Optimization of CHP and Thermal Storage under Heat Demand

(KIER Workshop)

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Introduction

- **Optimal operating mode determination to maximize the profit of a district heating company considering physical characteristics of CHP and actual operational aspects**
- **Each operational mode of CCGT-based CHP is defined and modeled mathematically**
- **Optimal operating points of CHP are determined under Korea electricity market rules and other environments such as thermal load, fuel prices, heat price, etc.**
- **Thermal storage is included to determine the thermal/electrical output that maximize the profit during a period**

Flow Chart of CHP Optimization

- Day-ahead Hourly Heat Demand Forecasting
- Electrical Load

- Day-ahead Power Market Forecasting & Analysis
- SMP, PSE(Unconstrained Output), MGO(Constrained Output)

- **CCGT-based CHP & Thermal Storage Optimization**

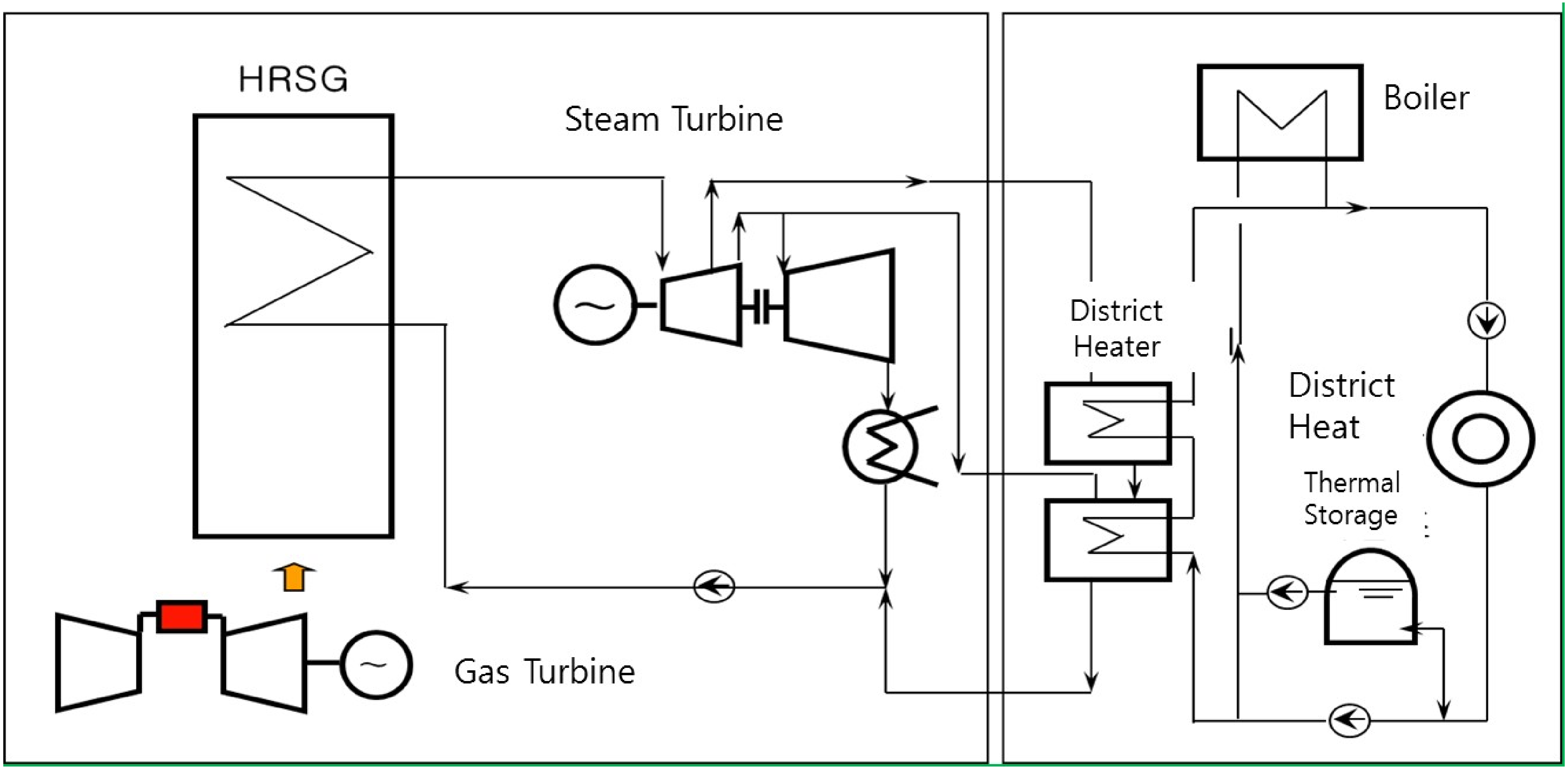
Results

- Operation mode
- Electrical output
- Thermal output
- Profit (contribution margin)

CCGT-based Cogeneration System (1)

CHP

District Heat



CCGT-based Cogeneration System (2)

Gas turbine(s) + HRSG + High/Low pressure Steam turbine(s)

- CHP: Various operations using several small-capacity gas turbines
- High efficiency can be maintained by separating steam turbines

Install 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 low pressure turbine and condenser during high thermal load season
- Optimize heat/power efficiency by operating low pressure turbine and condenser during low thermal load season

Operation Modes of Cogeneration System (1)

<u>MODE I</u> : Heat-match mode (winter)

- Operating facilities: gas turbine, HRSG, high pressure steam turbine, district heater
- Not Operating facilities: Low pressure steam turbine, condenser

MODE II : Gas turbine operation mode (abnormal 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-match mode (summer)

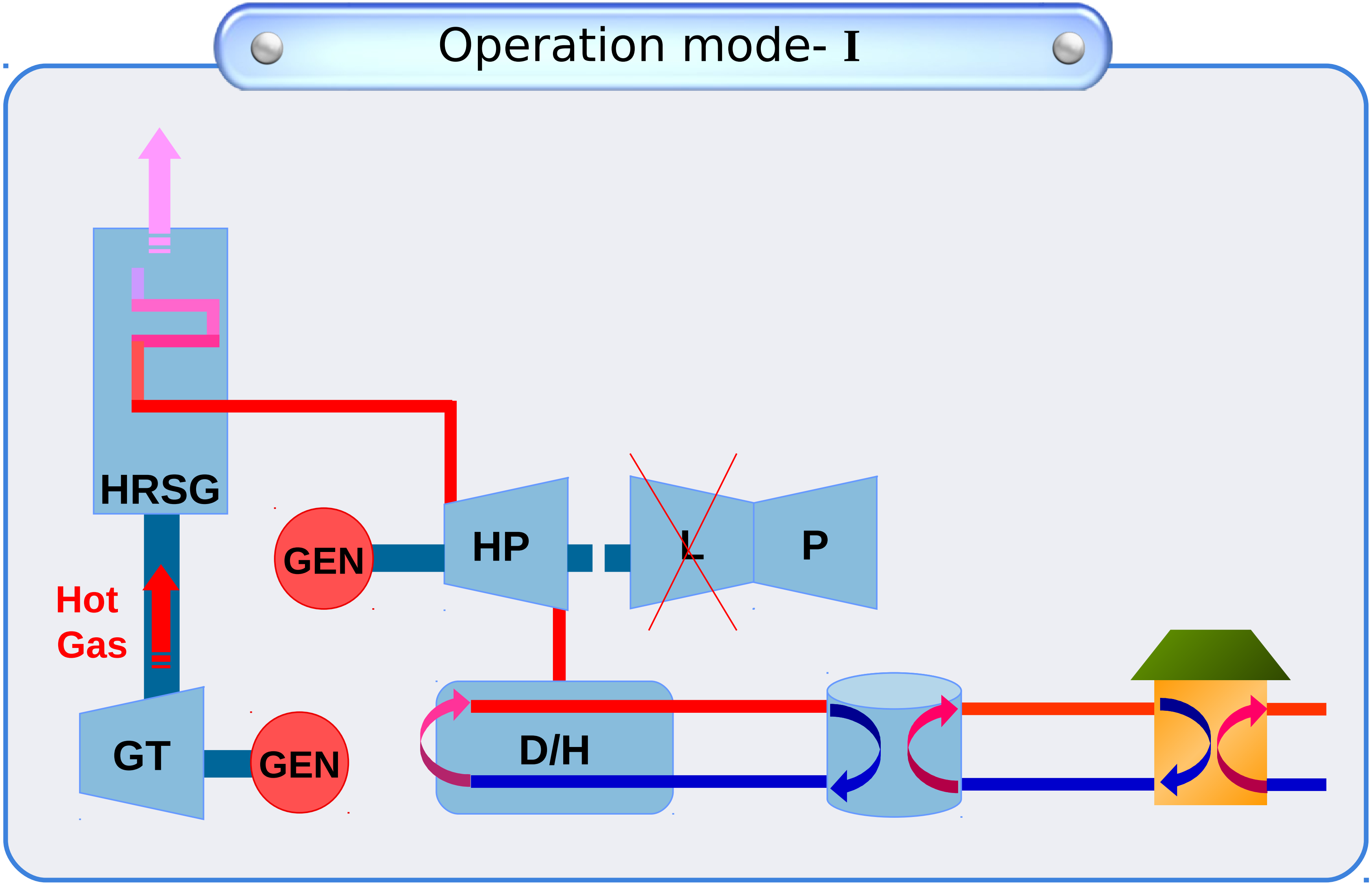
- Operating facilities: gas turbine, HRSG, high/low pressure steam turbine, condenser
- Not Operating facilities: district heater
- CCGT operation only for electricity

Operation Modes of Cogeneration System (2)

- **MODE IV : Excessive Thermal Load Mode (Heat Emergency)**
  - 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)

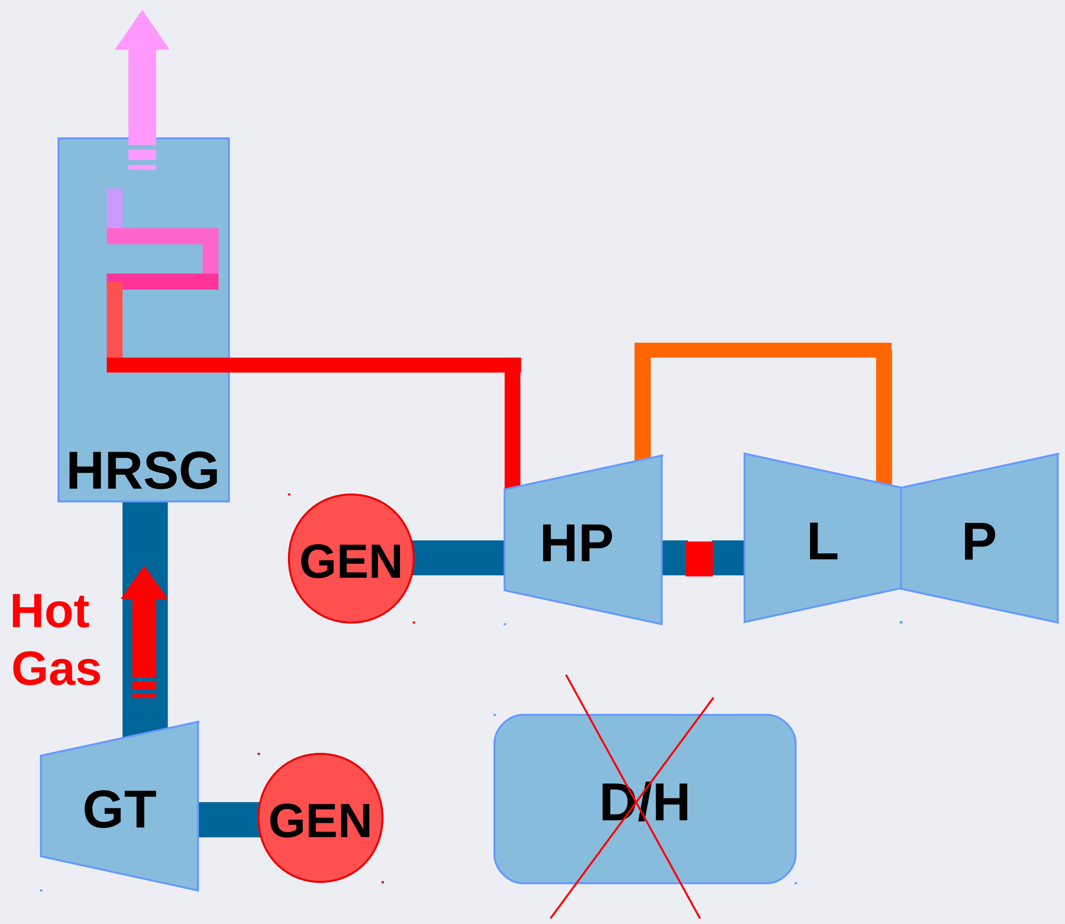
- **MODE V : Mixed-match mode (spring/fall, low thermal load)**
  - Operating facilities: gas turbine, HRSG, high/low pressure steam turbine, district heater

Configuration of operation mode (1)

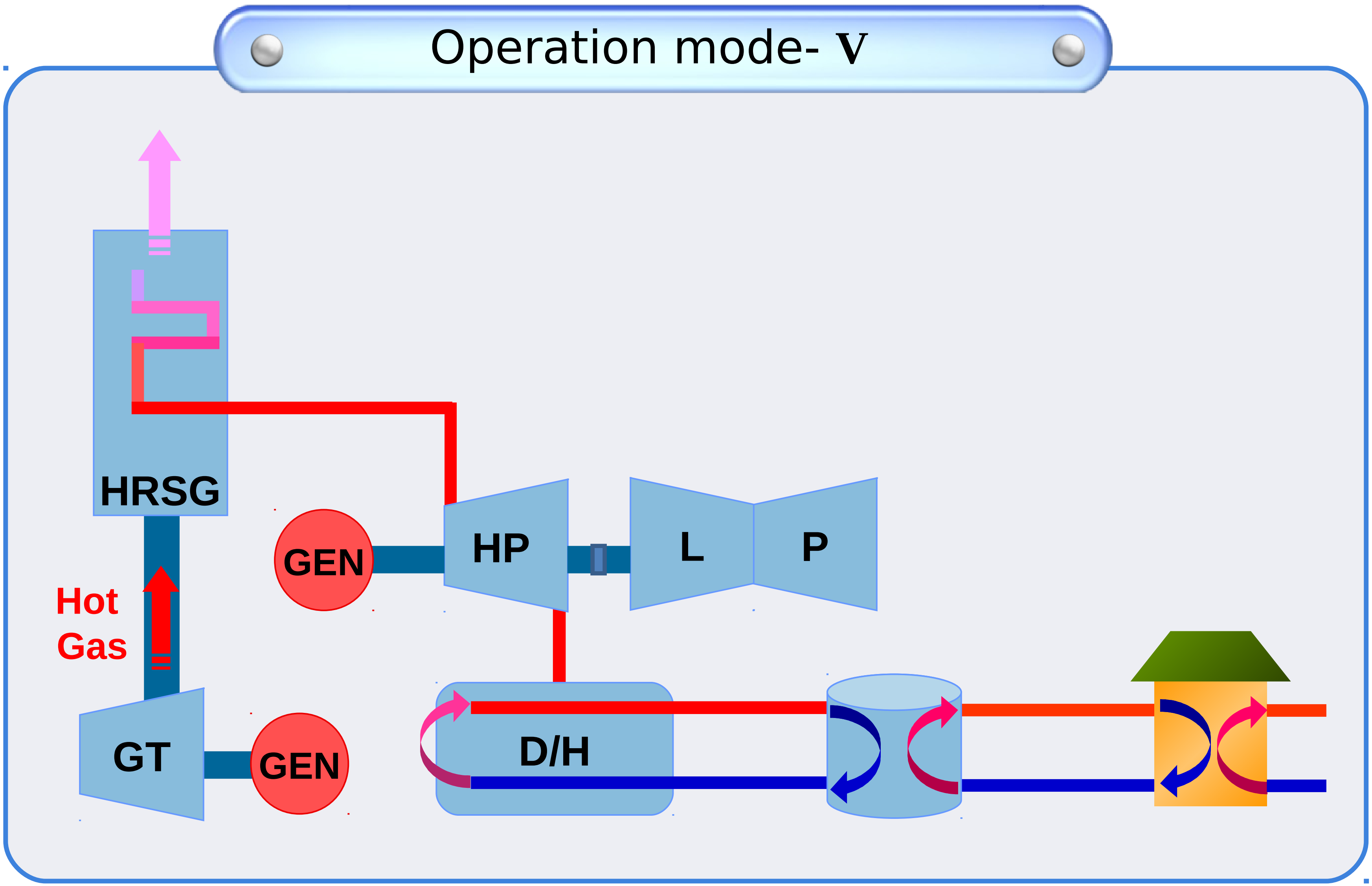


Configuration of operation mode (2)

Operation mode-III



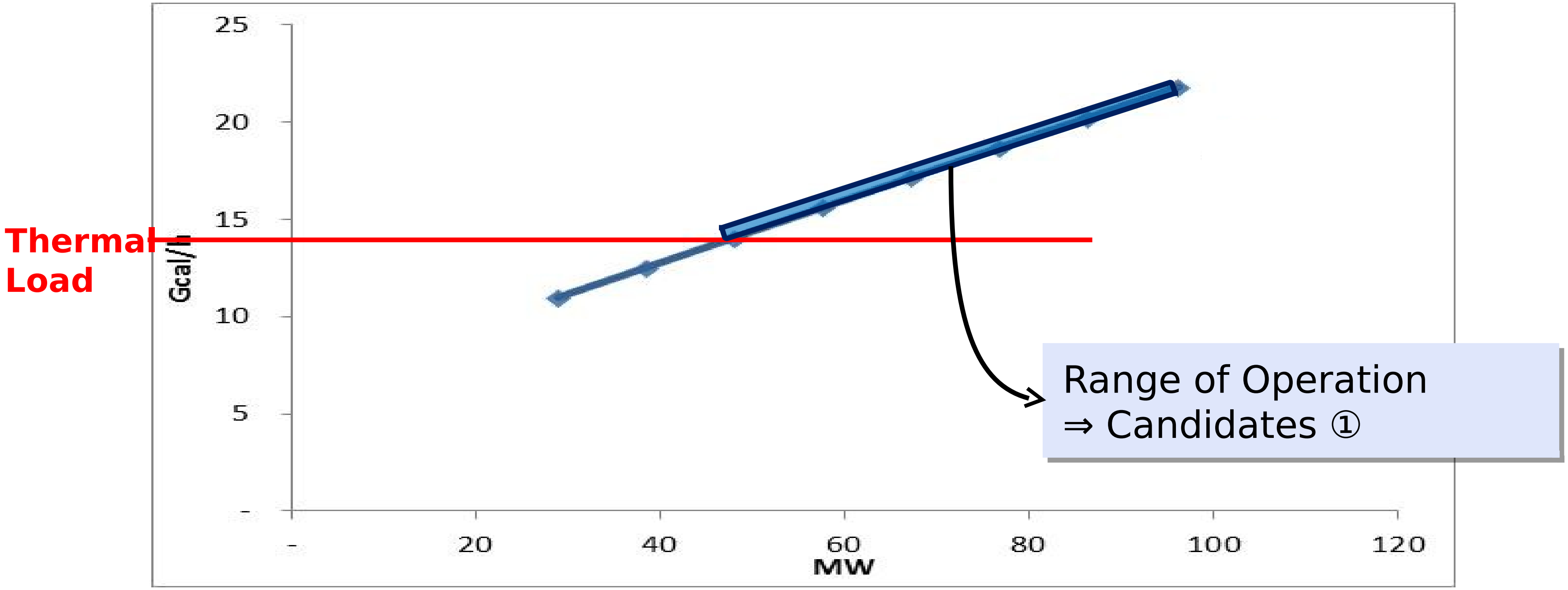
Configuration of operation mode (5)



Analysis Methodology (1)

Explore the optimum point equal to the thermal/electrical load
(comparing the contribution margin from each operation mode within range of operation)

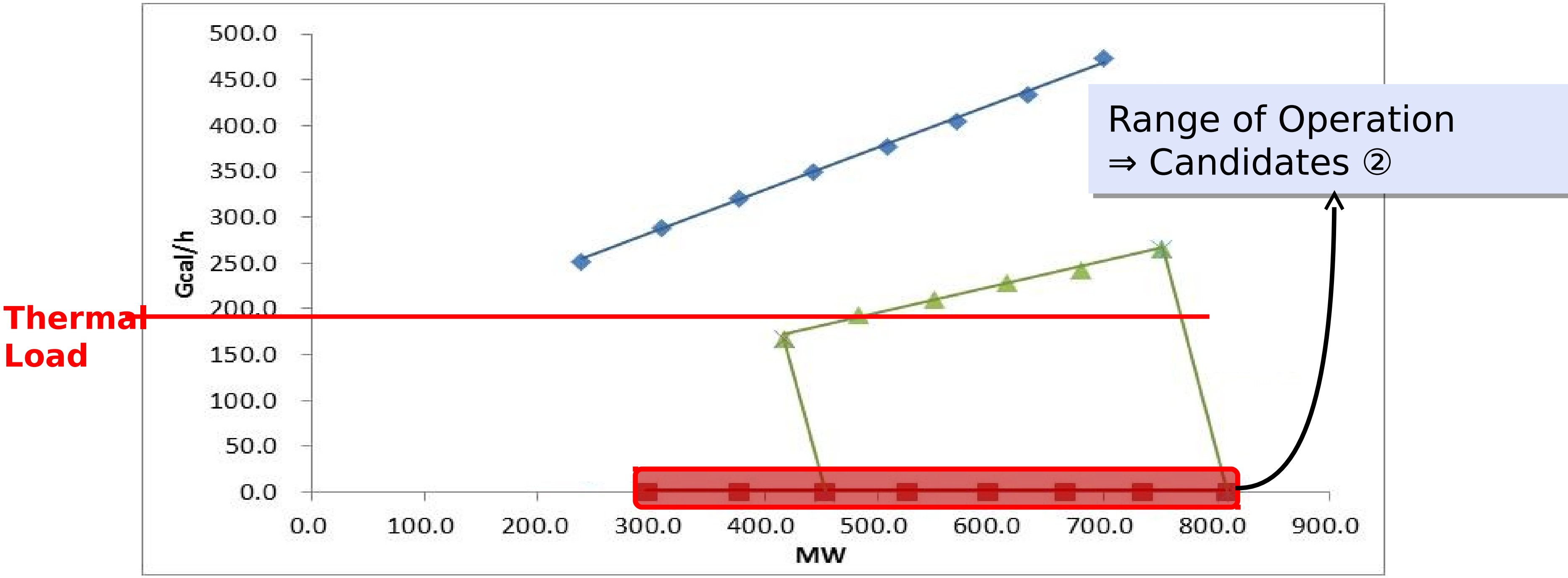
<MODE Ⅰ>



- Operational range of mode Ⅰ is given above the thermal load (blue line)
- After meeting the thermal load, operating point is determined based on the electricity market revenue such as SMP, PSE, MGO(or DAOS)
- Excess heat is rejected to the environment through coolers or the exhaust gases (without thermal storage)

Analysis Methodology (2)

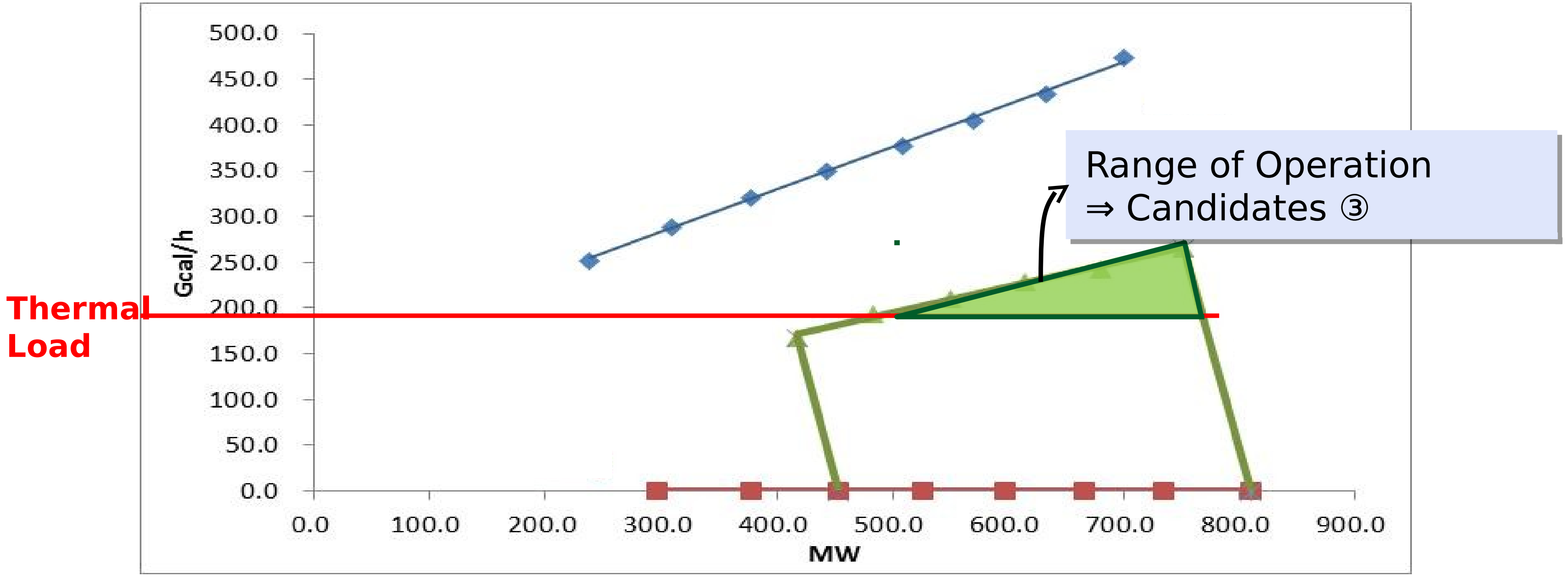
<MODE III>



☒◌ Electrical output that can maximize the contribution margin is determined, and the thermal requirement could be met by the PLB, thermal storage except CHP

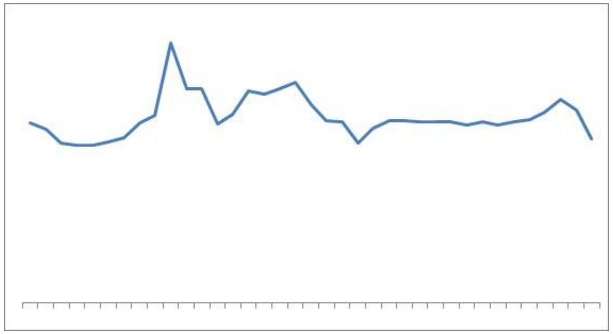
Analysis Methodology (3)

<MODE V >



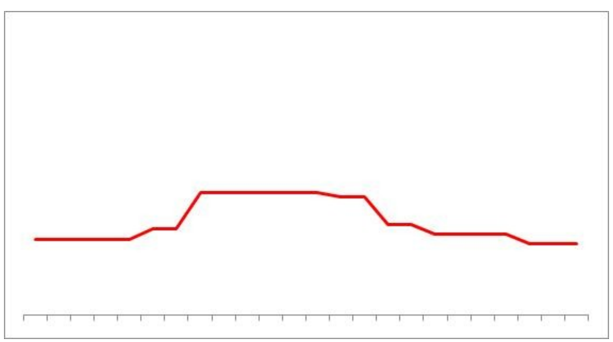
After comparing the contribution margin at each mode (①, ②, ③), determine operation mode, electrical/thermal output

System Composition



<Electrical Demand>

Electricity Market Forecasting



<Heat Demand>

$\rightarrow$ $MODE_t, P_t, H_t$

<CHP>

$\rightarrow$ TS_t^C, TS_t^D

<Thermal Storage>

Mathematical Formulation (1)

[Objective Function]

$$\text{maximize} \sum_{t=1}^{T}\sum_{j=1}^{3}\sum_{i=1}^{N} \begin{pmatrix} SEP_{i,j,t} + GSCON_{i,j,t} + SCON_{i,j,t} + COFF_{i,j,t} \\ +HL_t \times HP_t \\ -\left(a_{i,j}P_{i,j,t}^2 + b_{i,j}P_{i,j,t} + c_{i,j}\right) \times FP^{CHP} \end{pmatrix}$$

$$SEP_{i,j,t} : SMP_t \times P_{SEP,i,j,t}$$

$$GSCON_{i,j,t} : \min\left(a_{i,j}P_{GSCON,i,j,t}^2 + b_{i,j}P_{GSCON,i,j,t}, SMP_t \times P_{GSCON,i,j,t}\right)$$

$$SCON_{i,j,t} : \max\left(a_{i,j}P_{SCON,i,j,t}^2 + b_{i,j}P_{SCON,i,j,t} + c_{i,j}, SMP_t \times P_{SCON,i,j,t}\right)$$

$$COFF_{i,j,t} : SMP_t \times P_{COFF,i,j,t} - \left(a_{i,j}P_{COFF,i,j,t}^2 + b_{i,j}P_{COFF,i,j,t} + c_{i,j}\right)$$

SEP : Scheduled Energy Payment
GSCON : Payment by Market Price for Minimum Energy produced due to Generator-self Constraint
SCON : payment for energy produced due to System Constraints
COFF : Constrained-Off energy payment

Mathematical Formulation (2)

[Heat Balance Constraint]

$$HL_t \leq H_{i,j,t} - TS_t^C + TS_t^D$$

[Operation Limits Constrai

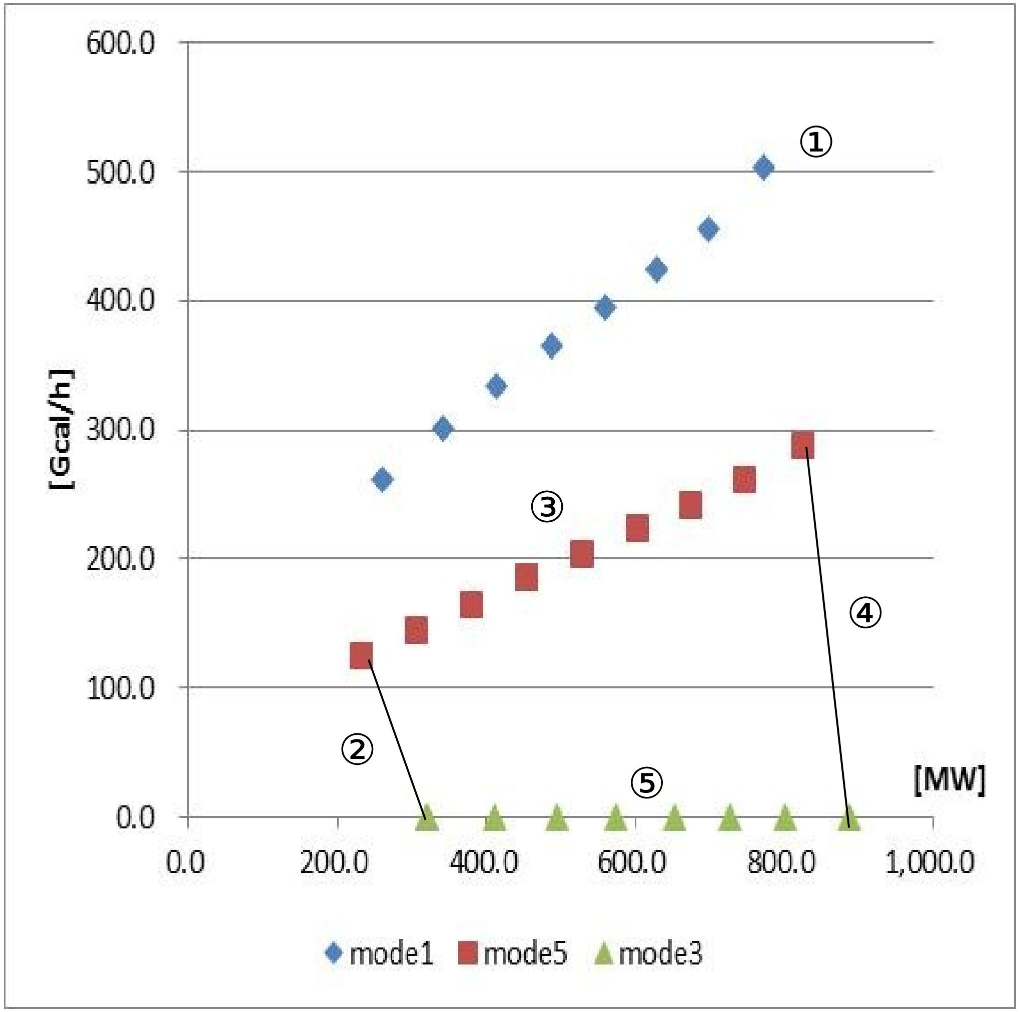
① $H_{i,1,t} = \alpha_1 P_{i,1,t} + \beta_1$

② $H_{i,5,t} \geq \alpha_{2,1} P_{i,5,t} + \beta_{2,1}$

③ $H_{i,5,t} \leq \alpha_{2,2} P_{i,5,t} + \beta_{2,2}$

④ $H_{i,5,t} \leq \alpha_{2,3} P_{i,5,t} + \beta_{2,3}$

⑤ $H_{i,5,t} \geq 0$



Mathematical Formulation (3)

[Thermal Storage Constraints]

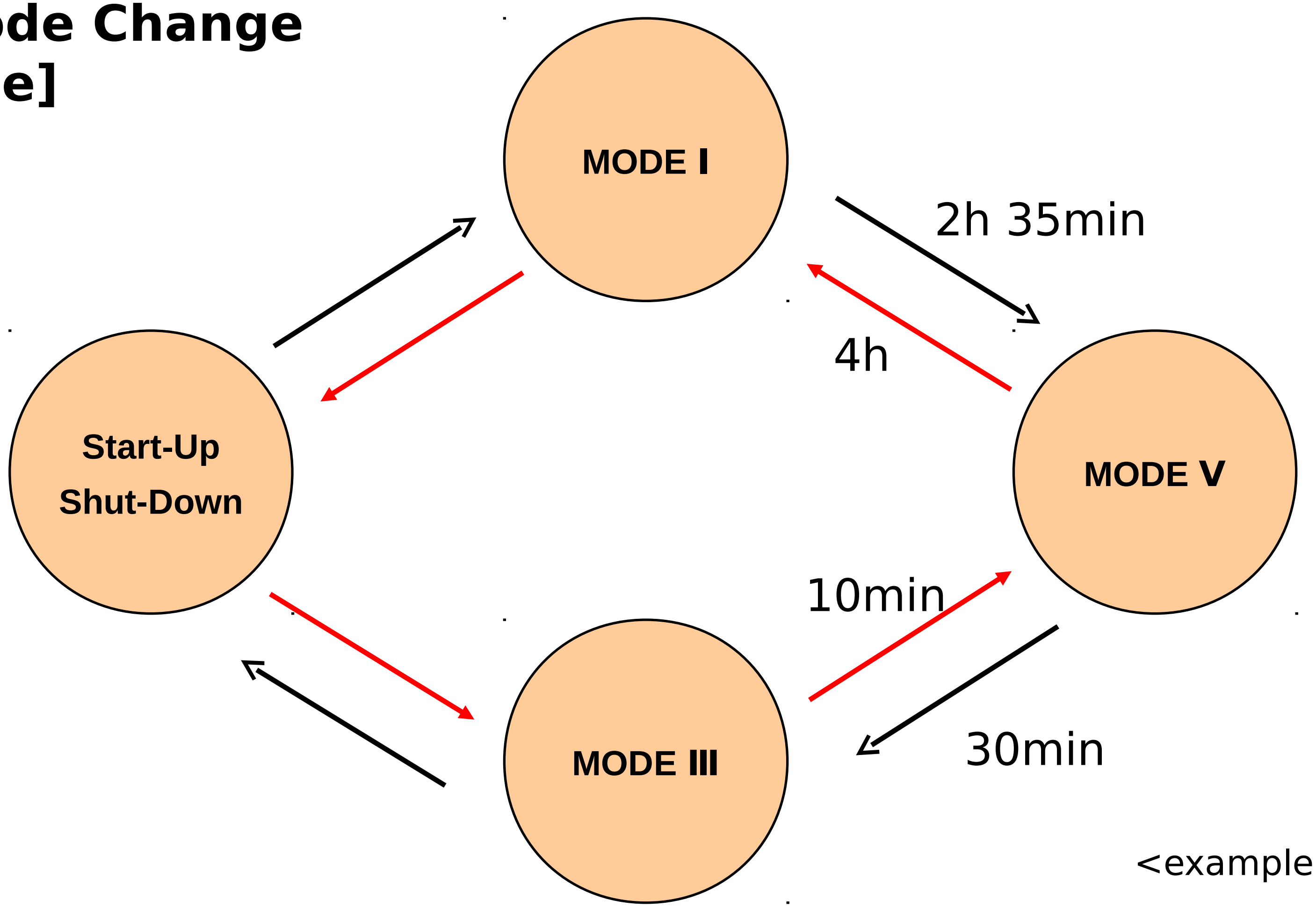
$$TS^{min} \leq TS_t^C \leq TS^{max}$$

$$TS^{min} \leq TS_t^D \leq TS^{max}$$

$$SOC^{min} \leq SOC_0 + \sum_{k=1}^{t} (TS_t^C - TS_t^D) \leq SOC^{max}$$

Mathematical Formulation (4)

[Mode Change Time]



<example>

Numerical Case Studies

Input Data (1)

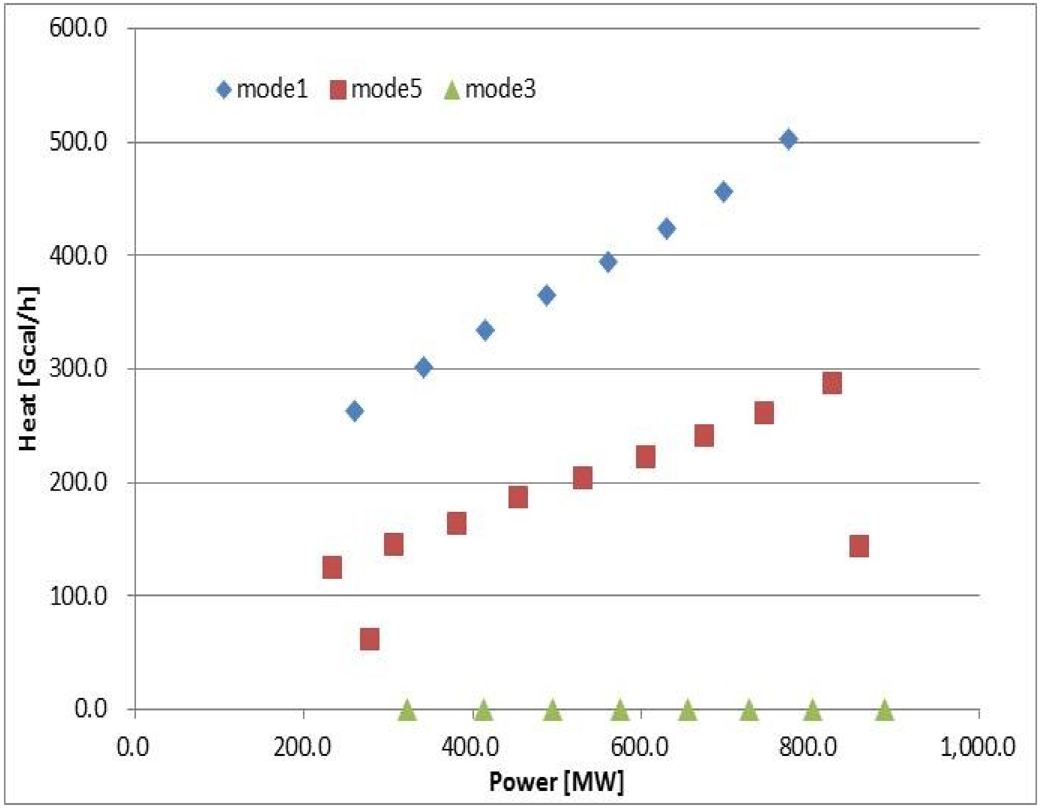
No.	SMP [KRW/kWh]	PSE [MW]	MGO [MW]	Heat Load [Gcal/h]	No.	SMP [KRW/kWh]	PSE [MW]	MGO [MW]	Heat Load [Gcal/h]
1	124.0	887.4	887.4	264.6	13	70.2	0.0	608.6	372.1
2	119.3	572.1	662.4	264.6	14	121.0	0.0	637.4	413.5
3	119.1	0.0	662.4	264.6	15	121.0	0.0	662.4	415.2
4	120.4	0.0	887.4	264.6	16	119.2	0.0	698.8	320.4
5	129.8	0.0	887.4	264.6	17	117.6	0.0	887.4	300.8
6	130.7	887.4	887.4	304.7	18	129.8	887.4	887.4	280.3
7	130.4	887.4	887.4	350.0	19	130.7	887.4	887.4	273.8
8	130.4	887.4	887.4	478.6	20	130.7	887.4	887.4	283.5
9	74.2	0.0	635.0	478.6	21	129.8	887.4	887.4	304.7
10	129.8	887.4	624.0	430.2	22	130.7	887.4	887.4	253.1
11	129.8	887.4	732.2	430.2	23	130.7	887.4	887.4	253.1
12	129.8	887.4	715.9	372.5	24	130.7	600.0	887.4	253.1

Fuel Price [KRW/Gcal]	Heat Price [KRW/Gcal]
80,000	90,000

Numerical Case Studies

Input Data (2)

[Heat – Power]



[Power - Fuel]

	a (QHC) [Gcal/MW2h]	b (LHC) [Gcal/MWh]	c (NLHC) [Gcal/h]
MODEI	0.0002	1.329	291.01
MODEIII	0.0002	1.1763	252.75
MODEV	0.0003	1.0938	319.19

[Thermal Storage]

Hourly Dischange [Gcal/h]	Discharge Hours [h]	Total Capacity [Gcal]
190	8	1,520

Numerical Case Studies

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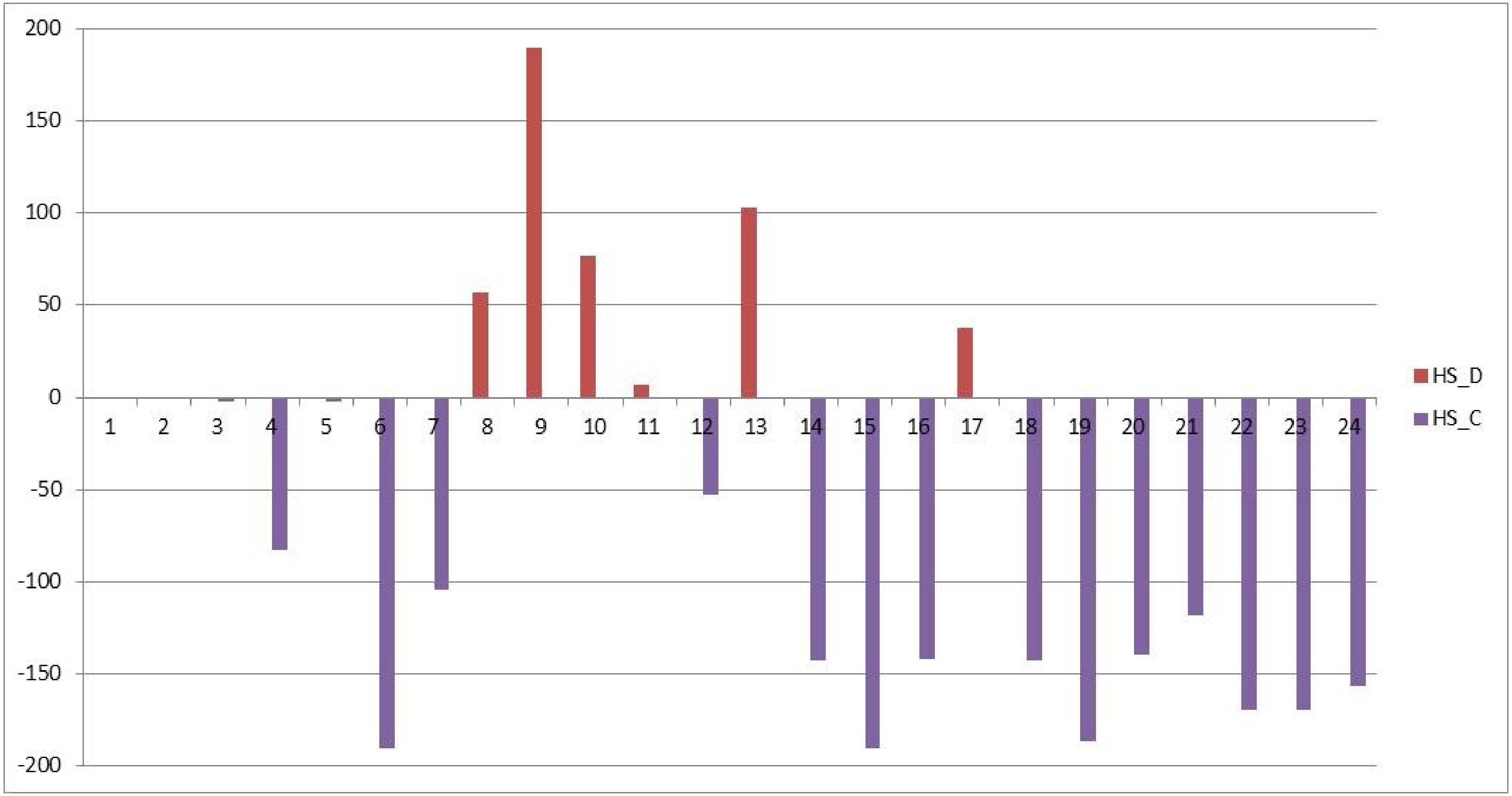
Result – Thermal Output - CHP (1)

Numerical Case Studies

Result – Thermal Output – Thermal Storage (2)



Numerical Case Studies

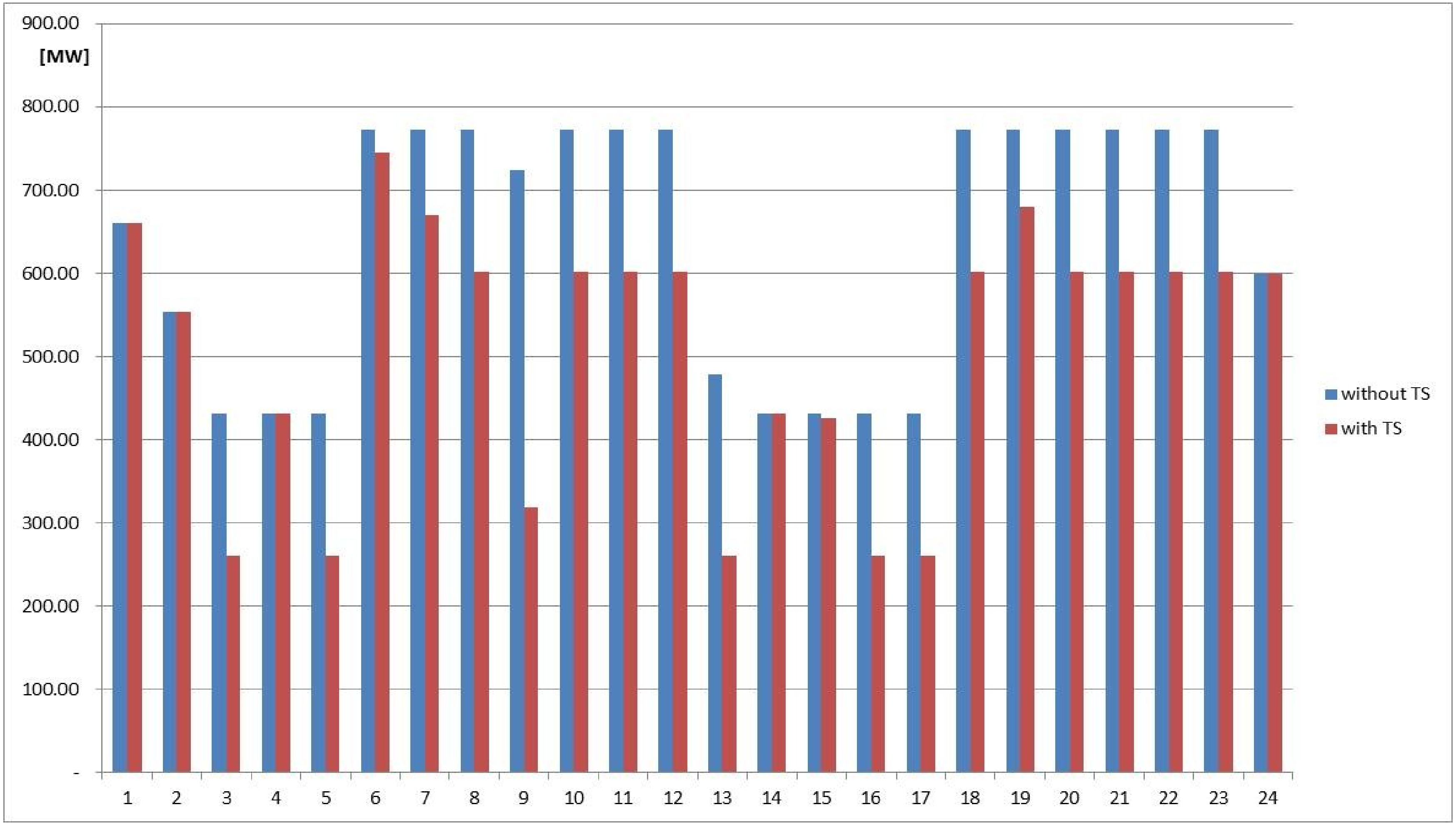
Result – Thermal Output (3)

NO.	Heat Load [Gcal/h]	with TS			without TS
		CHP	TS_C	TS_D	CHP
1	450.0	450.00	-	-	450.00
2	400.0	400.00	-	-	400.00
3	260.0	262.15	2.15	-	342.50
4	260.0	342.50	82.50	-	342.50
5	260.0	262.15	2.15	-	342.50
6	300.0	490.00	190.00	-	503.18
7	350.0	454.68	104.68	-	503.18
8	480.0	422.84	-	57.16	503.18
9	480.0	290.00	-	190.00	480.00
10	500.0	422.84	-	77.16	503.18
11	430.0	422.84	-	7.16	503.18
12	370.0	422.84	52.84	-	503.18

NO.	Heat Load [Gcal/h]	with TS			without TS
		CHP	TS_C	TS_D	CHP
13	365.0	262.15	-	102.85	365.00
14	200.0	342.50	142.50	-	342.50
15	150.0	340.00	190.00	-	342.50
16	120.0	262.15	142.15	-	342.50
17	300.0	262.15	-	37.85	342.50
18	280.0	422.84	142.84	-	503.18
19	273.0	459.31	186.31	-	503.18
20	283.0	422.84	139.84	-	503.18
21	305.0	422.84	117.84	-	503.18
22	253.0	422.84	169.84	-	503.18
23	253.0	422.84	169.84	-	503.18
24	265.0	421.69	156.69	-	421.69
SUM	**7587.0**	**9107.0**	**1992.2**	**472.2**	**10552.3**

Numerical Case Studies

Result – Electrical Output(1)



Numerical Case Studies

Result – Electrical Output (2)

NO.	without TS	with TS
1	660.28	660.28
2	553.83	553.83
3	431.41	260.37
4	431.41	431.41
5	431.41	260.37
6	773.50	745.44
7	773.50	670.25
8	773.50	602.46
9	724.15	319.65
10	773.50	602.46
11	773.50	602.46
12	773.50	602.46
13	479.32	260.37
14	431.41	431.41
15	431.41	426.10
16	431.41	260.37

NO.	without TS	with TS
17	431.41	260.37
18	773.50	602.46
19	773.50	680.11
20	773.50	602.46
21	773.50	602.46
22	773.50	602.46
23	773.50	602.46
24	600.00	600.00
SUM	**15,319.45**	**12,242.45**

[1000KRW]	Profit
with TS	222,019
without TS	194,820
	27,199 (+14%)

Conclusions & Further Studies

Present optimization system

- 1 CHP(3/5 modes), 1 thermal storage, heat demand, electricity market forecasting
- Implementation: MATLAB, CPLEX MILP

Future works

- Constraints of mode change time
- Termination condition of thermal storage
- Optimization considering multiple CHPs, Peak Load Boilers and other heat sources
- ESS(electrical Energy Storage System) so that electrical output is also optimized in electricity market

Thank You