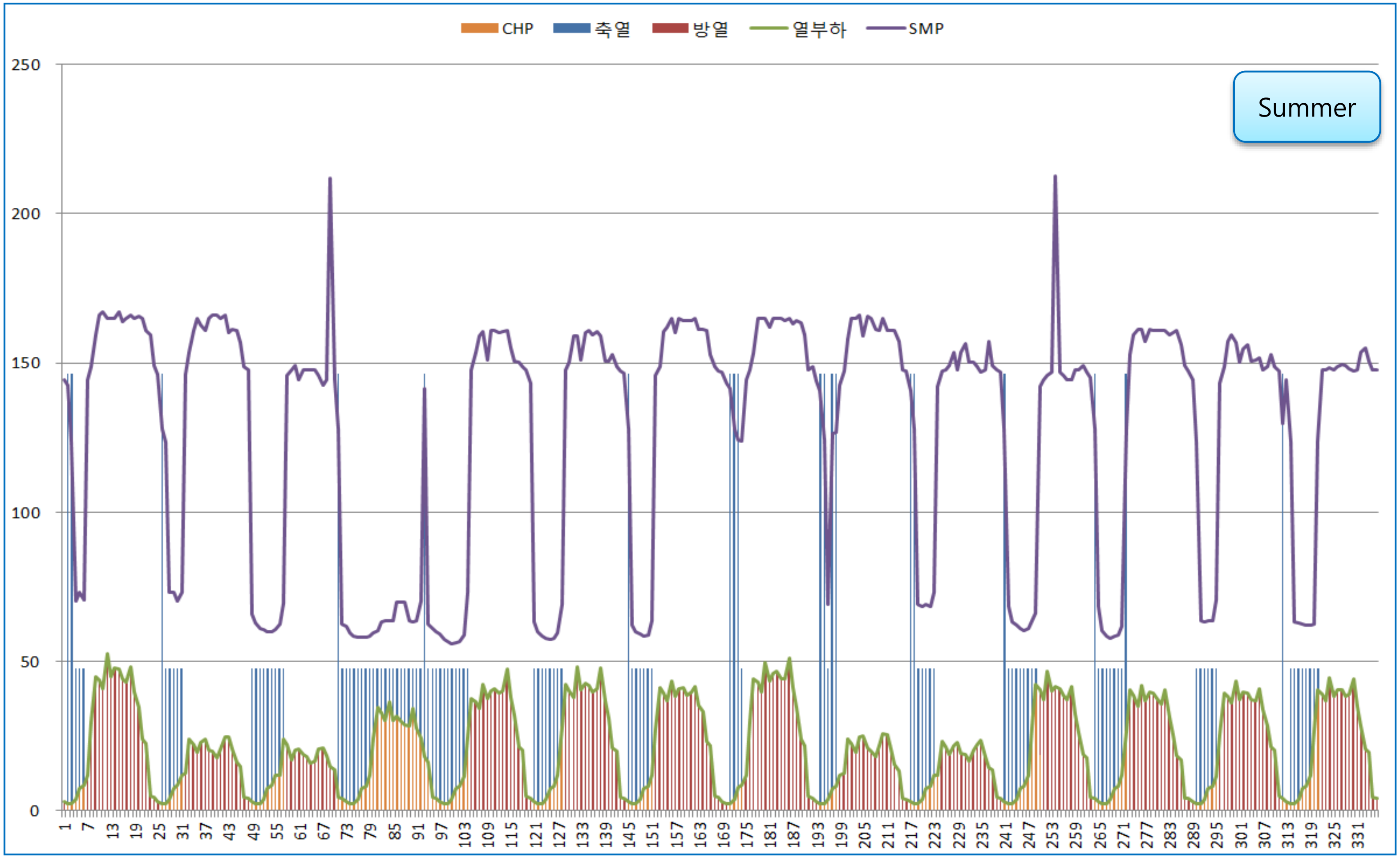
Real Optimization Results (Summer)



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

Thank You