Promotion Dynamics Analysis of Photovoltaics Based on Feed-in Tariff

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FL 12-22-1

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Today's Topic (January 17th)

- Background and Objective
- Definition of Model
- Promotion Dynamics Analysis of PV
  (1 decision player in a community)
- (Promotion Dynamics Analysis of PV)
  (2 decision player in a community)
  (Note : Next group meeting)
- Summary

Introduction

Energy Problem[1]

- Stable energy supply
- Low emission
- Energy secure

+ Safety

New Resource of Energy

Photovoltaics : PV

Advantage

Self energy management

Disadvantage

High cost of PV panel

Output variability

Promotion Policy of Renewable Energy [2][3]

Feed-in Tariff (FIT)

PV for residential setting

Power Supply Company

It is important to balance between promotion PV and consumer's load

Objective

Objective of Research

Promotion Dynamics Analysis of PV

- Robustness against imbalance of PV
- Energy Secure (Self energy management)

Promotion of Photovoltaics

Problems

- Complex connections between agents
  ⇨ Promotive rate of PV
  Evolutionary Game[4]
- Variance of output
  ⇨ Risk function

Power variance

- High cost of PV
  ⇨ Reallocation for promotive PV

Parameters Based on Feed-in Tariff

Demand Side

All consumers : $n = n_1 + n_2$

Promotion Rate of PV

$$x_1 = \frac{n_1}{n}$$

PV : w_j [kWh] $(j = 1, \cdots, n_1)$

All PV : w [kWh]

$$w = \sum_{j=1}^{n_1} w_j$$

Demand : d_i [kWh]

$(i = 1, \cdots, n_1 + n_2)$

All Demand : d [kWh] $d = \sum_{i=1}^{n} d_i$

n_1, n_2

PV

PV + Mega-infra power

Supply Side

Power companies

Mega-infra power

$g = E[d - w]$ [kWh]

Parameters Based on Feed-in Tariff

Demand Side

PV profit : χ [yen]

Solar panel cost : $C_{PV\,panel}$ [yen]

Lifetime of solar panel : $y_{lifetime}$ [year]

Cost by power imbalance : c [yen/kWh]

$C_{PV}E[w_j]$

$(C_{GP} + \alpha)E[d_i]$

Supply Side

$$\chi = \frac{C_{PV\,panel}}{365 \times 24 \times y_{lifetime}}$$

[day] [h]

The value of PV : C_{PV} [yen/kWh]

Mega-infra fee : C_{GP} [yen/kWh]

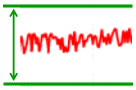
Additional fee : α [yen/kWh]

Power Imbalance Risk

Power balance : Load Frequency Control (LFC) [5]

$$|d-(w+E[d-w])| \le \epsilon E[d]$$

(Demand) – (Supply) Ability of power control



The value of ϵ : 0.01〜0.02 (1〜2%) [5]

If $|d-(w+E[d-w])| > \epsilon E[d]$, then power imbalance occurs

Assumption 1

- w_j and d_i are stochastic variables [6]
- $\{w_j\}_{j\in\mathcal{V}}$ and $\{d_i\}_{i\in\mathcal{N}}$ are independent and identically distributed
- Each w_j and d_i are independent

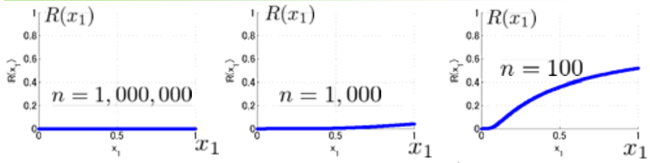
R : Probability of Power Imbalance

$$R = \Pr\{|w - n_1E[w_i]| > \epsilon n E[d_i]\} = \Pr\{\frac{|w-n_1E[w]|}{\sqrt{n_1}\sigma} > \frac{[d_i]}{\sqrt{n_1}\sigma}\}$$

$$\approx \frac{2}{\sqrt{2\pi}}\int_{\frac{\epsilon n E[d_i]}{\sqrt{n_1}\sigma}}^{\infty} e^{-\frac{t^2}{2}}dt = \mathrm{erfc}\left(\frac{\epsilon n E[d_i]}{\sqrt{2n_1}\sigma}\right)$$

PV rate increase, then risk increase

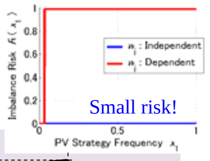
Process of New Imbalance Risk



It is too strong condition to assume independent of PV

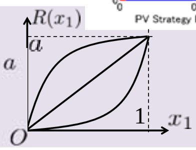
All PV generate power at same time :

⇨ Imbalance risk existed between and

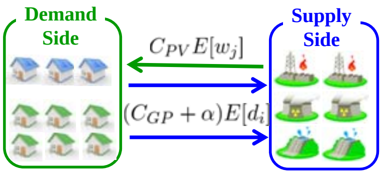


We define new risk function

$$\begin{cases} R_1(x_1) = -a(1-x_1)^2 + a \\ R_2(x_1) = ax_1 \\ R_3(x_1) = ax_1^2 \end{cases}$$



Utility of PV Installer and No PV Installer



Expectation Utility of PV Installer : $y(x_1)$

$$y(x_1) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i] + \chi - C_{PV}E[w_j]\}$$
$$-R(x_1)cE[d_i]$$

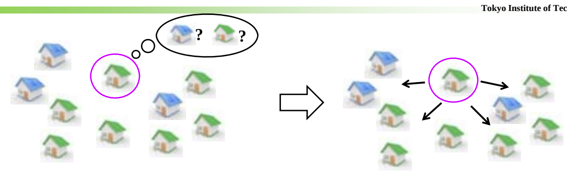
Demand → Supply ? ?

Expectation Utility of No PV Installer : $z(x_1)$

$$z(x_1) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i]\} - R(x_1)cE[d_i]$$

Demand → Supply

Promotion Dynamics of PV



Promotion Dynamics of PV (#)

$\dot{x_1} = (f_1(x_1) - \phi(x_1))x_1$ **If PV installation is better than average strategy, PV installation increases**

$f_1(x_1) = y(x_1)$ ($f_1(x_1)$: **Expectation of selecting strategy 1**)

$\phi(x_1) = y(x_1)x_1 + z(x_1)(1-x_1)$ ($\phi(x_1)$: **Average expectation**)

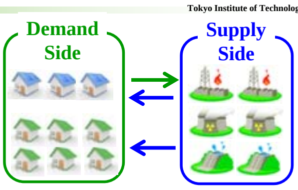
Promotion rate of PV : x_1 Expectation of PV installer : $y(x_1)$

Expectation of no PV installer : $z(x_1)$

Promotion Dynamics of PV

Promotion Dynamics of PV (#)

$$\dot{x_1} = (f_1(x_1) - \phi(x_1))x_1$$
$$f_1(x_1) = y(x_1)$$
$$\phi(x_1) = y(x_1)x_1 + z(x_1)(1-x_1)$$



Concrete Objective

Theoretic analysis between Imbalance Risk and PV promotion rate on promotion dynamics of PV (#)

Existence of stable points

$$(f_1(x_1)-\phi(x_1))x_1 = 0, \quad \frac{d((f_1(x_1)-\phi(x_1))x_1)}{dx_1} < 0 \quad (*)$$

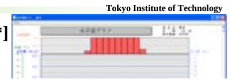
Existence of unstable points

$$(f_1(x_1)-\phi(x_1))x_1 = 0, \quad \frac{d((f_1(x_1)-\phi(x_1))x_1)}{dx_1} > 0 \quad (**)$$

Simulation of Promotion Dynamics (#)

Common Parameters Setting

Reference[*]



All consumer $n = 1,000,000$

PV power [*] $E[w_j] = 0.4268$ [kWh]

Reference[7]

Demand[7] $E[d_i] = 0.7336$ [kWh]

PV fee [**] $C_{PV} = 42$ [yen/kWh]

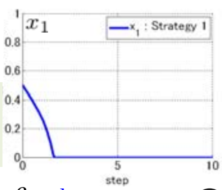
Reference[**]

Mega-infra fee $C_{GP} = 16$[yen/kWh]

Cost by power imbalance[8] $c = 1,000$[yen/kWh]

Solar panel cost $C_{PV\,panel} = 2,000,000$[yen]

Lifetime of solar panel $y_{lifetime} = 10$ [year]



Result (Note)

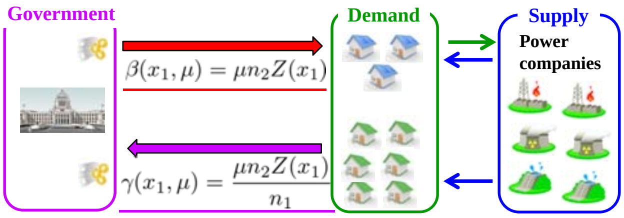
Dynamics(#) convergence only $x_1 = 0$ **or** $x_1 = 1$

(χ **is the dominated member**)

Next, We consider concrete reallocation β and γ

Reallocation Mechanism (Model 1)

Model of promotion Dynamics of PV with reallocation (Model 1)



$$Z(x_1) = ((1 - R(x_1)C_2 + R(x_1)C_4)$$
$$C_4 = cE[d_i]$$
$$C_2 = C_{GP}E[d_i]$$

Utility with Reallocation (Model 1)

Expectation Utility of PV Installer : $y(x_1,\mu)$

$$y(x_1,\mu) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i] + C_1\} - R(x_1)C_4 + \frac{\mu n_2 Z(x_1)}{n_1}$$

Demand ⬅ Supply ? Government ➡ Demand

?

$$C_1 = \chi - C_{PV}E[w_j]$$

Expectation Utility of No PV Installer : $z(x_1,\mu)$

$$z(x_1,\mu) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i]\} - R(x_1)C_4 + \mu Z(x_1)$$

Demand ⬅ Supply Demand ➡ Government

A Theorem of Model 1

Theorem1

Suppose that risk function is $R = R_1(x_1) = -a(x_1-1)^2 + a$.
Under the assumption of given x_1, the promotion dynamics of PV (##) has stable points iff the bellow condition of a is satisfied such that

$$0 < a < \frac{((2+A)x_1 - 4) + \sqrt{(A^2+8A)x_1^2 - 24Ax_1 + 16A}}{2(A-1)x_1(x_1-2)^2} \quad (1)$$

Sketch of Proof

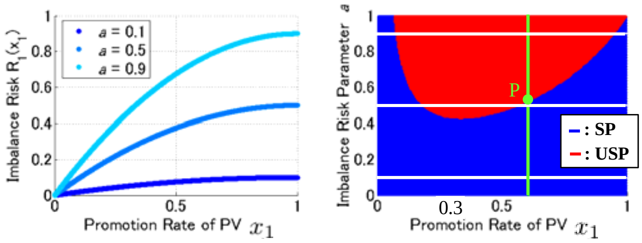
(##) can represent $\dot{x_1} = x_1(1-x_1)(y(x_1,\mu) - z(x_1,\mu))$
Calculating these inequalities (*), we can lead the above condition.

The inequality (1) says there are no relation between stable points and C_{PV}.
And we transform the inequality (1) and represent $A = c/C_{GP}$, then

$$0 < a < \frac{2}{x_1\left(\sqrt{((2+A)x_1-4)^2 + 4(A-1)(x_1-2)^2} - ((2+A)x_1 - 4)\right)}$$

The cost by power imbalance c prevents from promotion of PV

Simulation of Model 1 ($R=R_1$)



On simulation with common parameters (p. 10),

- **If we want to promote PV about 30% [1]** $(x_1 = 0.6)$ **in** $R = R(x_1)$ **a max of parameter** a **is under point P**

Summary (January 17th)

Summary

Promotion dynamics analysis of PV
(1 decision player in a community)

- **Formulation of Promotion dynamics of PV**
- **Derivation of the relation between a reachable PV rate and parameters**
- **Simulation**

Next (Group meeting on January 21st)

2 decision players in a community

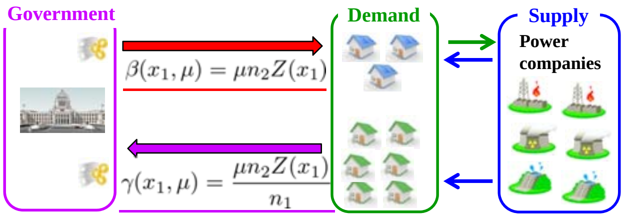
- **Formulation of Promotion dynamics of PV**
- **The promotion dynamics Analysis by simulation**

Today's Topic (January 21st)

- **Background and Objective**
- **Definition of Model**
- **Promotion Dynamics Analysis of PV (1 decision player in a community)**
  (Note : The contents of local group meeting)
- **Promotion Dynamics Analysis of PV (2 decision player in a community)**
- **Progress**

Reallocation Mechanism (Model 1)

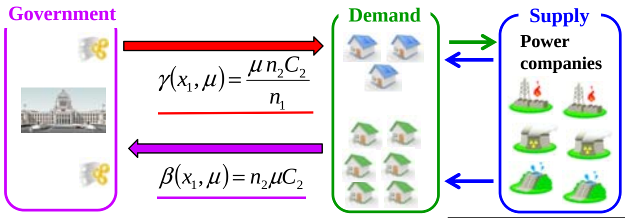
Model of promotion Dynamics of PV with reallocation (Model 1)



$$Z(x_1) = ((1 - R(x_1)C_2 + R(x_1)C_4)$$
$$C_4 = cE[d_i]$$
$$C_2 = C_{GP}E[d_i]$$

Reallocation Mechanism (Model 2)

Reallocation from no PV installer to PV installer



$(C_1 = \chi - C_{PV}E[w_j])$

Expectation Utility of PV Installer : $y(x_1,\mu)$

$$y(x_1,\mu) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i] + C_1\} - R(x_1)C_4 + \frac{\mu n_2 C_2}{n_1}$$

Expectation Utility of No PV Installer : $z(x_1,\mu)$

$$z(x_1,\mu) = -(1-R(x_1))\{(C_{GP}+\alpha)E[d_i]\} - RC_4 - \mu C_2$$

A Theorem of Model 2

Theorem4

Suppose that risk function is $R = R_1(x_1) = -a(1-x_1)^2 + a$.
Under the assumption of given x_1, the promotion dynamics of PV (##) has stable points iff the bellow condition of a is satisfied such that

$$0 < a < \frac{1}{x_1(4-3x_1)} \quad (4)$$

Sketch of Proof

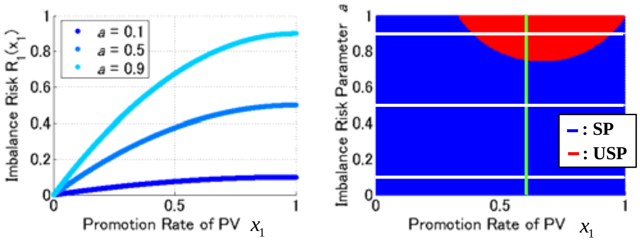
Same as sketch of proof about theorem1.

The inequality (4) says there are no relation between stable points and parameters C_{PV}, C_{GP}, c, and so on.

The minimum upper bound of a is 0.75 when x_1 equals 2/3.

$$\because \frac{1}{x_1(4-3x_1)} = \frac{1}{-3(x_1-2/3)+4/3}$$

Simulation of Model 2 ($R=R_1$)



On simulation with common parameters (p. 10) supposed that $R = R_1(x_1)$,

- **If we want to promote PV about 35% [1]**$(x_1 = 0.6)$ **(green line) , a parameter** a **is no constraint if** $a < 0.75$ **.**

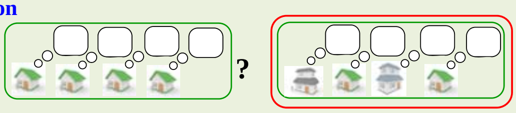
Percentage of demand power

$$0.35 \times \frac{E[d_i]}{E[w_j]} = 0.35 \times \frac{0.7336}{0.4268} \approx 0.60$$

Mixture of Strategies

Motivation

A community

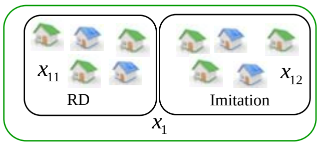


System

Mixture of 2 Learning Algorithms (LAs)

LA1 : Replicator Dynamics (RD)

LA2 : Imitation



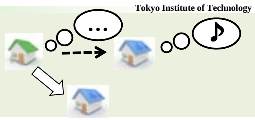
PV rate of LA1 : x_{11}
PV rate in LA2 : x_{12}
Rate of LA1 in a community : η
Imitation rate : r

PV rate of all consumers : $x_1 = \eta x_{11} + (1-\eta)x_{12}$

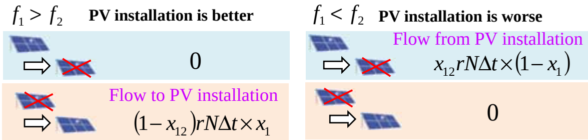
Imitation[9]

Decision Sequence

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



1. $f_1 > f_2$ **PV installation is better** $f_1 < f_2$ **PV installation is worse**



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

$$\begin{cases} N\Delta x_{12} = x_1(1-x_{12})rN\Delta t & (f_1 > f_2) \\ N\Delta x_{12} = -x_{12}(1-x_1)rN\Delta t & (f_1 < f_2) \end{cases}$$

r : Rate of doing imitation

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

$$\dot{x}_1 = \begin{cases} rx_1(1-x_{12}) & (f_1 \geq f_2) \\ 0 & (f_1 = f_2) \\ -rx_{12}(1-x_1) & (f_1 < f_2) \end{cases}$$

Imitation (Most easily model)

Simulation Setting

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Promotion Dynamics of PV (mixture of LAs)

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

$$\text{LA1}: \dot{x}_{11} = x_{11}(1-x_1)(y(x_1,\mu) - z(x_1,\mu))$$

$$\text{LA2}: \dot{x}_{12} = \begin{cases} r x_1 (1-x_{12}) & (y(x_1,\mu) > z(x_1,\mu)) \\ 0 & (y(x_1,\mu) = z(x_1,\mu)) \\ -r x_{12}(1-x_1) & (y(x_1,\mu) < z(x_1,\mu)) \end{cases}$$

Utility of PV installer : $y(x_1,\mu)$ ← Same as p. 19

Utility of no PV installer : $z(x_1,\mu)$

x_{11} : PV rate of LA1
x_{12} : PV rate in LA2
η : Rate of LA1 in community
r : Imitation rate

Concrete Objective

analysis between Imbalance Risk and PV popularization rate on promotion dynamics of PV (###) by simulation $\left(x_1 = [x_{11} \quad x_{12}]^T\right)$

Existence of stable points

$$\dot{x}_1 = 0, \quad \frac{d\dot{x}_1}{dx_1} = \begin{bmatrix} \partial \dot{x}_{11}/\partial x_{11} & \partial \dot{x}_{11}/\partial x_{12} \\ \partial \dot{x}_{12}/\partial x_{11} & \partial \dot{x}_{12}/\partial x_{12} \end{bmatrix} < 0 \qquad (***)$$

Simulation of Promotive Dynamics (###)

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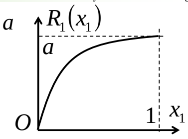
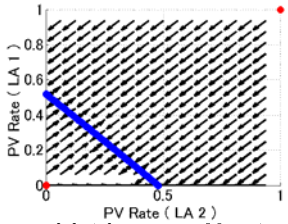
- Risk of Imbalance : $R(x_1) = R_1(x_1) = -a(1-x_1)^2 + a$
- Imitation rate : $r = 0.001$
- Rate of LA 1 agents : $\eta = 0.5$
- **Common parameters are same as p. 10**
- **Model 2 is used**





$x_1 = 0.0, 1.0$ **are unstable points**

There are linear shaped stable points

Stable point : ●
Unstable point : ●
Vector fields : →
Learning Algorithm(LA)1 Replicator Dynamics
Learning Algorithm(LA)2 Imitation
Reallocation rate : $\mu = 0.1$
Risk fun. parameter : $a = 0.1$

Changes of Reallocation Rate

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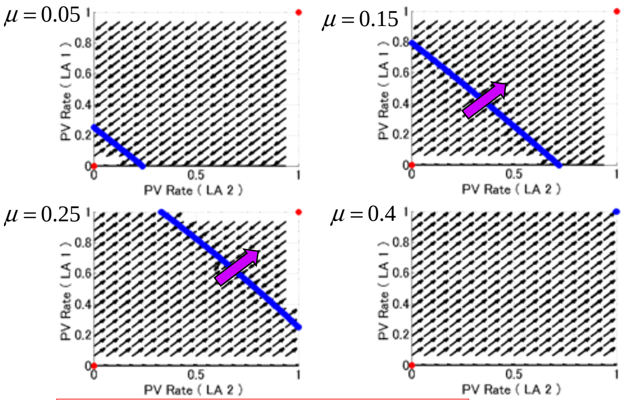

A parameter μ relates the total PV rate x_1

Changes of Imbalance Risk Parameter

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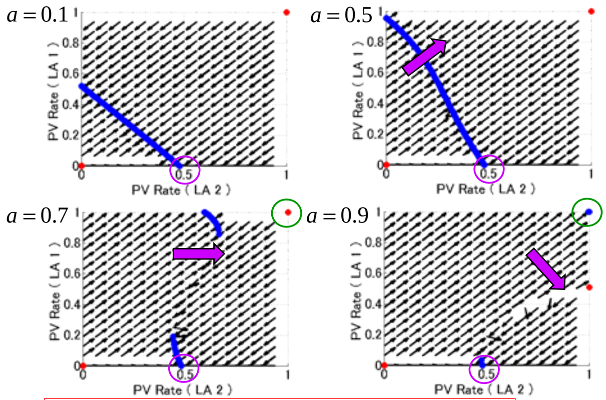

A parameter a relates the shape of stable points

Distribution of promotive rate of PV

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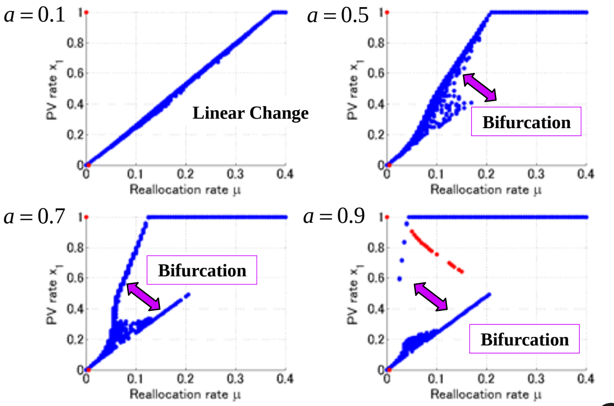

Comparison of 1 Decision Model

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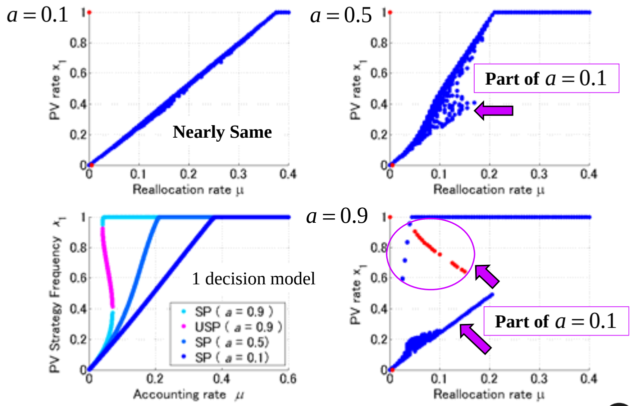

Summary (January 21st)

Summary

Promotion dynamics analysis of PV

- **1 decision player in a community**
  - **Formulation of Promotion dynamics of PV**
  - **Derivation of the relation between a reachable PV rate and parameters**
  - **Simulation**

- **2 decision players in a community**
  - **Formulation of Promotion dynamics of PV**
  - **The promotion dynamics Analysis by simulation**

Feature Works

- **More than 3 strategy**
- **Derivation of parameter's relation about promotion dynamics with 2 decision players in a community**

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