Analysis of Photovoltaic Popularization Dynamics Considering Feed-in Tariff

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Outline

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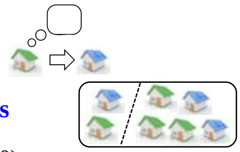
■ Progresses and Feature Works (p. 20)



Background

Energy Problem
・Stable energy supply
・Low emission
・Energy secure

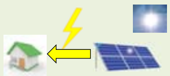
New Resource of Energy

Photovoltaics : PV
(Using solar energy)
⇩
Electric energy

Wind Power

[*]

Advantage



Disadvantage

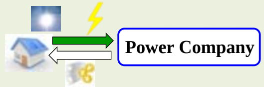
High cost of PV panel

Output variability

Feed-in Tariff

Policy of Renewable Energy Popularization[7][8]

Feed-in Tariff (FIT)
PV for residential setting



Germany
Starting in 2000

Spain
Starting in 2007

⇩
" Solar Mania ", PV installation over their plan
⇩

Reconsidered in 2009 and 2012
Reconsidered in 2008 and 2010

・Many companies go bankrupt
・Consumers have to pay extra fee for PV installation
・They set PV fee more cheaper

PV fee is important for appreciate PV installation
⇨ **Objective of control**

Objective

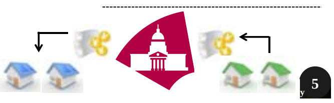
■ **Objective of Research**

Regulation of renewable energy(PV)
・Robustness against imbalance of PV
・Optimization of PV rate and aids

Problems
・Complex connections between agents
⇨ **PV Popularization rate**
Evolutionary Game

・Variance of output
⇨ **Risk function**

・High cost
⇨ **Reallocation of PV cost**

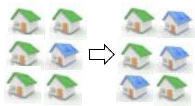


PV Popularization Dynamics

PV Popularization Dynamics

$$\dot{x}_1 = (f_1 - \phi) x_1$$

$$f_1 = y(x_1, \mu), \quad \phi = y(x_1, \mu) x_1 + z(x_1, \mu)(1 - x_1)$$



PV installation f_1 is better than average strategy
⇨ **PV installation increase**

Note
This contents include mid-presentation
See Appendix

Expectation of PV installer : $y(x_1, \mu)$
Expectation of no PV installer : $z(x_1, \mu)$
Average Expectation $\phi(x_1, \mu)$

PV popularization rate : x_1
Reallocation rate : μ

Concrete Objective
Regulation of PV popularization with reallocation $\beta(\mu)$ being smaller

Imbalance Between Supply and Demand

Risk function: Load Frequency Control (LFC) [6]

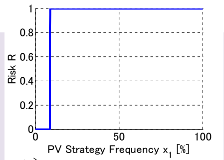
$(1-\varepsilon)\times E[d] \leqq$ Demand d − Total PV power $w \leqq (1+\varepsilon)\times E[d]$

Generator supply — Demand – PV supply — Generator supply

$(1\pm\varepsilon)\times E[d]$

Ability of power generator control

If $d-w<(1-\varepsilon)E[d]$, then imbalance leads blackout



R : **Probability of Imbalance** such that $w>\varepsilon d$

$$R=\Pr\{d-w<(1-\varepsilon)[d]\}=\Pr\{w>\varepsilon NE[d_i]\}$$

$$=\Pr\left\{\frac{w-n_1E[w_i]}{\sqrt{n_1}\sigma}>\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{n_1}\sigma}\right\}$$

$$\approx\frac{1}{\sqrt{\pi}}\int_{\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}}^{\infty}e^{-x^2}dx=\begin{cases}\frac{1}{2}\left(1-\mathrm{erf}\left(\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}\right)\right) & (\varepsilon NE[d_i]>n_1E[w_i])\\ \frac{1}{2}\left(1+\mathrm{erf}\left(\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}\right)\right) & (\varepsilon NE[d_i]\le n_1E[w_i])\end{cases}$$

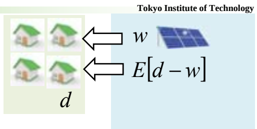
(∵ Central limit theorem)

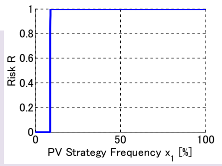
c.f. Imbalance Between Supply and Demand

Risk function: Modeling approach

$$-\varepsilon' d\le d-(w+E[d-w])\le\varepsilon' d$$

If $|d-w-E[d-w]|>\varepsilon' d$, then imbalance leads blackout





R : **Probability of Imbalance** such that $w>\varepsilon d$

$$R=\Pr\{w>\varepsilon d\}=\Pr\{w>\varepsilon NE[d_i]\}$$

$$=\Pr\left\{\frac{w-n_1E[w_i]}{\sqrt{n_1}\sigma}>\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{n_1}\sigma}\right\}$$

$$\approx\frac{1}{\sqrt{\pi}}\int_{\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}}^{\infty}e^{-x^2}dx=\begin{cases}\frac{1}{2}\left(1-\mathrm{erf}\left(\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}\right)\right) & (\varepsilon NE[d_i]>n_1E[w_i])\\ \frac{1}{2}\left(1+\mathrm{erf}\left(\frac{\varepsilon NE[d_i]-n_1E[w_i]}{\sqrt{2n_1}\sigma}\right)\right) & (\varepsilon NE[d_i]\le n_1E[w_i])\end{cases}$$

(∵ Central limit theorem)

Simulation Setting

A customer's demand — d_i: Constant (Variance)

PV power — w_i: Constant (Variance)

Standard variance σ : 0.2279 — From NEDO data in Hiroshima

Assumption : Standard variance of d_i and w_i are same

Population — N : 1,000,000

Costs caused by imbalance[5] — c_i : 1,000 yen/kWh

Electrical utility of PV — C_{PV} : Constant (Variance)

Electrical utility of grid — C_{GP} : 16 yen/kWh

Simulation time span — **1 week** — **Considered PV install time**

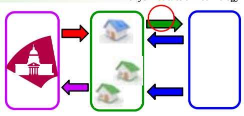
Variation of PV Utility Fee

Setting

Useful life-span of PV Panel : 10 years

A PV Generation : 0.0959 × 4.45 kWh/h

A demand[9] : 0.7336 kWh/h



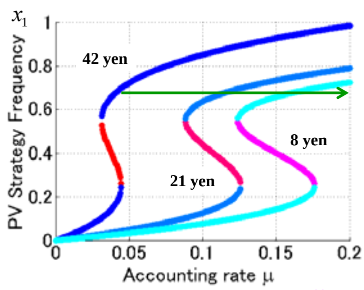
Decision Model

Replicator Dynamics

$$\dot{x}_1=(f_1(x_1,\mu)-\phi(x_1,\mu))x_1$$

PV utility fee : Variation

42 yen/kWh, 21 yen/kWh 8 yen/kWh,



PV utility fee become cheaper, then PV popularization is choked off

Decision Model

In the discussions so far,

Simply benefit base utility of power charges

Only

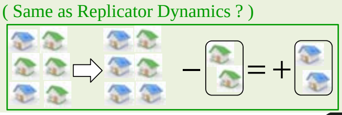
In reality,

There are many factors for decisions[15][16]

- **Imitation**
- **Strategic thinking**
- **Learning**

Application of Decision Model

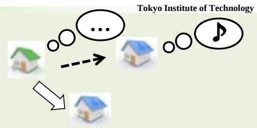
- **Win-Stay-Lose-Shift[13]** (Same as Replicator Dynamics ?)
- **Imitation[16]**
- **Trial and error[16]**



Imitation

■ **Decision Sequence**

1. Select an agent and an opponent randomly
2. **If the opponent looks good, the agent imitates opponent's strategy**



1. $f_1\ge f_2$ **PV installation is better** — $f_1<f_2$ **PV installation is worse**

	$f_1\ge f_2$	$f_1<f_2$
Flow from PV installation	0	$x_1 rN\Delta t\times(1-x_1)$
Flow to PV installation	$(1-x_1)rN\Delta t\times x_1$	0

2. **Variance of the number of PV installation**

$$\begin{cases}N\Delta x_1=x_1(1-x_1)rN\Delta t & (f_1\ge f_2)\\ N\Delta x_1=-x_1(1-x_1)rN\Delta t & (f_1<f_2)\end{cases}$$

r : Rate of doing imitation

$f_1=f_1(x_1,\mu),\ f_2=f_2(x_1,\mu)$

$$\dot{x}_1=\begin{cases}rx_1(1-x_1) & (f_1\ge f_2)\\ -rx_1(1-x_1) & (f_1<f_2)\end{cases}$$

Imitation (Most easily model)

Imitation[16]

Decision Sequence

1. Select an agent and an opponent randomly
2. **If the opponent looks good, the agent imitates opponent's strategy**

Simulation Setting

Same as slide No. 9

PV utility fee : 42 yen/kWh

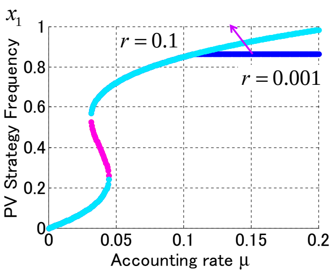
Decision Model

Imitation (Most easily model)

$$\dot{x}_1 = \begin{cases} rx_1(1-x_1) & (f_1 > f_2) \\ -rx_1(1-x_1) & (f_1 \le f_2) \end{cases}$$

r : const $(r = 0.001)$

PV popularization is stopped



r **become bigger, then the dynamics close in Replicator Dynamics**

Trial and Error

Decision Sequence

- Select an agent and an opponent randomly
- **Every agent has trend based on reinforcement and forgetting**

Trend of player i selecting PV installation

$$P_{i1}(t+1) = (1-\varphi)P_{i1}(t) + R_{i1}(t)$$

Forgetting — Reinforcement

$R_{i1}(t)$: Reinforcement of PV installation

φ : Rate of forgetting

Rate which player i selects PV installation : x_{i1} (abbr. x_i)

$$x_i(t) = \frac{P_{i1}(t)}{P_{i1}(t)+P_{i2}(t)} = \frac{P_{i1}(t)}{P(t)}$$

$$\Delta x_i = x_i(t+1) - x_i(t) = \frac{P_{i1}(t+1)}{P_{i1}(t+1)+P_{i2}(t+1)} - x_i(t) = \cdots = \frac{(R_{i1} - x_i(t)(R_{i1}+R_{i2}))}{P_{i1}(t+1)+P_{i2}(t+1)}$$

Trial and Error

Payoff table (1 VS 1)

Own side \ Opposite side	PV	no PV
PV	a	b
no PV	c	d

Payoff table (1 VS Others)

Own side \ Opposite side	
PV	f_1
no PV	f_2

Own / Opp.	Rate of selection	Δx_i at rate of selection
PV / PV	$x_i x$	$(1-x_i)a/((1-\varphi)P(t)+a)$
PV / no PV	$x_i(1-x)$	$(1-x_i)b/((1-\varphi)P(t)+b)$
no PV / PV	$(1-x_i)x$	$-x_i c/((1-\varphi)P(t)+c)$
no PV / no PV	$(1-x_i)(1-x)$	$-x_i d/((1-\varphi)P(t)+d)$

Numerator of $E[\Delta x_i]$

$$= x_i x_1(1-x_i)a + x_i(1-x_1)(1-x_i)b + (1-x_i)x_1 x_i c + (1-x_i)(1-x_1)x_i d$$

$$= x_i(1-x_i)(x_1 a + (1-x_1)b + x_1 c + (1-x_1)d) = x_i(1-x_i)(f_1 - f_2)$$

$$E[\Delta x_i] = \alpha x_i(1-x_i)(f_1 - f_2)$$

Trial and error

α : approximate value (Constant)

Trial and Error[16]

Decision Sequence

- Select an agent and an opponent randomly
- **Every agent has trend based on reinforcement and forgetting**

Simulation Setting

Same as slide No. 9

PV utility fee : 42 yen/kWh

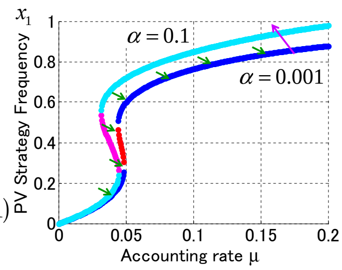
Decision Model

Trial and error

$$\dot{x}_1 = \alpha x_1(1-x_1)(f_1 - f_2)$$

α : const $(\alpha = 0.001)$

Suppress PV popularization



α **become bigger, then the dynamics close in Replicator Dynamics**

Mixture of Strategies

Motivation

It is hardly possible that one community contains one decision model

A community ?

Setting

Mixture of 2 Learning Algorithms (LAs)

LA1 : Imitation LA2 : Trial and error

x_{11} Imitation — x_{12} Trial and error

PV Dynamics

$$\text{LA1}: \dot{x}_{11} = \begin{cases} rx_{11}(1-x_{11}) & (f_1(x_1,\mu) > f_2(x_1,\mu)) \\ -rx_{11}(1-x_1) & (f_1(x_1,\mu) \le f_2(x_1,\mu)) \end{cases}$$

$$\text{LA2}: \dot{x}_{12} = \alpha x_{12}(1-x_{12})(f_1(x_1,\mu) - f_2(x_1,\mu))$$

$$\text{All}: \dot{x}_1 = \eta \dot{x}_{11} + (1-\eta)\dot{x}_{12} - \gamma x_1$$

x_{11} : PV rate of LA1

x_{12} : PV rate of LA2

$x_1 = \eta x_{11} + (1-\eta)x_{12}$

η : Rate of LA1 (const)

$-\gamma x_1$: **Break down of PV system**

PV Dynamics with 2 Decision Model

Stable and Unstable Point

Stable point : ●

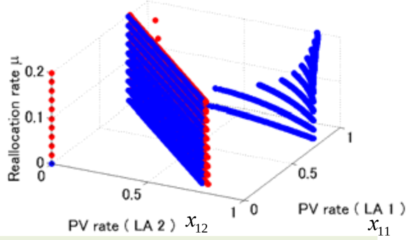
Unstable point : ●

Learning Algorithm(LA)1
Imitation

Learning Algorithm(LA)2
Trial and error

Rate of LA 1 agents : 0.5

A community: x_{11} Imitation — x_{12} Trial and error



There exists 2 stable points areas

- PV rate convergences to about 0.39 (Linear area : left blue area)
- PV rate convergences (Nonlinear area : right blue area)

PV Dynamics with 2 Decision Model

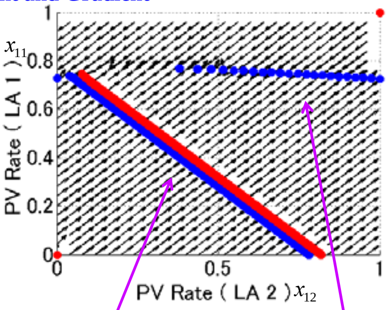
■ Stable and Unstable Point and Gradient

Stable point : ●
Unstable point : ●
Vector fields : →

Learning Algorithm(LA)1
Imitation
Learning Algorithm(LA)2
Trial and error

Rate of LA 1 agents : 0.5

Reallocation rate : $\mu = 0.005$

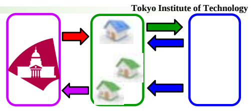


PV rate convergences to about 0.39 (linear area)
PV rate convergences from 0.42 to 0.87 (nonlinear area)

Progresses and Feature Works

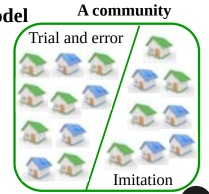
■ Progresses

- **Modeling considered Feed-In Tariff**
- **Analysis of the model**
  - Verifies of parameters (PV utility fee, PV power etc.)
  - Applying of decision model
- **Analysis of mixture model of 2 decision model**



■ Feature Works

- **Theoretical analysis of mixture of 2 decision model**
- Applying evaluation function to mixture model
- Applying new penalty for PV installer
- **Applying variance of parameters**
  - **PV panel cost** Experience curve
  - **PV utility fee** Difference between reference and present PV rate



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■Evolutionary Game

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