Game Theoretic Optimal Power Allocation: Social Welfare Design

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FL12-04-1
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Outline

This Seminar

Objective: I tell you the objective of my research
Show the result (examples) of Social Welfare Design

- Introduction to my research
  - Objective (pp. 3-4)
- Problem Setting
  - Situations (pp. 5-6)
  - Social Welfare Design (pp. 7-12)
  - Simulation (pp. 13-14)
- Future Work

Other Seminars

- Introduction to Game Theory (5/9)
- Power Spectrum and Coherence Analysis in details (5/11)

Background

National Strategy "S+3E"

Propose a new energy best mix in the light of
(i) Energy Security
(ii) Economic Efficiency
(iii) Environment
+ (iv) Safety (after 3.11)

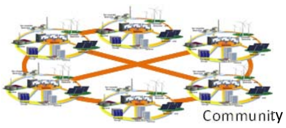
Realization of Optimal Supply Structure: Fossil Fuel | Nuclear Power | Renewable Energy
Realization of Energy-Saving Type Demand Structure: Energy/Carbon
Development of New Energy System (Stable Supply, Competitive, Economic Efficiency)
Development of New Energy Technology
International Strategy: Securing Resources | Contribution for Global Warming Prob. | International Cooperation

[*] 経済産業省 "エネルギー政策見直しの基本的視点," 2011/6

One of the Solution

Distributed Cooperative Energy Management System (DCEMS)
➡ Robustness to event uncertainty

Problems
Renewables Volatility
➡ Demand and Supply Balance
Frequency Stabilization

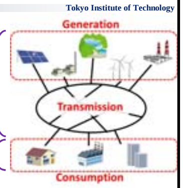


Solutions Optimization or Game Theory   Distributed Cooperative EMS

Objective

Target

Unbundling-based Power Network (Development of New Energy System)
(Unbundling: Supply Part is divided into Generation and Transmission)
➡ Electricity Liberalization



Problem

Optimal Power Allocation Problem
(Many Power Sources (PV), Many Consumers
Each consumer chooses needed power sources)

Approach

Game Theoretic Control (Development of New Energy Technology)
(Utility Design: Welfare Game (Potential Game)[4]
Learning Design: Payoff-based Learning[5,6])

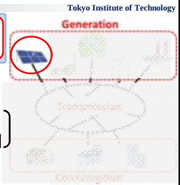
Merits: Scalability, Adaptability in real time
Solve the more complex situations than other approaches easily

Objective: Propose a new method of energy best mix

Situation: Resources

Supply Elements $\mathcal{V} = \{V_1, \cdots, V_n\}$ (Renewable Energy)

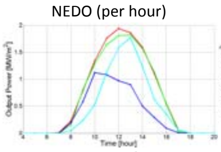
Renewable Energy (RE) Resources V_i
(All REs are Solar Energy (Photovoltaics: PV))



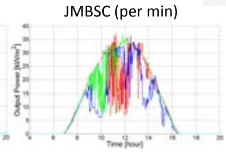
Measured Data: Global Solar Radiation
(Integrated value per hour at each hour [MJ/m^2] [*]
Instantaneous value per second at each min. [kJ/m^2] [**])

Ex. Maebashi (Horizontal Plane)

NEDO (per hour)



JMBSC (per min)

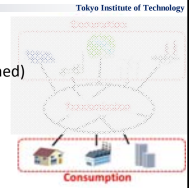


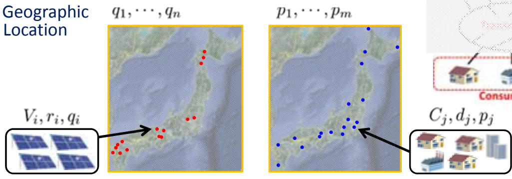
Measured Value $\hat{r}_i$ [W/m^2] η [.] : Coefficient
➡ Generated Energy $r_i = \hat{r}_i \times \eta S_i$ S_i [m^2] : Panel Size

[*] NEDO, Data-base, http://www.nedo.go.jp/library/nissharyou.html
[**] Japan Meteorological Business Support Center(JMBSC), http://www.jmbsc.or.jp/

Situation: Players and Actions

	Supply Elements	Demand Elements
	$\mathcal{V} = \{V_1, \cdots, V_n\}$	$\mathcal{C} = \{C_1, \cdots, C_m\}$
Parameter	$r_1, \cdots, r_n$ (Generated)	$d_1, \cdots, d_m$ (Consumed)
Geographic Location	$q_1, \cdots, q_n$	$p_1, \cdots, p_m$

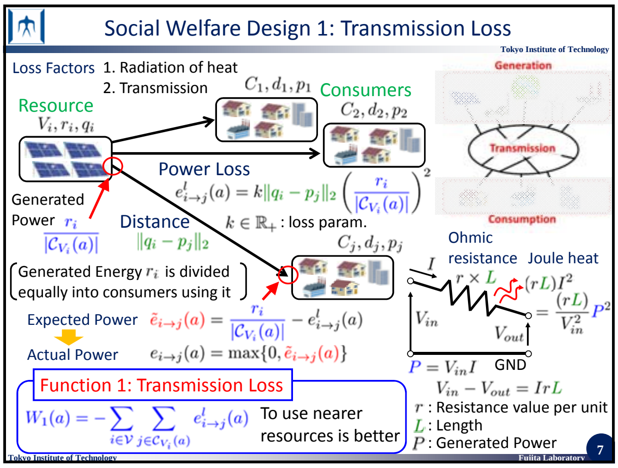




Each consumer (player) C_j select the using generators $a_j \in 2^{\mathcal{V}}$
➡ Players set chosen a resource V_i: $\mathcal{C}_{V_i}(a) = \{C_j \in \mathcal{C} : V_i \in a_j\}$

Problem: Each consumer C_j select the using generators a_j to optimize the system

What's "optimum" ? ➡ Design Evaluation Functions


Social Welfare Design 1: Transmission Loss
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Loss Factors 1. Radiation of heat
2. Transmission
Resource
V_i, r_i, q_i
C_1, d_1, p_1 Consumers
C_2, d_2, p_2
Generation
Transmission
Consumption
Power Loss
$e^l_{i\to j}(a) = k\|q_i - p_j\|_2 \left(\frac{r_i}{|\mathcal{C}_{V_i}(a)|}\right)^2$
Generated Power $\frac{r_i}{|\mathcal{C}_{V_i}(a)|}$
Distance $\|q_i - p_j\|_2$
$k \in \mathbb{R}_+$: loss param.
C_j, d_j, p_j
Generated Energy r_i is divided equally into consumers using it
Expected Power $\tilde{e}_{i\to j}(a) = \frac{r_i}{|\mathcal{C}_{V_i}(a)|} - e^l_{i\to j}(a)$
Actual Power $e_{i\to j}(a) = \max\{0, \tilde{e}_{i\to j}(a)\}$
Ohmic resistance Joule heat
$r \times L$ $(rL)I^2$
$= \frac{(rL)}{V_{in}^2}P^2$
V_{in} V_{out} GND
$P = V_{in}I$
$V_{in} - V_{out} = IrL$
r : Resistance value per unit
L : Length
P : Generated Power
Function 1: Transmission Loss
$W_1(a) = -\sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{C}_{V_i}(a)} e^l_{i\to j}(a)$
To use nearer resources is better
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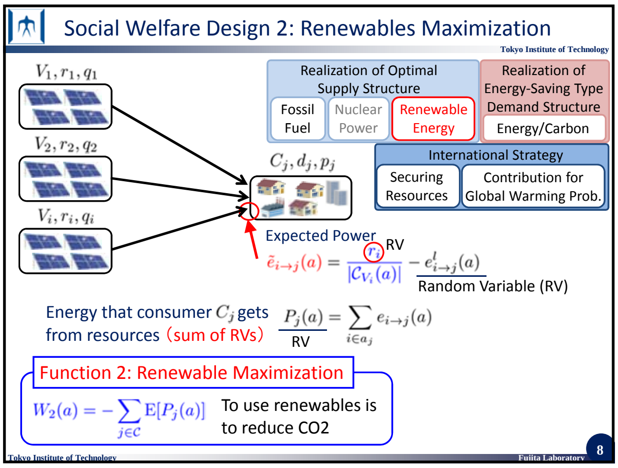
Social Welfare Design 2: Renewables Maximization
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V_1, r_1, q_1
V_2, r_2, q_2
V_i, r_i, q_i
Realization of Optimal Supply Structure
Fossil Fuel
Nuclear Power
Renewable Energy
Realization of Energy-Saving Type Demand Structure
Energy/Carbon
International Strategy
Securing Resources
Contribution for Global Warming Prob.
C_j, d_j, p_j
Expected Power
RV
$\tilde{e}_{i\to j}(a) = \frac{r_i}{|\mathcal{C}_{V_i}(a)|} - e^l_{i\to j}(a)$
Random Variable (RV)
Energy that consumer C_j gets from resources (sum of RVs)
$P_j(a) = \sum_{i\in a_j} e_{i\to j}(a)$
RV
Function 2: Renewable Maximization
$W_2(a) = -\sum_{j\in\mathcal{C}} \mathrm{E}[P_j(a)]$
To use renewables is to reduce CO2
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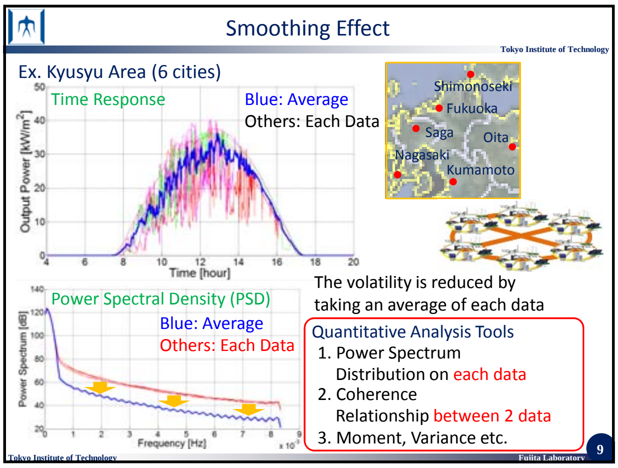
Smoothing Effect
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Ex. Kyusyu Area (6 cities)
Time Response
Blue: Average
Others: Each Data
Output Power [kW/m²]
Time [hour]
Shimonoseki
Fukuoka
Saga
Oita
Nagasaki
Kumamoto
The volatility is reduced by taking an average of each data
Power Spectral Density (PSD)
Blue: Average
Others: Each Data
Power Spectrum [dB]
Frequency [Hz]
Quantitative Analysis Tools
1. Power Spectrum Distribution on each data
2. Coherence Relationship between 2 data
3. Moment, Variance etc.
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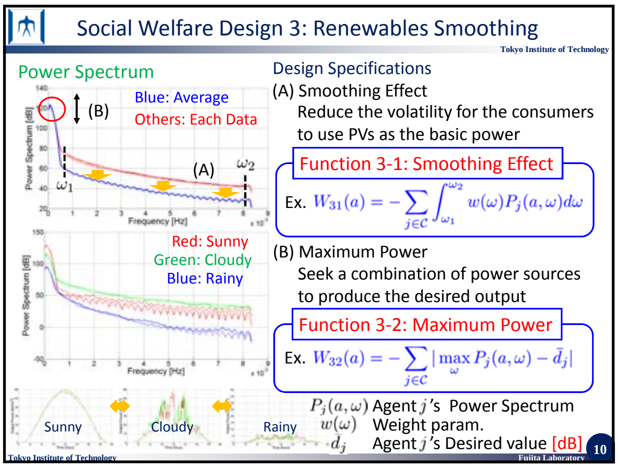
Social Welfare Design 3: Renewables Smoothing
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Power Spectrum
(B)
Blue: Average
Others: Each Data
(A)
ω_1 ω_2
Frequency [Hz]
Red: Sunny
Green: Cloudy
Blue: Rainy
Sunny
Cloudy
Rainy
Design Specifications
(A) Smoothing Effect
Reduce the volatility for the consumers to use PVs as the basic power
Function 3-1: Smoothing Effect
Ex. $W_{31}(a) = -\sum_{j\in\mathcal{C}}\int_{\omega_1}^{\omega_2} w(\omega)P_j(a,\omega)d\omega$
(B) Maximum Power
Seek a combination of power sources to produce the desired output
Function 3-2: Maximum Power
Ex. $W_{32}(a) = -\sum_{j\in\mathcal{C}}|\max_{\omega} P_j(a,\omega) - \bar{d}_j|$
$P_j(a,\omega)$ Agent j's Power Spectrum
$w(\omega)$ Weight param.
$\bar{d}_j$ Agent j's Desired value [dB]
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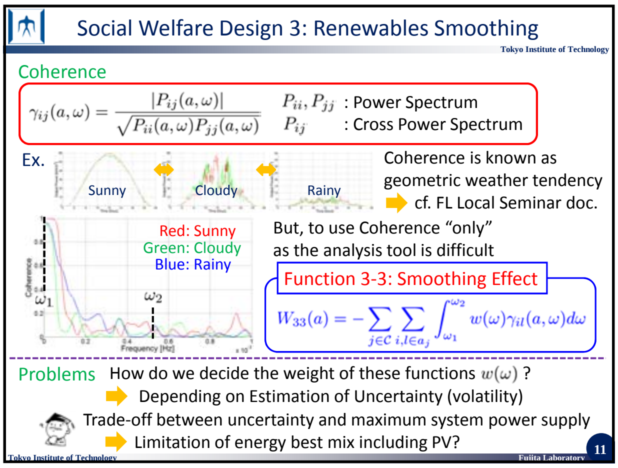
Social Welfare Design 3: Renewables Smoothing
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Coherence
$\gamma_{ij}(a,\omega) = \frac{|P_{ij}(a,\omega)|}{\sqrt{P_{ii}(a,\omega)P_{jj}(a,\omega)}}$
P_{ii}, P_{jj} : Power Spectrum
P_{ij} : Cross Power Spectrum
Ex.
Sunny
Cloudy
Rainy
Coherence is known as geometric weather tendency
cf. FL Local Seminar doc.
Red: Sunny
Green: Cloudy
Blue: Rainy
ω_1 ω_2
Frequency [Hz]
But, to use Coherence "only" as the analysis tool is difficult
Function 3-3: Smoothing Effect
$W_{33}(a) = -\sum_{j\in\mathcal{C}}\sum_{i,l\in a_j}\int_{\omega_1}^{\omega_2} w(\omega)\gamma_{il}(a,\omega)d\omega$
Problems How do we decide the weight of these functions $w(\omega)$?
Depending on Estimation of Uncertainty (volatility)
Trade-off between uncertainty and maximum system power supply
Limitation of energy best mix including PV?
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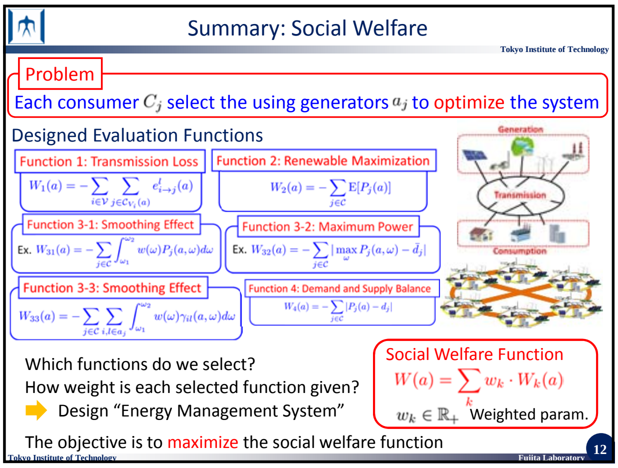
Summary: Social Welfare
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Problem
Each consumer C_j select the using generators a_j to optimize the system
Designed Evaluation Functions
Function 1: Transmission Loss
$W_1(a) = -\sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{C}_{V_i}(a)} e^l_{i\to j}(a)$
Function 2: Renewable Maximization
$W_2(a) = -\sum_{j\in\mathcal{C}}\mathrm{E}[P_j(a)]$
Function 3-1: Smoothing Effect
Ex. $W_{31}(a) = -\sum_{j\in\mathcal{C}}\int_{\omega_1}^{\omega_2} w(\omega)P_j(a,\omega)d\omega$
Function 3-2: Maximum Power
Ex. $W_{32}(a) = -\sum_{j\in\mathcal{C}}|\max_{\omega} P_j(a,\omega) - \bar{d}_j|$
Function 3-3: Smoothing Effect
$W_{33}(a) = -\sum_{j\in\mathcal{C}}\sum_{i,l\in a_j}\int_{\omega_1}^{\omega_2} w(\omega)\gamma_{il}(a,\omega)d\omega$
Function 4: Demand and Supply Balance
$W_4(a) = -\sum_{j\in\mathcal{C}}|P_j(a) - d_j|$
Generation
Transmission
Consumption
Which functions do we select?
How weight is each selected function given?
Design "Energy Management System"
Social Welfare Function
$W(a) = \sum_k w_k \cdot W_k(a)$
$w_k \in \mathbb{R}_+$ Weighted param.
The objective is to maximize the social welfare function
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Example: Settings

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Situation Local production for local consumption Model

Players $\mathcal{C}(=\mathcal{V})=\{1,2,3,4,5,6\}$ (6 points in Kyusyu area)

Welfare Function $W=W_1'(a)+W_2'(a)+W_3'(a)$

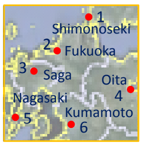
$$W_1'(a)=\sum_{j\in\mathcal{C}}u_{j1}(a)\quad u_{j1}(a)=-w_1\sum_{i\in a_j}e^l_{j\to i}(a)\quad k=3.9\times10^{-7}$$

$$W_2'(a)=\sum_{j\in\mathcal{C}}u_{j2}(a)\quad u_{j2}(a)=-w_2\int_{\omega_1}^{\omega_2}w(\omega)P_j(a,\omega)d\omega$$

$$W_3'(a)=\sum_{j\in\mathcal{C}}u_{j3}(a)\quad u_{j3}(a)=w_3\max_{\omega}P_j(a,\omega)$$

$$w_1=5\times10^2\quad w_2=2\times10^{-2}\quad w_3=1\times10^{-6}$$

$$\omega_1=4\times10^{-4}\quad \omega_2=8.3\times10^{-3}\quad w(\omega)=\omega/\omega_1$$



Data

2010/8, 6-18h

(720*31 data)

PSD data

Before 1month

(720*31 data)

Utility Function $U_j(a)=u_{j1}(a)+u_{j2}(a)+u_{j3}(a),\ \forall j\in\mathcal{C}$

(This component includes Potential Game/Welfare Game: WLU)

Initial Action $a_j(0)=\{j\},\ \forall j\in\mathcal{C}$

Restricted Action $\mathcal{R}_j(a_j)=\{a_j'\subseteq\mathcal{A}_j|\max\{a_j'\backslash a_j,a_j\backslash a_j'\}\in\{0,1\}\},\ \forall j\in\mathcal{C}$

Algorithm PIPIP $\varepsilon(k)=\max\{0.3-0.0001k,0.005\}\quad \kappa=0.1$

Application Method Resource Allocation at 8/2 10:00 (repetition)

Example: Results

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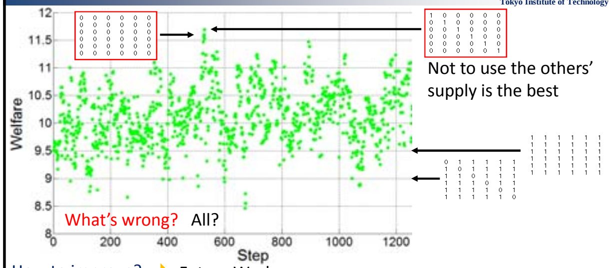

How to improve? ➡ Future Works

Target area is too small? ➡ Analysis on National Size[7]

Including Zero matrix!! ➡ Restricted Action

$$\mathcal{R}_j(a_j)=\{a_j'\subseteq\mathcal{A}_j\backslash\{\emptyset\}|\max\{a_j'\backslash a_j,a_j\backslash a_j'\}\in\{0,1\}\},\ \forall j\in\mathcal{C}$$

Sparse Network? ➡ To analyze denser network and compare them

Bad Social Welfare Functions? etc.

Reference

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[1] 七原, "大量導入時における太陽光, 風力発電の出力変動特性," オペレーションズリサーチ, Vol. 56, No. 7, pp. 375-380, 2011.

[2] J. R. Marden, G. Arslan and J. S. Shamma, "Cooperative Control and Potential Games," *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 39, No. 6, pp. 1393-1407, 2009.

[3] R. Gopalakrishnan, J. R. Marden and A. Wierman, "An Architectural View of Game Theoretic Control," *ACM SIGMETRICS Performance Evaluation Review*, Vol. 38, No. 3, pp. 31-36, 2011.

[4] J. R. Marden and A. Wierman, "Distributed Welfare Games," *Operations Research*, submitted, 2008.

[5] T. Goto, T. Hatanaka and M. Fujita, "Payoff-based Inhomogeneous Partially Irrational Play for Potential Game Theoretic Cooperative Control of Multi-agent Systems," (available at arXiv: 1107.4838), 2011.

[6] J. R. Marden, G. Arslan and J. S. Shamma, "Joint strategy fictitious play with inertia for potential games," *IEEE Transactions on Automatic Control*, Vol. 54, No. 2, pp. 208-220, 2009.

[7] 畑中, 藤田, "ゲーム理論的学習アルゴリズムに基づく最適再生可能エネルギー管理に関する考察," 2012年度第1回高信頼制御通信研究会, 2012 (to be presented).