Regional Demand-Supply Management based on Dynamic Pricing in Multi-period Energy Market

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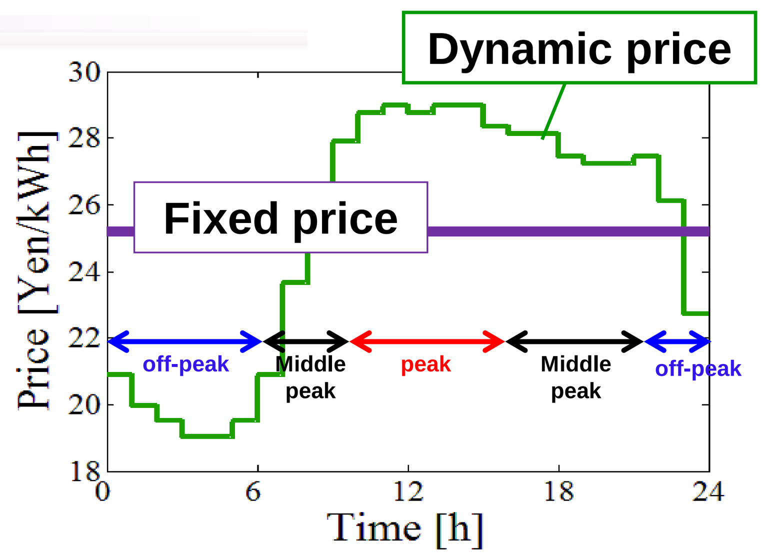
Dynamic Pricing in Smart Grid

Dynamic Pricing

Price changes at short time intervals

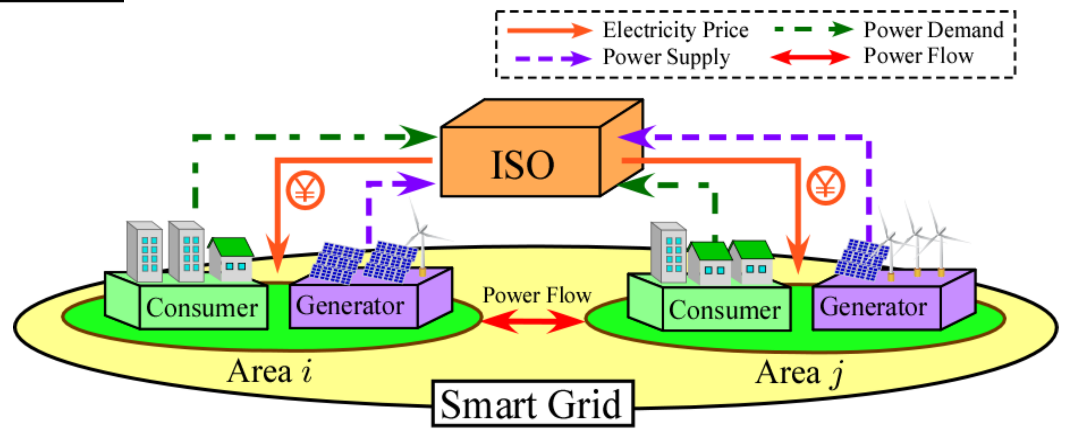
➡ • Efficient use of energy
• Economic benefits



◆ Smart grid with energy market

Market players
- ISO*
- Power consumer
- Power generator

* Independent system operator (ISO)
- a nonprofit organization which manages the energy market and power grid.

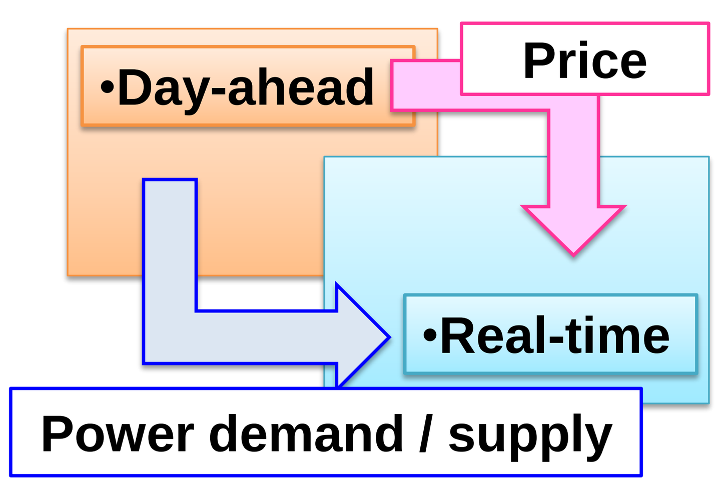


Goal

Design of the energy market mechanism to derive the optimal regional electricity price in social welfare maximization problem

Regional Demand-Supply Management in Multi-period Energy Market

◆Multi-period energy market



Day-ahead: Regional power demand-supply management by using retail and wholesale prices

➕ Power flow

Real-time: Regional power adjustment with negative-watt trading

◆Behavior models of market players

Consumer

$$d_i(t) = \arg\max_{x} \; v_i(x|t) - \pi_i(t)x,$$

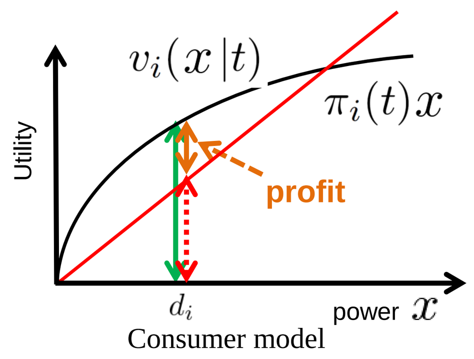
Utility — Electric power cost

$v_i(x|t)$: utility function

$\pi_i(t)$: regional price

x : power demand

Assumption 1
$v_i(x|t)$ is in $\mathcal{C}^2$, strictly increasing and strictly concave.



Generator

$$s_{1_i}(t) = \arg\max_{x} \; \pi_i(t)x - c_{1_i}(x)$$

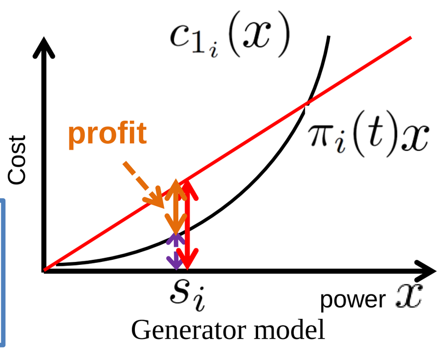
Electric power sale — Cost

$c_{1_i}(x)$: cost function

$\pi_i(t)$: regional price

x : power supply

Assumption 2
$c_{1_i}(x)$ is in $\mathcal{C}^2$, strictly increasing and strictly convex.



◆Power grid model

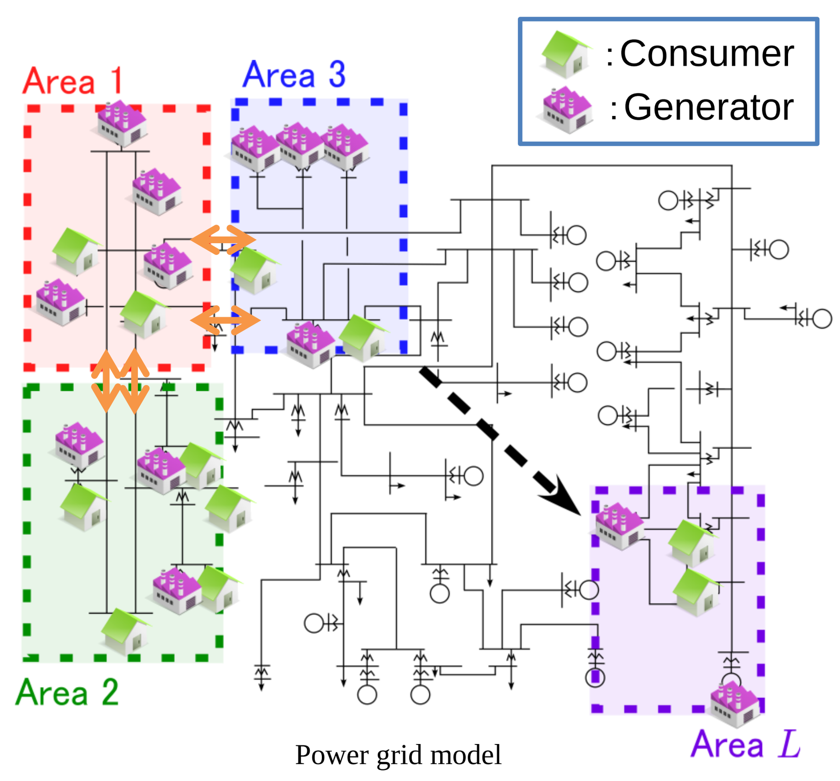
➢ Active power flow equation in Area i

$$\underbrace{s_{1_i}(t) + s_{2_i}(t)}_{\text{Supply}} - \underbrace{d_i(t)}_{\text{Demand}} = \underbrace{\sum_{j \in \mathcal{A}_i} P_{ij}(t)}_{\text{Power flow}}$$

☐ Power flow between Areas i and j

$$P_{ij}(t) = \sum_{(i_k, j_l) \in \mathcal{N}_{ij}} B_{i_k j_l}(\theta_{i_k}(t) - \theta_{j_l}(t))$$

θ_{i_k} : voltage phase angle $B_{i_k j_l}$: susceptance of line



◆ Multi-period power demand-supply management

• Day-ahead: Regional power management with dynamic pricing

Social welfare maximization problem

$$\max_{\boldsymbol{d}(t), \boldsymbol{s}_1(t), \boldsymbol{s}_2(t), \boldsymbol{\theta}(t)} \sum_{i \in \mathcal{A}} \left\{ \underbrace{v_i(d_i(t)|t)}_{\text{Utility}} - \underbrace{c_{1_i}(s_{1_i}(t)) - c_{2_i}(s_{2_i}(t))}_{\text{Cost of generators}} - \underbrace{f_i(\boldsymbol{\theta}_i(t))}_{\text{Cost of power flow}} \right\}$$

$$\text{s. t.} \quad \boldsymbol{s}_1(t) + \boldsymbol{s}_2(t) + \bar{\boldsymbol{B}}\boldsymbol{\theta}(t) = \boldsymbol{d}(t),$$

⬅ Active power flow equation

Dual problem

$$\min_{\boldsymbol{\pi}(t)} \max_{\boldsymbol{d}(t), \boldsymbol{s}_1(t), \boldsymbol{s}_2(t), \boldsymbol{\theta}(t)} \sum_{i \in \mathcal{A}} \underbrace{\{v_i(d_i(t)|t) - \pi_i(t) d_i(t)\}}_{\text{Profit of consumer}} + \sum_{i \in \mathcal{A}} \underbrace{\{\pi_i(t) s_{1_i}(t) - c_{1_i}(s_{1_i}(t))\}}_{\text{Profit of generator}}$$
$$+ \boldsymbol{\pi}(t)^T \{\boldsymbol{s}_2(t) + \bar{\boldsymbol{B}}\boldsymbol{\theta}(t)\} - \sum_{i \in \mathcal{A}} \{c_{2_i}(s_{2_i}(t)) + f_i(\boldsymbol{\theta}_i(t))\}$$

➡ Optimal dual variable $\pi^*(t)$ = Optimal regional electricity price

• Real-time: Regional power adjustment with negative-watt trading

Consumer

$$\rho_i(t) = \arg\max_{\rho_i} \; \underbrace{v_i(d_i^a(t) - \rho_i|t)}_{\text{Utility}} - \underbrace{\pi_i^a(t)\{d_i^a(t) - \rho_i\}}_{\text{Electric power cost}} + \underbrace{\hat{\pi}_i(t) g_i(\rho_i)}_{\text{Incentive}}$$

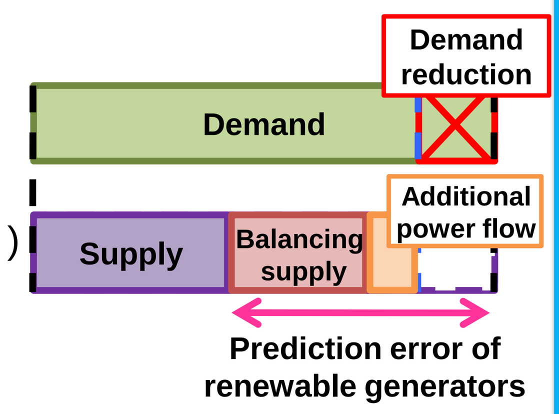
Demand reduction

➢ Incentive design using day-ahead price

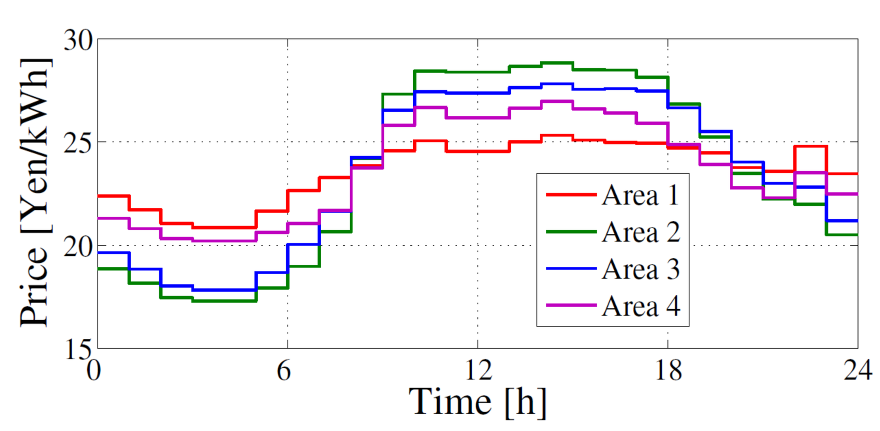
Incentive price: $\hat{\pi}_i(t) = \Pi_i(t) - \pi_i^a(t)$ Day-ahead price

Reducing function: $g_i(\rho_i) = \rho_i + \alpha$ (α is independent of ρ_i)

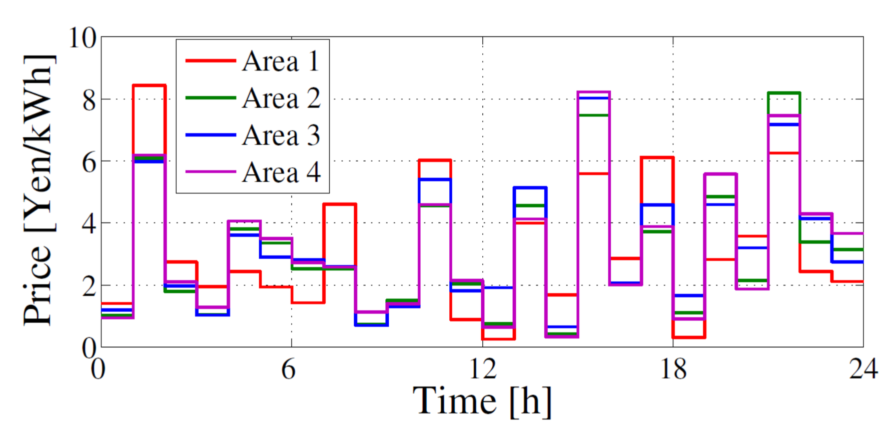
➡ Optimal allocation between demand reduction and balancing supply with power flow



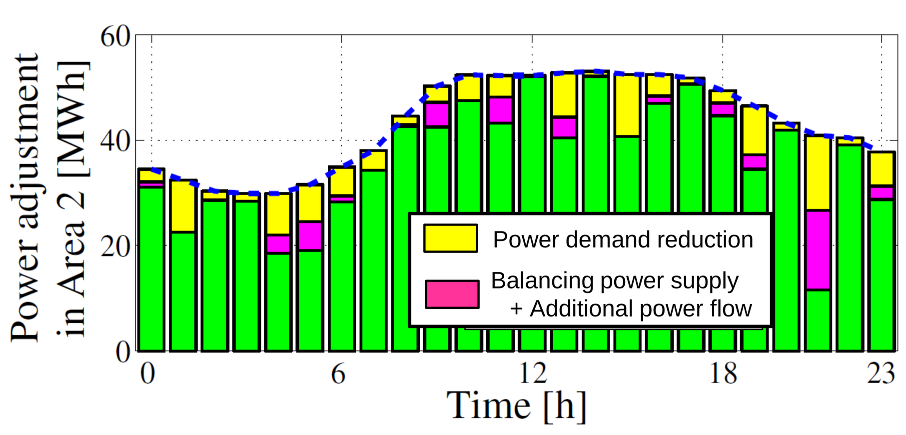
◆Simulation results



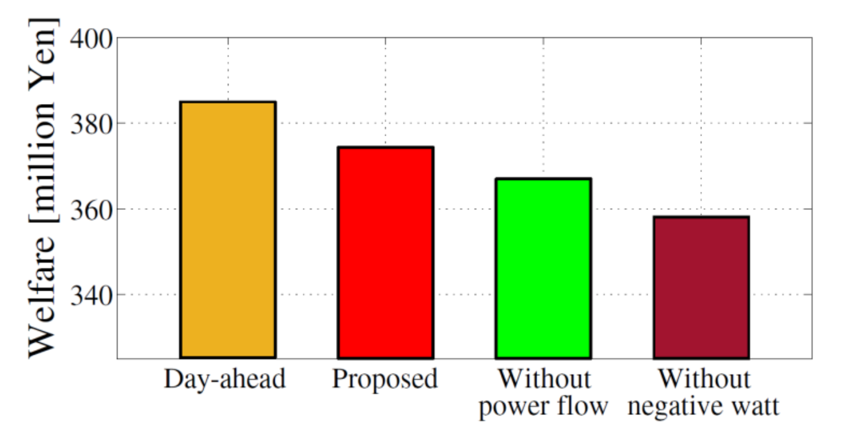
Regional day-ahead price



Incentive price in a real-time market



Power adjustment in a real-time market



Social welfare with real-time power adjustment

Conclusion and Future work

Power demand-supply management in multi-period energy market

➡ Efficient regional power management based on the dynamic pricing

◆Future work
- Incentive design by using the mechanism design
- Modeling of AC power grid without the DC power flow approximation

Publications

◆Journals

[1] Yoshihiro Okawa, Toru Namerikawa, "Distributed Dynamic Pricing Based on Demand-supply Balance and Voltage Phase Difference in Power grid", *Control Theory and Technology*, 2015

[2] Yoshihiro Okawa, Yu Haraikawa, and Toru Namerikawa, "Distributed Optimal Dynamic Pricing Considering Electric Power Flow", *Trans. of the Society of Instrument and Control Engineers*, Vol. 50, No. 3, pp. 245-252, 2014 (in Japanese).

◆International conference papers

[1] Yoshihiro Okawa and Toru Namerikawa, "Dynamic Electricity Pricing via the H∞ Control Considering Uncertainties in Market Participants' Behavior", *Proc. of the 14th European Control Conference 2015* (accepted).

[2] Yoshihiro Okawa and Toru Namerikawa, "Distributed Dynamic Pricing with Alternating Decision Making of Market Players", *Proc. of the SICE Annual Conference 2015* (accepted).

[3] Yoshihiro Okawa and Toru Namerikawa, "Dynamic Pricing Considering Constraints of Power Grids", *Proc. of the SICE Annual Conference 2014*.