25th CEE Symposium with NEDO

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Generation scheduling technologies supporting large Introduction of Renewable Energy

再生可能エネルギー大量導入時代を支える需給運用／計画技術

Oct. 19 2016

Hitachi, Ltd
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Contents

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1. Backgrounds and Objectives

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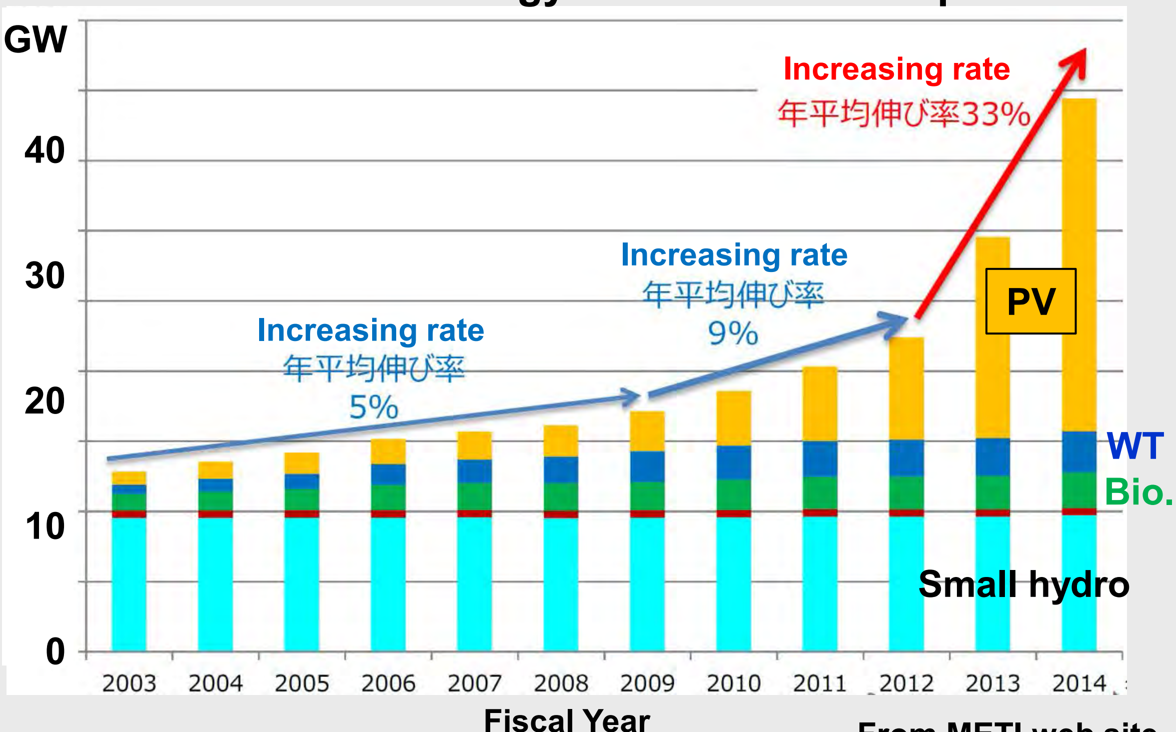
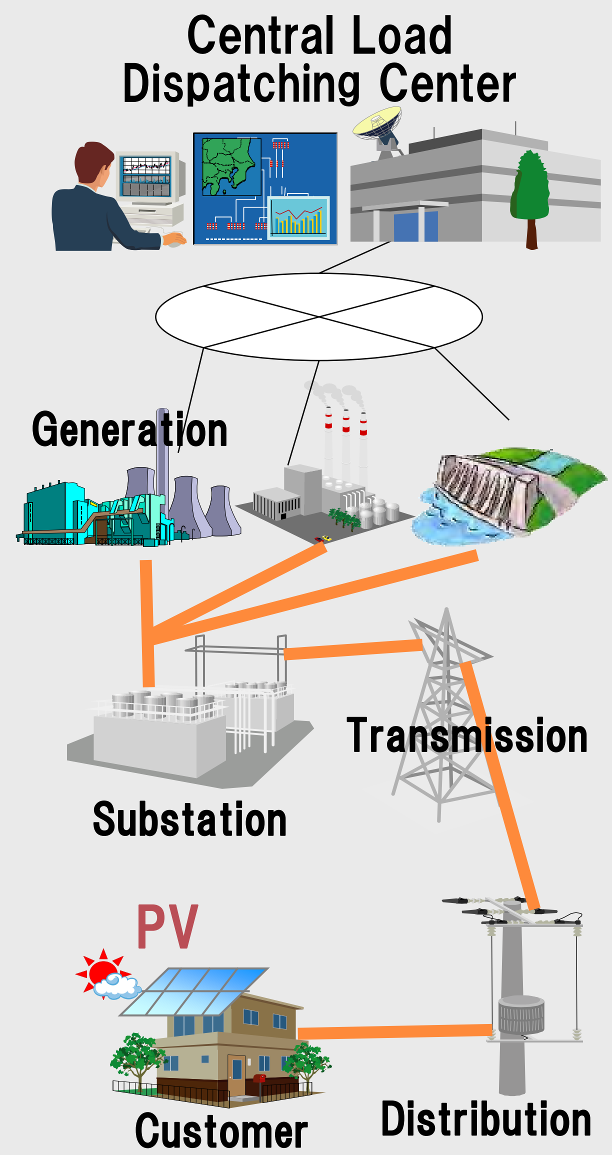
Back-grounds
- Large introduction of PV and WG
- Reduce Generation costs

Objectives
- Generation Scheduling considering
  - Low generation costs
  - Uncertainty renewable generations

Renewable Energy Introduction In Japan



From METI web site



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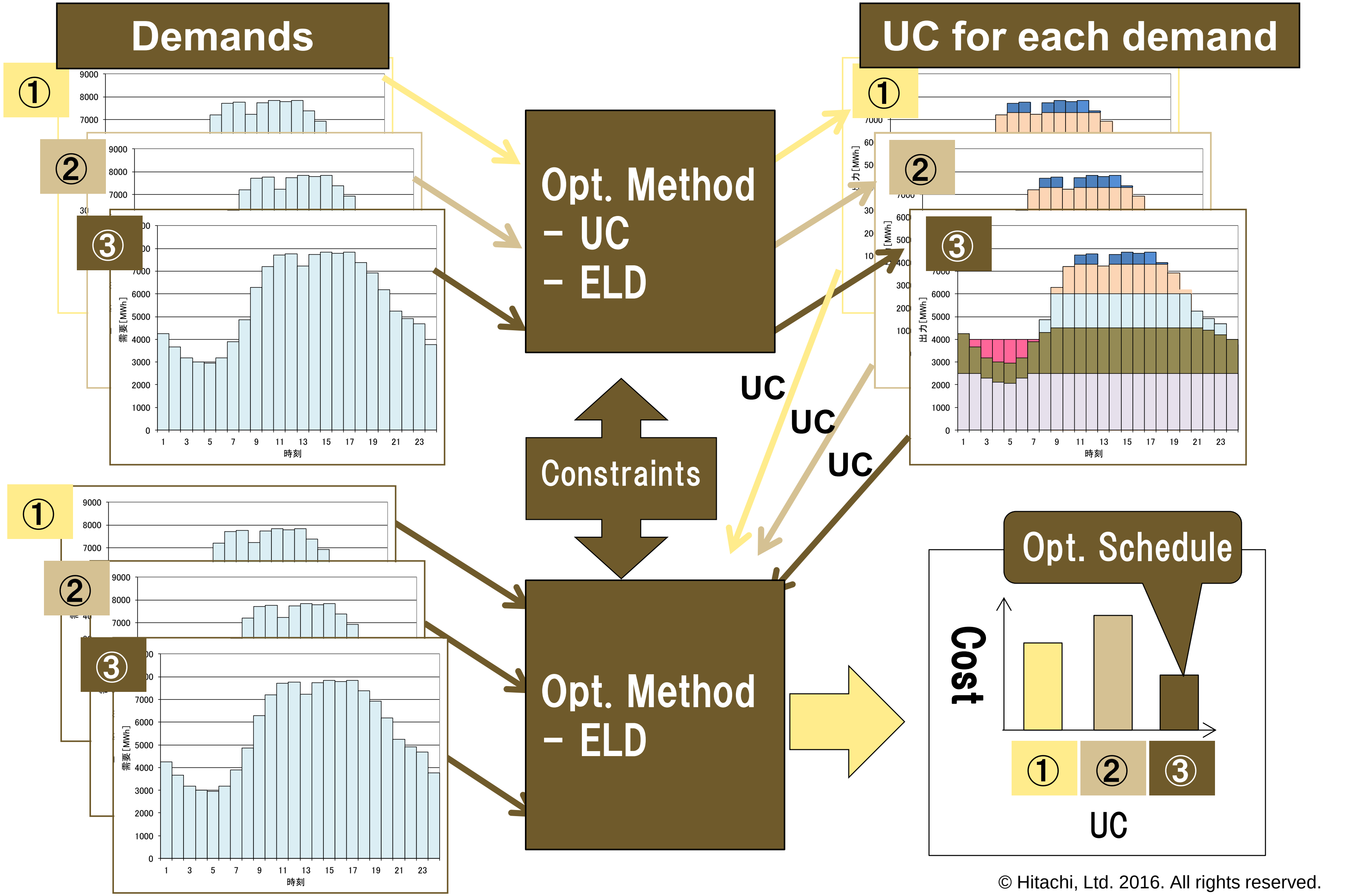
2-1. Normal Method : Combination of UC and Demand

Select Optimal Schedule: Estimate each UC for all demands



2-2. Conventional Method : Fixed UC for base Demand

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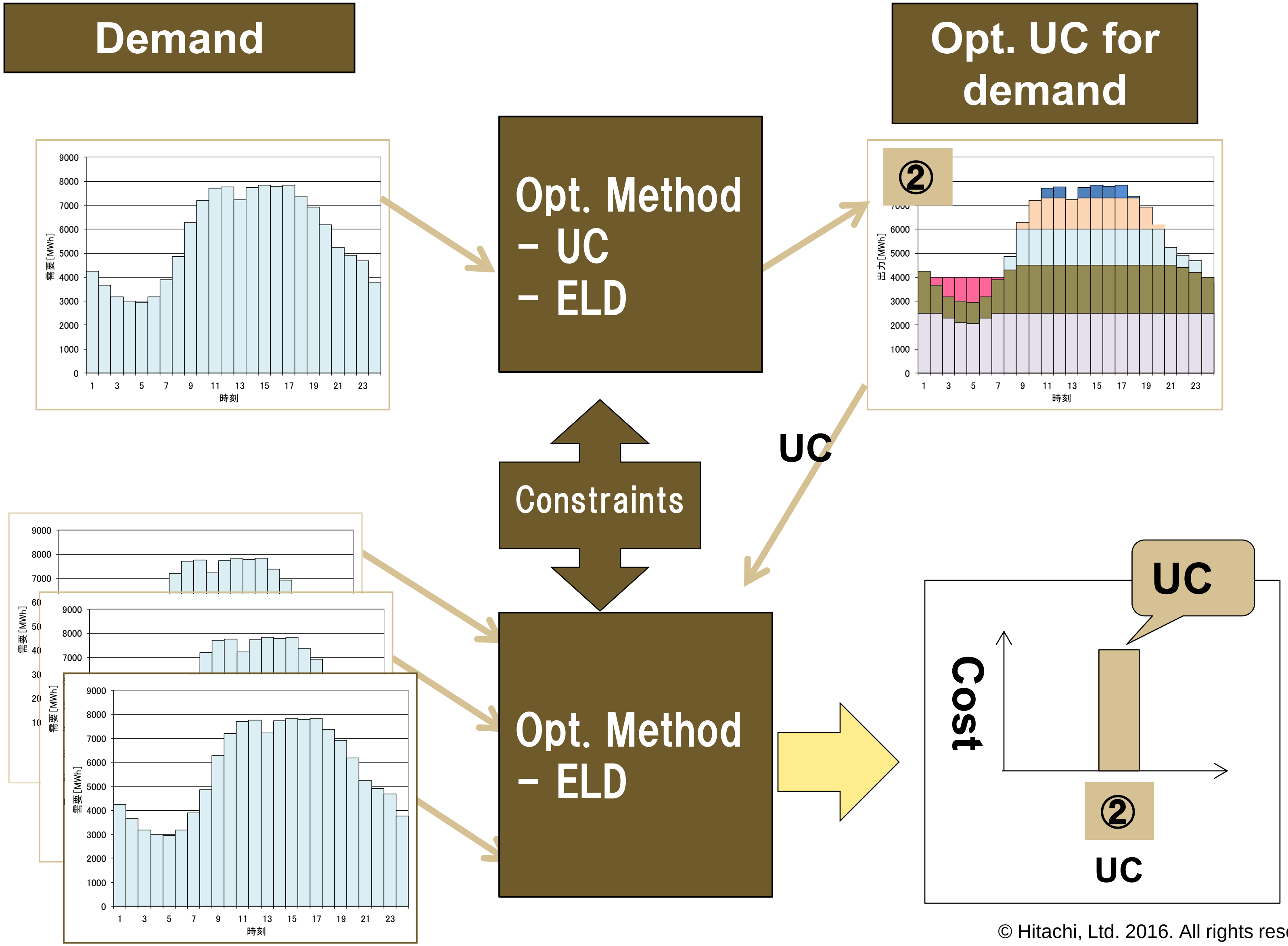
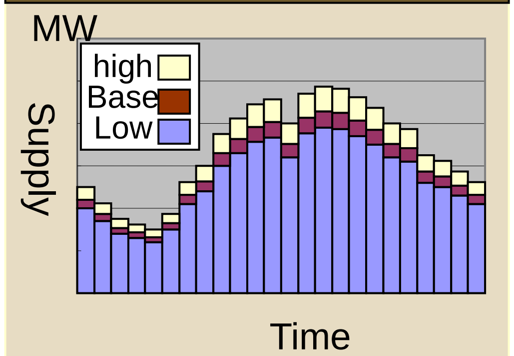
UC is optimal for base demand



2-3. Proposed Method : One Optimal UC for all demands

One optimal UC is calculated by Simultaneous Optimization method

Demand Curves

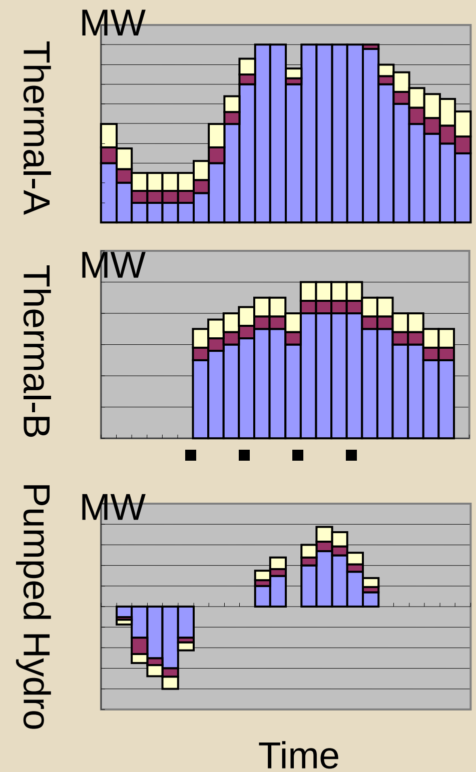


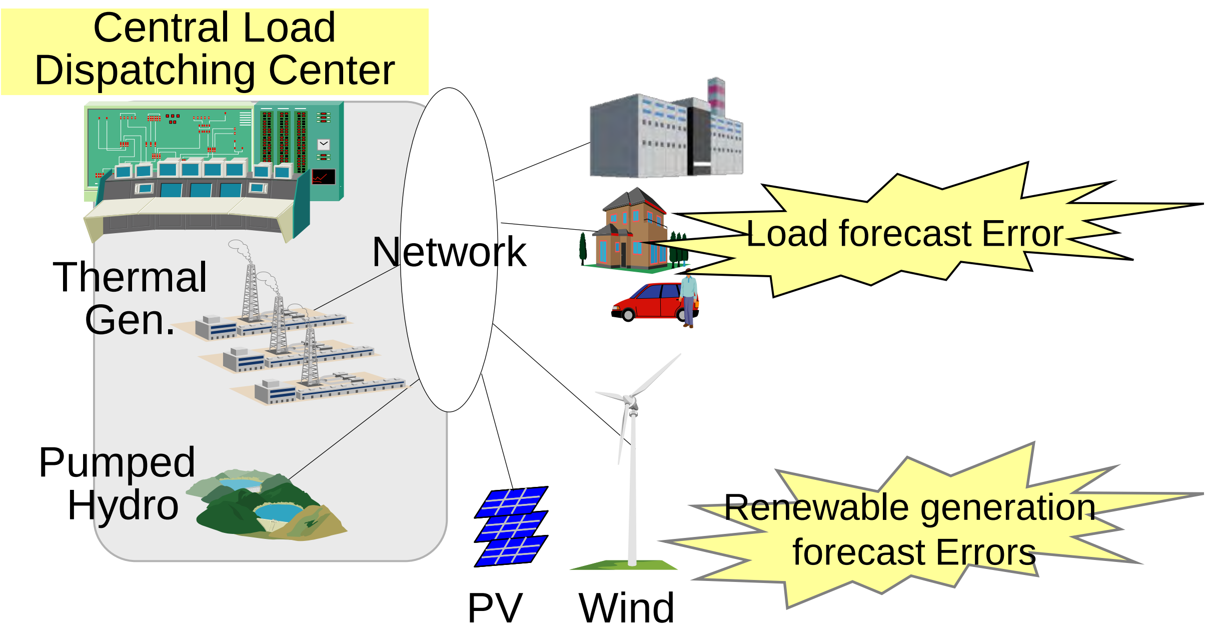
Simultaneous Optimization

- UC; Unit Commitment
- ELD; Economic load Disp.

Optimal Schedule

- One UC
- ELD for each load curve





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3-1. Simultaneous Optimization method for UC and ELD

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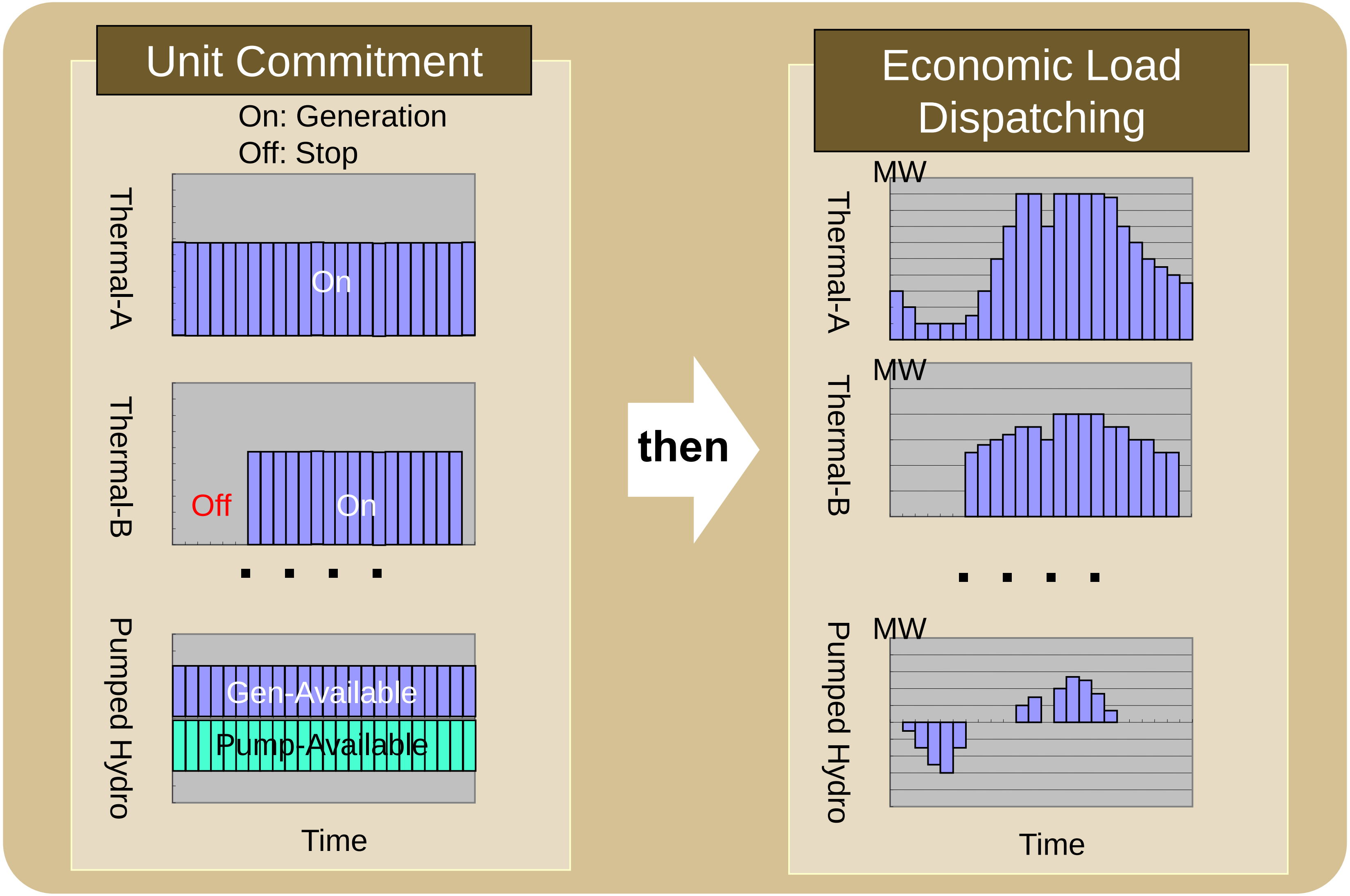
Simultaneous Optimization using Quadratic Programming



3-2. Formulation for Integrated Unit Commitment

Objective Function：Generation Costs → min

$$F(P,u)=\sum_{t=1}^{T}\sum_{i=1}^{N}C_i(P_{it},u_{it})+\sum_{i=1}^{N}SC_i(v_i) \quad \cdots(1)$$

Mixed integer programming problem
↓
Quadratic programming problem

Fuel Cost

$$C_i(P_{it})=a_iP_{it}^2+b_iP_{it}+c_iu_{it}$$

Start-up Cost

$$SC_i(v_i)=v_iS_i$$

Newly added Constraints

Thermal UC Variable u_{it}	$0 \leqq u_{it} \leqq 1$	relaxing binary to continuous
Increasing UC Variable	$u_{it} \leqq u_{it+1}$	when demand increasing
Decreasing UC Variable	$u_{it} \geqq u_{it+1}$	when demand decreasing

Main constraints

- Generation Capacity and minimum generation
- System demand and supply balance
- Minimum up and down times
- LNG Consumption
- Hydro unit power, load limit and reservoir water level
- Spinning Reserve
- Transmission Constraints

3-3. Quadratic Programming to Apply Problems

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Constraints

Thermal UC variables are relaxed from binary to continuous.

$u_{it}=0 \text{ or } 1 \quad \Rightarrow \quad 0 \leqq u_{it} \leqq 1$

(Mixed Integer Programming Problem) ⇒ (Quadratic Programming Problem)

Problem 1: Feasible Operational Unit Commitment

⇒ Thermal units start up or shut down more than once per day.

u_{it}	1	0	1	0	1	0	1	0	1	0

1 3 5 7 9 11 13 15 17 19 21 23

Time

Problem 2: Converging UC Variables to 0 or 1

⇒ Thermal UC variables are usually not 0 or 1.

u_{it}	0.9	0.1	0.6	0.3	1.0	0.2	1.0	0.3	0.6	0.2

1 3 5 7 9 11 13 15 17 19 21 23

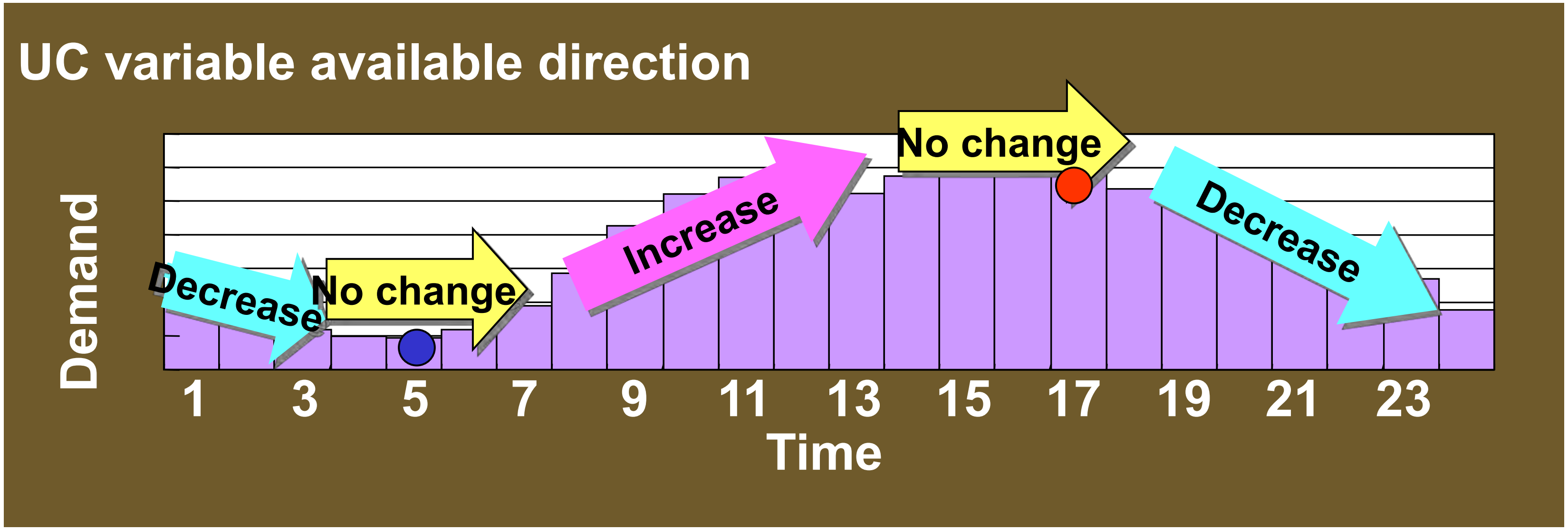
Time

3-4. Measure against Problem 1

1. Adding New Constraints

A) From minimum to maximum demand time, the value of u_{it} does not decrease, and from maximum to last demand time, that of u_{it} does not increase.

B) In low demand periods, the value of u_{it} is the same, and in the peak demand periods, that of u_{it} is the same.



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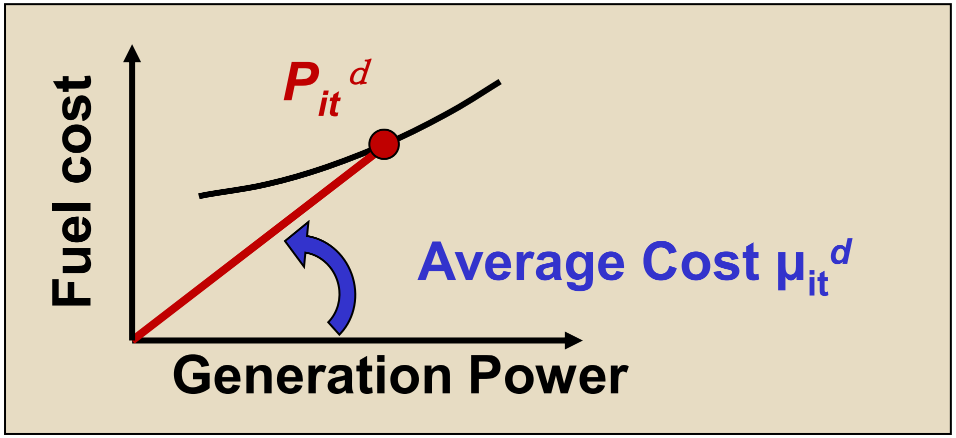
2. Adding New Penalty Costs to Objective Function

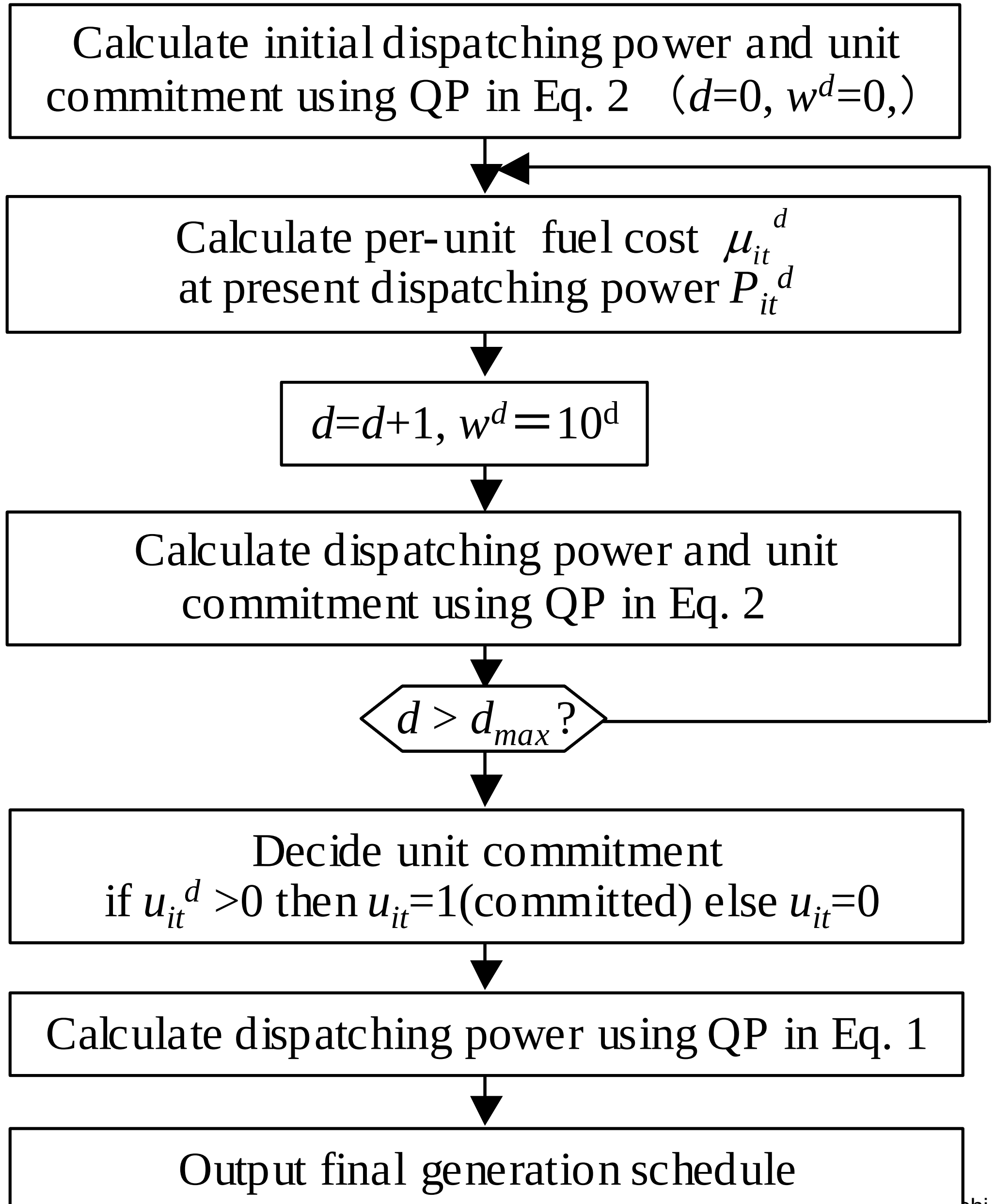
A) New Objective Function

$$RF(P^d, u^d) = F(P^d, u^d) + w^d \sum_{t=1}^{T} \sum_{i=1}^{N} \mu_{it}^{d-1} u_{it}^{d} \quad \cdots (2)$$

d **is iteration number;**
w^d **is penalty weighting factor;**
μ_{it}^{d} **is average cost of thermal unit *i* at time *t* with the *d*-th iteration.**



3-6. Flowchart for generation scheduling



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4-1. Mathematical Formation for generation scheduling

Objectives **Generation costs = Fuel costs ＋ Start-up costs ⇒ min**

$$F(P,u)=\sum_{j=1}^{L}\sum_{t=1}^{T}\sum_{i=1}^{M} w^j C_i(P_{it}^j, u_{it}) + \sum_{i=1}^{N} S_i(u_{iP}-u_{iN}) \quad \cdots\cdots\cdots\cdots\cdots \text{(1)}$$

$C_i(P_{it}^j, u_{it}) = a_i P_{it}^{j\,2} + b_i P_{it}^j + c_i u_{it}$: Fuel consunption function

u_{it} : Operation state variable

P_{it}^j : Generation of Thermal Unit i for Demand curve j

S_i : Start - up cost

w^j : Weight coefficient for demand curve j

N, P : Times of bottom and peak demand

Constraints

(a) Balance $\sum_{i=1}^{M} P_{it}^j + \sum_{k=1}^{K}(GH_{kt}^j - LH_{kt}^j) = D_t^j$

D_t^j : Demand for curve j GH_{kt}^j, LH_{kt}^j : Generation power and Pump load

(b) Reserves for increasing and decreasing powers

$$\sum_{i=1}^{N}\left(P_i^{\max} - P_{it}^j\right)\cdot u_{it} + \sum_{k=1}^{K}\left(GH_k^{\max} - GH_{kt}^j + LH_{kt}^j\right) \geq R_t$$

$$\sum_{i=1}^{N}\left(P_{it}^j - P_i^{\min}\right)\cdot u_{it} + \sum_{k=1}^{K}\left(LH_k^{\max} - LH_{kt}^j + GH_{kt}^j\right) \geq Q_t$$

R_t, Q_t : Requirment reserves at Time t

$P_i^{\max}, P_i^{\min}$: Maximun and minimum powers

(c) Generation Capacity and minimum generation
(d) Minimum up and down times
(e) LNG Consumption
(f) Hydro unit power and load limit and reservoir water level

4-2. Conditions of Scheduling Problem

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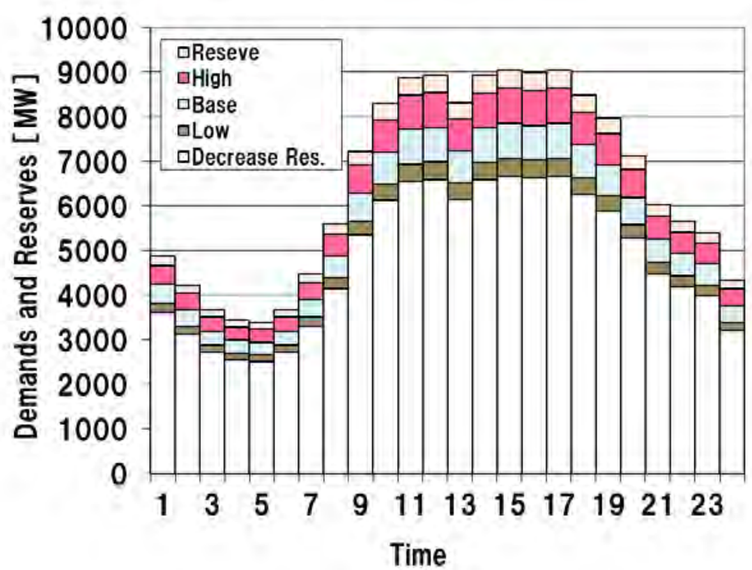
Setting Conditions

- Use three demand curves, high, base and low
- Uncertainty renewable generation and demand, ±10% for Base demand
- Reserves for up and down power; ±15% for Base demand

Method	Demand and Weight coefficient			Reserves
	High	Base	Low	
Conventional	0% 0.0	0% 1.0	0% 0.0	Base±15%
Proposed	+10% 0.25	0% 0.5	-10% 0.25	Base±15%



Horizontal time		24
Thermal unit	Num.	29
	Capacity	12,529MW
	mdt	3
	mut	5
Pumped -hydro	Num.	1
	Capacity	1,000MW

Σ(Weight coefficient)＝1.0

mdt：Minimum down-times

mut：Minimum up-times

Contents

5-1. Conventional method : Using one curve for base demand

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Result Higher priority units are ON except Unit-11 and 20

Time / Capacity (MW)

Unit Number (Priority order)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Capa
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	713
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	729
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	450
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
6	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	250
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	600
9	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	250
10	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	250
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
13	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	250
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	325
15	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	325
16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	250
17	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	250
18	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	250
19	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	256
21	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	375
22	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	600
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	450
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	156

ON

OFF

5-2. Proposed method : Simultaneous Optimization method using three demand curves

Result Higher priority units are ON except Unit-17

Time / Capacity (MW) / Unit Number (Priority order)

Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Capa
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	713
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	729
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	450
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	600
9	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	250
10	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	600
12	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
13	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	250
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	325
15	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	325
16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	250
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250
18	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	250
19	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	250
20	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	256
21	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	375
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	450
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	156

ON
OFF

5-3. Differences of Unit commitments

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Difference

- Differences of UC are one and two units in bottom and peak times respectively
- Other differences are start-up and shut-down time

ON by only Proposed method

ON by only Conventional method

Time

Capacity (MW)

Unit Number (Priority order)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Capa
6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	600
8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	600
9	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	250
10	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	600
12	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	250
13	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	250
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	325
15	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	325
16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	250
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	250
18	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	250
19	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	250
20	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	256
21	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	375
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600

Bottom

Peak

600MW Unit-11 ON
250MW Unit-12 ON

Proposed
Conventional

600MW-11+256MW-20 Units ON
600MW-22+250MW-17 Units ON

5-4. Results : In case of high demand, base + 10%

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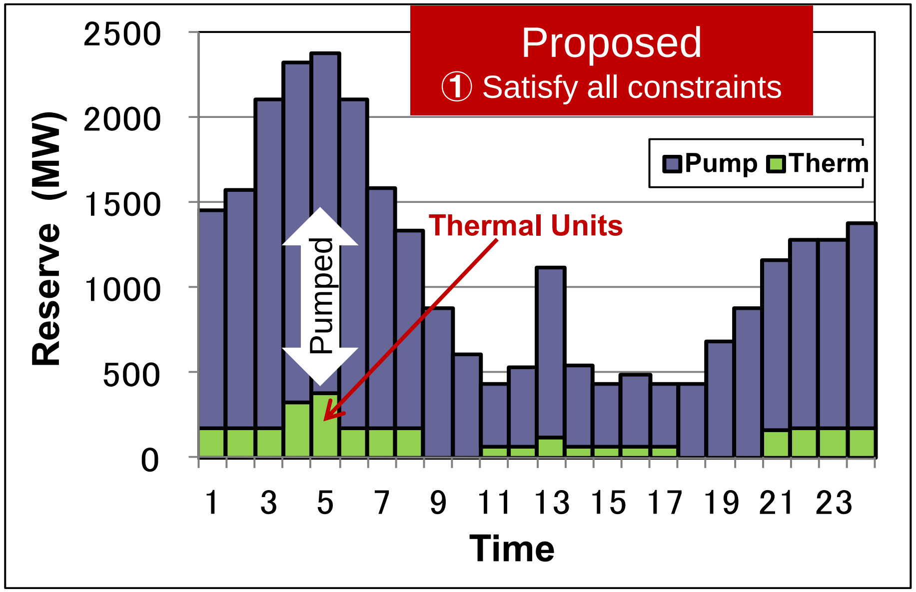


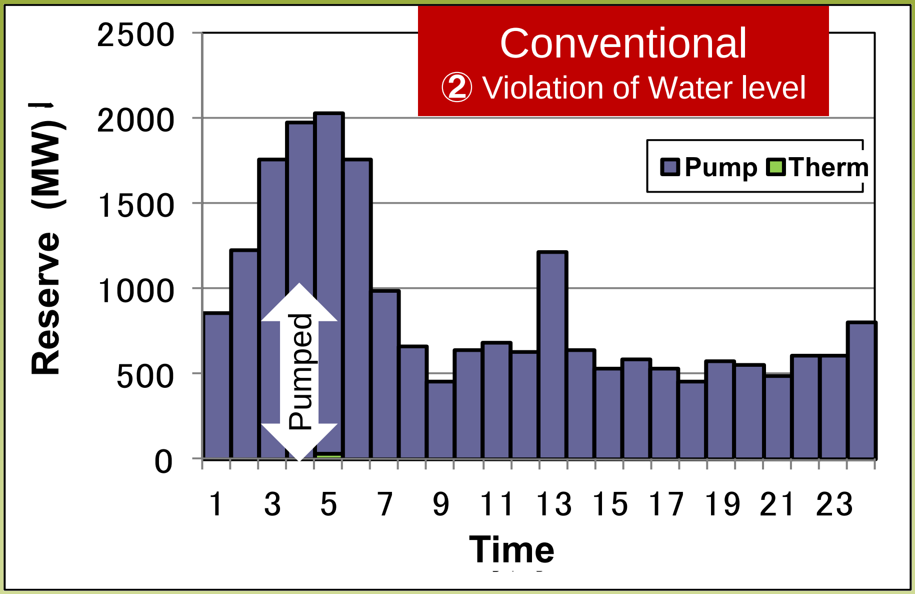
① All constraints are satisfied in case of 15 % reserve for base demand.

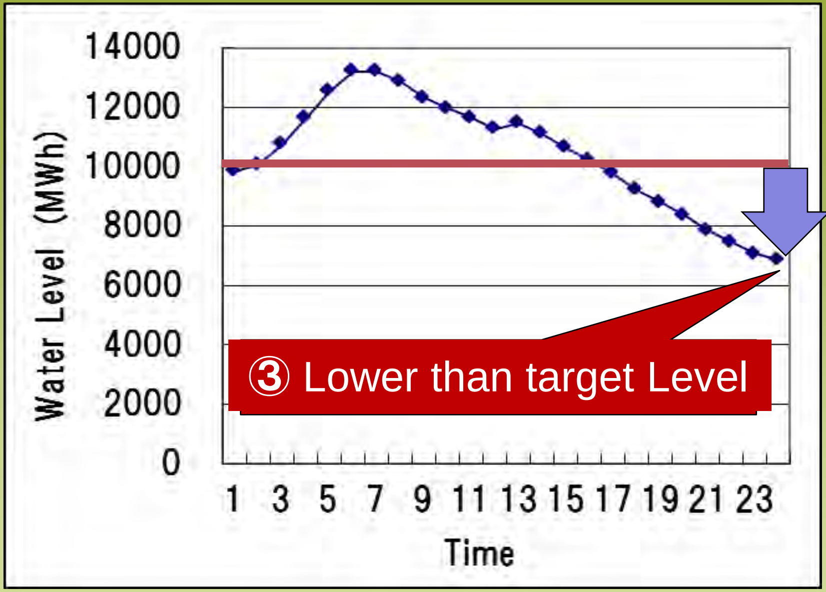
② Final water level ＜ Target level

Power [kW] can balance at each time but not energy [kWh]

③ Compensation costs are added to raise target water level

Average unit cost [k¥/kWh] × ΔWater Level [kWh]





5-5. Comparison of Generation costs

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- **Expected generation costs of proposed method are 0.233 % less than that of Conventional method.**

Costs are normalized by generation costs of Conventional method

Costs	Generation	Fuel	Start-up
Conventional	100.000	99.249	0.751
Proposed	99.767	99.140	0.627
Reduction (%)	0.233	0.110	0.123

	Start-up Units
Conventional	256MW, 600MW
Proposed	250MW, 600MW

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6-1. Conclusions

- Generation Scheduling method has been developed for uncertainties such as large introduction of renewable energy.
  - Using Quadratic Programming
  - Solving simultaneously UC and ELD

- Simulation results from proposed method show
  - Satisfy all constraints
  - Reduce generation costs by 0.233%.

- Pumped-hydro as energy storage system is important for uncertainties to keep not only kW-power balance but also kWh-energy balance.

6-2. Future works

- **Simulate and estimate more realistic cases considering**
  - **Uncertainties for each time dependent**
  - **Network constraints**

Thank you for your kind attention!

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