Self-organization Model for the Formation of Distributed Energy Network

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1. Overview

Recently, Japan witnessed a serious nuclear power plant accident, owing to which a large amount of CO_2 from thermal power plant was emitted into the atmosphere. Given the background of this unfortunate event, at present, there is a need to increase the generation of photovoltaic (PV) power from the viewpoint of saving electricity and reducing the CO_2 emission. Therefore, in order to meet this requirement, the legal support required for purchasing the total amount of power generated and for granting the subsidies on PV power generation have been established. Moreover, the Japanese government aims to introduce 53 million kW of PV power in 2030. However, the following technical problems occur when a large amount of PV power is introduced at one time: (1) disparity between the supply and demand for electricity, (2) increase in voltage, and (3) destabilization of frequency.

One possible way of solving such technical problems is to use a smart grid technology which is one of the countermeasures to reduce the influence on grid. Moreover, it is necessary to introduce a large number of PV batteries to manage the surplus PV electricity. It should be noted that a distributed energy supply system is expected to reduce both the battery capacity and the influence on grid.

The distributed energy network system consists of a network in which electricity and heat can be transferred between the distributed generators and the renewable energy resources, and it can supply stable energy to an urban district. From a long-term point of view, it is thought that it will be difficult to maintain consistency in terms of purchasing the total generated PV power in the case when a large number of PV systems are to be introduced. In addition, the distributed energy system is introduced at random and can be randomly updated by the consumers. Therefore, facilities connected to the distributed energy network will always fluctuate. It is desirable that an optimal energy network emerges while the energy facilities are being constantly updated.

Living organism and ecosystem are the example that acquired overall stability and the optimality by local interaction. In the ecosystem, an example of an optimum energy network is a colony populated by living organisms. It is essential for self-organized distributed energy systems such as the “energy colony” shown in Fig. 1 to have high stability and robustness. Carreras et al.(1) studied techniques based on a biological approach to develop a hierarchical energy network, which is also known as an energy web.

The Turing model that is famous for the formation of swarm of animal and the formation of the

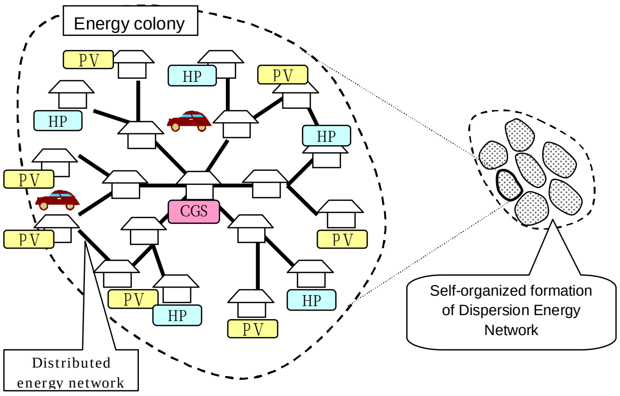

Fig.1. Outline of energy colony

living body design shows that various pattern forms by the interaction of activate factor and inhibitor factor.(2) Concerning PV,CGS (cogeneration system) and HP (heat pump system) in the energy network, various relation are formed such as PV with HP which consumed surplus supply of PV electricity, CGS and PV which absorb night electricity of CGS, and CGS with HP which compete to supply heat. These relations indicate the interaction of activate factor and inhibitor factor, and it is thought that the possibility that a specific pattern (energy colony) is formed for equipment installation

2. Objective

In this study, we constructed a self-organization model for the formation of a distributed energy network. Our model is a type of a multi-agent system, where each distributed energy system (e.g., a fuel cell cogeneration system (CGS), heat pump (HP) system, and photovoltaic (PV) system) installed in a house is considered to be an agent. In addition, we simulated a scenario where it was possible to create a self-organizing energy colony with coexistence and competing relation of the distributed energy systems.

We also showed that the multi-agent model, which has rules for introduction of energy facilities (CGS, HP, PV, and conventional system), could realize the following three functions.

1) It could exchange energy between adjacent houses, where the surplus energy was consumed by an urban district.
2) It could form an energy colony by self-organization.
3) Its robustness increased with the formation of an energy colony.

In addition, although various types of distributed energy network are considered, we assumed the block space only houses existing in this study. The energy facilities of the house regarded four kinds of facilities as PV, HP, CGS and conventional system. We do not think about battery and the battery of the electric car. Considering cooperation of these 4 type energy facilities, we thought the possibility of stabilization of the energy supply of the block. Example cooperation is as follow, surplus PV electricity and conventional facilities, electricity of CGS and PV electricity in the case of bad weather. Figure 2. shows the outline of block targeted for an evaluation. In addition, we assign limitation not to be able to sent electricity only adjacent or nearby agent. Generally, the exchange of the electricity is carried out using power transmission line, and there are not limitations to transmit electricity to the adjacent only. On the other hand, considering about real electricity grid, the exchange with the away agent interval is not realistic, and it is thought that the electricity exchange is more likely to be gathered in a restrictive district. From the original point of view of the dispersion energy network which does not affect grid, it is realistic to constitute a colony each small consumers group and hierarchize these colonies.

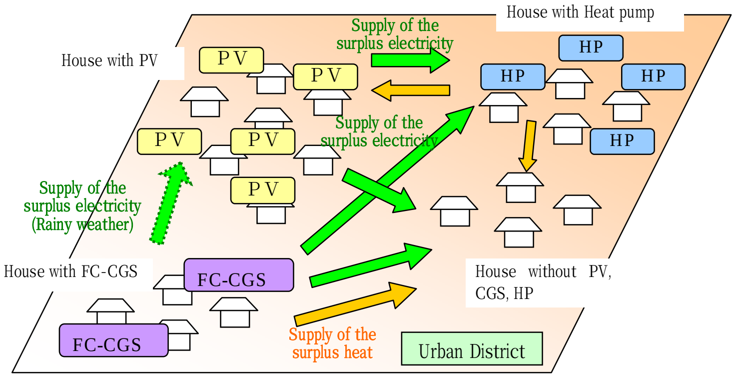

Fig.2. Distributed energy network system used in study

3. Methods

3.1 Simulation field

As shown in Figure 3, we used a triangular mesh space to denote a model of a city block.

3.2 Elements of simulation

The attributes of a house placed in each mesh include the types of energy facilities installed within the house and the age of the facilities. The following four types of energy facilities are installed in a particular house (figure 4).

1) House installed conventional system (that includes the purchased electricity power, a heat pump air conditioner, and a gas water heater .)
2) House installed PV system that includes (PV, purchased electricity power, a heat pump air conditioner, and a gas water heater.)
3) House installed HP system that includes the purchased electricity power, a heat pump air conditioner, and a heat pump water heater.)
4) House installed CGS that includes several (fuel cells, CGS a heat pump air conditioner, and a gas water heater).

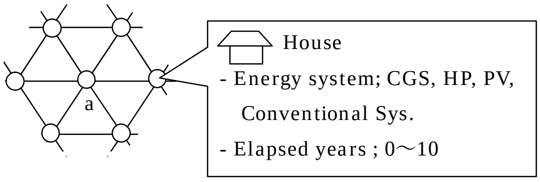

Fig.3.Triangle grid model

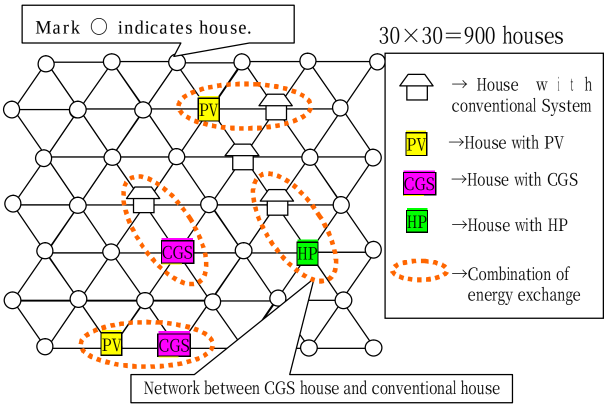

Fig. 4. Model of city block

3.3 Energy supply and demand model

In the case of evaluating local optimum energy network model, we have to considered following factors.

- Energy demand of houses (difference of seasons, hourly difference of day)
- Capacity of energy equipment (CGS, HP and PV system)
- Range of energy network
- Electricity generation of PV system (surplus of electricity, shortage of electricity of house)

However, we modeled it as follows because model was complicated when we considered all these factor.

1) We only considered the combination of energy facilities, not considered the detailed facilities capacity and hourly energy demand. If there is specific facilities pair on adjacent mesh space, we assumed that energy exchange is established without electricity surplus and shortage. For example, if there are one PV systems house and two conventional houses, electricity surplus is consumed between this combination.

2) We assumed that energy exchange range is only adjacent cells. PV house can send surplus electricity to 6 adjacent cells, and conventional house or HP houses can receive electricity and heat from adjacent house (PV or CGS house). Indeed there is no restrict to exchange energy between adjacent houses in real grid, but it is preferable to consume electricity in small district from the view of electricity loss of the transformer substation and ease of the information processing.

3) In the case of CGS, we assumed that we can supply electricity and heat to distant cells. We expressed the range that could supply electricity and heat of CGS with a potential level in these models. Potential level P obeyed an expression (1) of the following normal distribution around CGS (figure 5). The electricity potential set it to be more extensive than heat potential. The standard setting of parameter f assumed it 0.07 at the time of electricity potential calculation, the f=0.04 at the time of heat potential calculation.

$$P = \frac{1}{\sqrt{2\pi}} \exp\left(- \frac{(fx)^2}{2} \right) \qquad (1)$$

x : distance from CGS

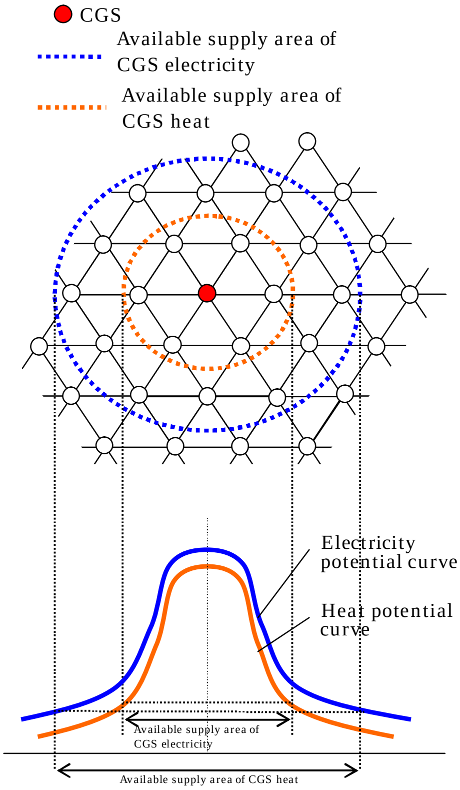

Fig.5. Outline of potential fields of electricity and heat

We supposed that electricity and heat from CGS could be supplied in the range of mesh that potential level is more than specific threshold. Threshold is the vale from 1 to 10, which is divided potential level into 10 parts between the maximum – minimums vale. Standard threshold is as follow.

Electricity threshold = 2
Heat threshold =2

3.4 Multi agent model

We assumed that the house existing on each mesh was an agent. The facility of the next step was determined by the state of the central cell itself and the states of the six neighboring cells. In the case when the age of the facilities installed in the house was 10 years, each agent (house) was supposed to update either of the abovementioned four types of facilities. The choice of the type of facilities depends on an introduction rules. On the basis of this rule, facilities are selected depending on the number of adjacent facilities. Generally the detailed facilities capacity or load data of the adjacent house are unidentified, but it is possible to know facilities kinds in the update of the real equipment of a house. Thus it is proper to judge from the kind of facilities.

3.5 Agent action rules

Rule of facility replacement is the rule to be decided on potential level (electricity and heat) and the facilities kind of the adjacent house. By dividing electricity and heat potential level into two each, we can divide the energy supply field into four domain (I - IV) to show it in Figure 6. Domain I is the area that electricity and heat supply possibility of CGS is low together, and domain II is the area that only CGS electricity is supplied to, but heat is not supplied to, domain IV are the domains where electricity and heat of CGS is supplied. We made the facilities update rules in each domain showing in Table 1. In our model, replacement of facilities is judged only by the replacement rules, thus it was not used evaluation function.

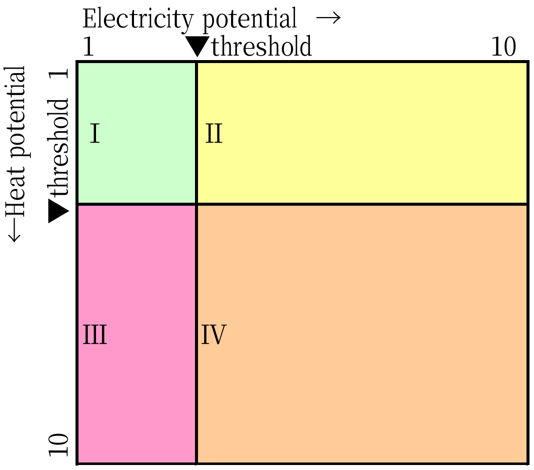

Fig.6. classification of potential fields

Table 1. Standard rules of replacement of facility

	Number of facility of adjacent mesh	Renewal facility	Classification of potential fields	Explanation of rule
1	CGS=0 & HP=0 & PV=0	CGS	Ⅰ	If electricity / heat potential are low level and if adjacent mesh are only conventional facility, CGS is introduced.
2	CGS=0 & HP= indefiniteness & PV= indefiniteness	HP	Ⅱ	If heat potential are low level and if adjacent mesh are not CGS, HP is introduced.
3	CGS=0 & HP=0 & PV≧4	HP	Ⅰ	If electricity / heat potential are low level , if adjacent mesh are not CGS, HP and if PV are more than 4, HP is introduced.
4	CGS=0 & HP≧2 & PV= indefiniteness	PV	Ⅰ Ⅲ	If electricity potential is low level , if adjacent mesh are not CGS and if HP are more than 2,PV is introduced.
5	Conventional facility≧1 & Conventional facility≦3	PV	Ⅰ Ⅱ Ⅲ Ⅳ	If adjacent mesh are 1 -3 conventional facility, PV is introduced.
6	CGS= indefiniteness & HP= indefiniteness & PV= indefiniteness	Conventional facility	Ⅳ	If electricity / heat potential are high level , conventional facility is introduced.
7	CGS=0 & HP=0 & PV≧2	Conventional facility	Ⅰ Ⅲ	If electricity potential is low level , if adjacent mesh are not CGS, HP and if PV are more than 2, conventional facility is introduced.

- CGS : fuel cell cogeneration system, HP : heat pump system, PV : photovoltaic

3.6 evaluation indicator

We made the two evaluation indicators to indicate the amount of energy exchange in the simulation field.

Evaluation indicator of fine weather: The total number of combinations of facilities that the following conditions are concluded.

1) the number of conventional facilities which is in 3 neighborhood mesh of CGS and is in the domain that electricity, heat potential are more than threshold.
2) the number of HP facilities which is in 3 neighborhood mesh of CGS, and is in the domain that electricity potential are more than threshold and heat potential are less than threshold.
3) the number of PV and adjacent conventional facilities other than condition 1).

Furthermore, when the PV generation output decreases such as at the time of rainy weather, it is desirable to put up the output of CGS in the energy network, and makes up for decline of the PV output, and reduce the electricity change of grid. We made one more indicator to evaluate at the rainy weather condition.

Evaluation indicator of rainy weather: The total number of combinations of facilities that the following conditions are concluded.

1) the number of PV, HP and conventional facilities which is in 6 neighborhood mesh of CGS.

4. Results

Our simulation results indicated that it was possible to achieve stable energy exchange when an energy colony was formed in a district under specific parameters. Figure 7 shows an example of the simulation result. In this figure, each facility is denoted by a different-colored circle. Conventional facilities (black circles) are distributed around the CGS (red circles), whereas the PV system (yellow circles) and the HP system (green-circles) are distributed around the conventional facilities. This result indicated that the colony of facilities is emergent with some introduction rules.

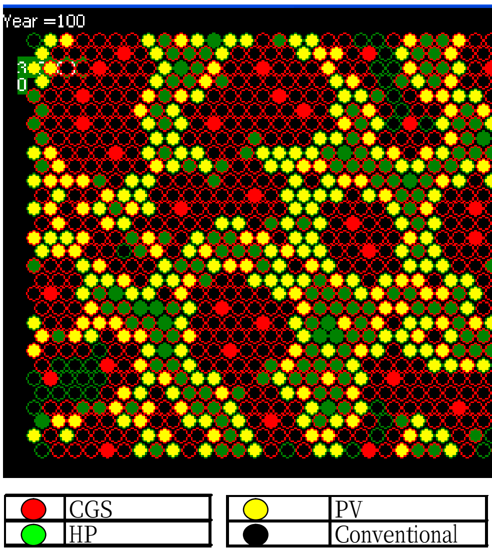

Fig. 7. Example of the simulation result

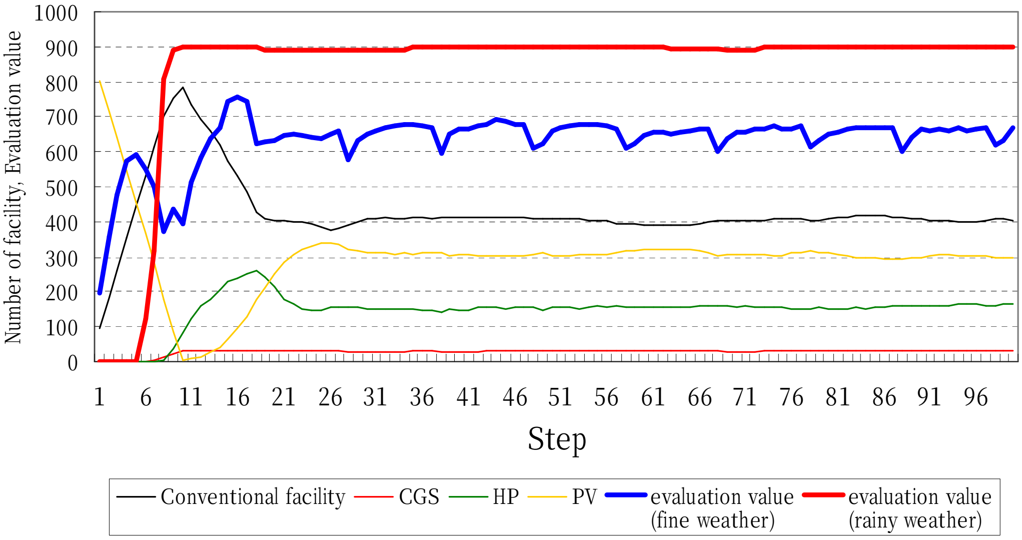

Fig.8. Facility number with standard rules

Figure 8 shows the number of facilities and evaluation indicators of each step. The number of each facility fluctuates to 30 steps greatly, but approximately constant composition ratio after it was observed. It is indicated that the colony showing in figure 7 formed in 30 years in the case of 10 years replacement interval. Because the normal facilities update is about for 15-20 years, a long period is necessary for colonization. On the other hand, it is thought that we can form colony early to use some policy when the form of the colony is clear.

In addition, it is understand that an evaluation index is 600-700 (at the time of fine weather), and evaluation index (at the time of rainy weather) is around 900 after 30 step that facilities composition ratio was constant. From this results, we understand that the energy exchange with the adjacent house can realize about around 600-700 among 900 houses at the time of the fine weather. On the other hand, from the evaluation index (at the time of rainy weather), almost all houses could be received energy supply by CGS. This is enabled by the colony that the CGS being distributed uniformity.

Figure 9 and Figure 10 show the results when parameter f at the time of the potential calculation changed. Other conditions are same as standard conditions. From definition of parameter f, when f grows big, the high potential range becomes small. In figure 9, the density of CGS increases and existence area of PV and HP becomes small, when parameter f of the electricity potential became big so that electric power supply range by CGS becomes small. In the case of f=0.06, only CGS can hardly exist. In figure 10, the density of HP increases and existence area of CGS and conventional houses becomes small, when parameter f of the heat potential became big so that heat supply range by CGS becomes small.

Figure 11 shows the number of the facilities in the facilities distribution map showing in Figure 9, figure 12 shows the evaluation values according to parameter f.. This result shows that the evaluation index (at the time of fine weather) grows big when electricity potential parameter f are increased, and evaluation value is closer to an approximately constant value when facilities colony is formed. This evaluation value is the value of 100 step, and this value fluctuates each step. So it is difficult to specify the optimum parameter value. We can say that the evaluation value rises when the colony is formed.

. The case of f=0.07 was the result of only CGS distribution, and the evaluation value is as same as the value of colony formation. This CGS distribution is not desirable facilities distribution from the viewpoint to reduce the output change with mass PV introduction.

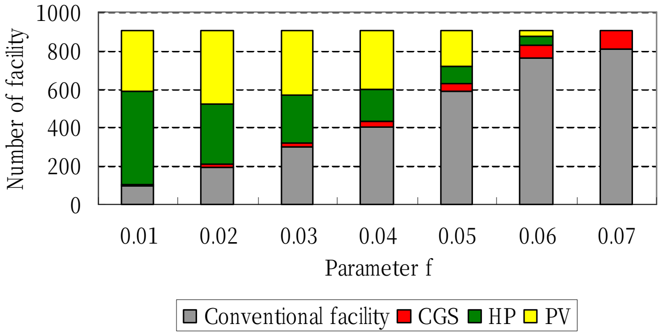

Fig.11. Facility number by parameter f of the electricity potential formula (at the time of 100 steps)

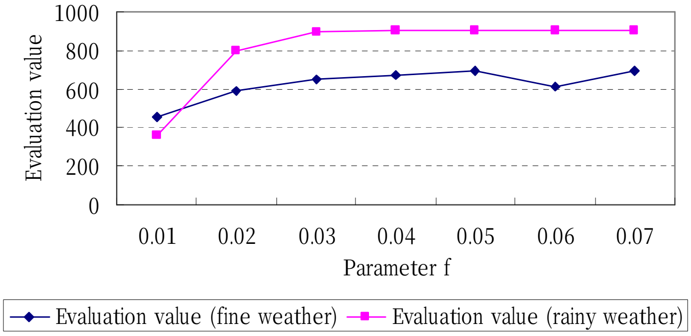

Fig.12. Evaluation values by parameter f of the electricity potential formula (at the time of 100 steps)

Figure 13 shows the number of the facilities in the facilities distribution map showing in Figure 10, figure 14 shows the evaluation values according to parameter f.. This result shows that the evaluation index (at the time of fine weather) grows small when heat potential parameter f are increased, and evaluation value is around 600 – 700 when facilities colony is formed. The case of f=0.04 was the result of only CGS distribution, and the evaluation value is highest than the value of colony formation. This single CGS distribution is not desirable facilities distribution from the viewpoint to reduce the output change with mass PV introduction.

These result indicated that the colony of facilities is emerged with some introduction rules and the balance of supply area of electricity and heat potential of CGS. Self organized colony was emerged under the situation of random facilities replacement, and was maintained the constant composition ratio of facilities kind with some facilities replacement rules. These distributed colony is desirable under the condition of rainy weather.

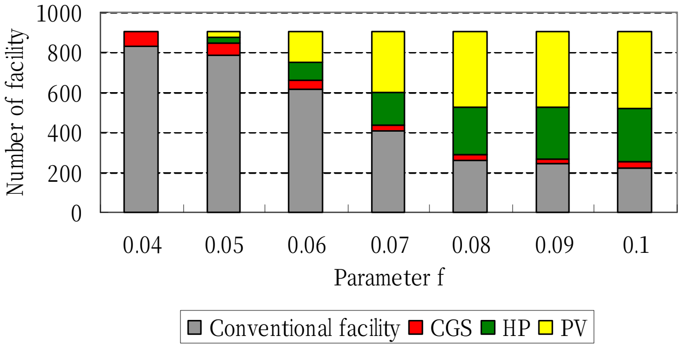

Fig.13. Facility number by parameter f of the heat potential formula (at the time of 100 steps)

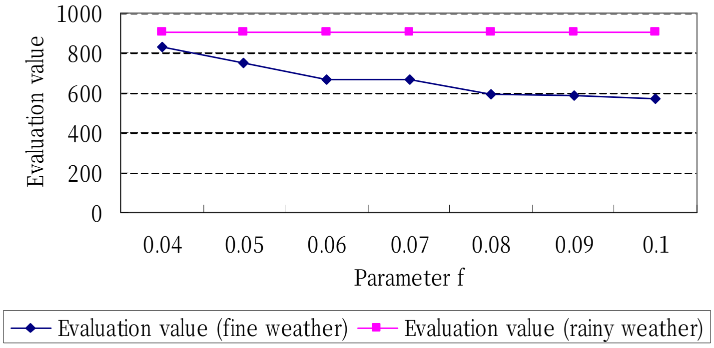

Fig.14. Evaluation values by parameter f of the heat potential formula (at the time of 100 steps)

5. Conclusion

Our computer model shows the possibility of self organized energy colony with the interaction of some kinds of energy facilities. These colony formation provide the relatively high frequency energy exchange in the urban district. Thus it is thought that the introduction of the biological swam formation into the energy network is connected for new sociotechnological frontier and it is enable to construct higher society systems.

References

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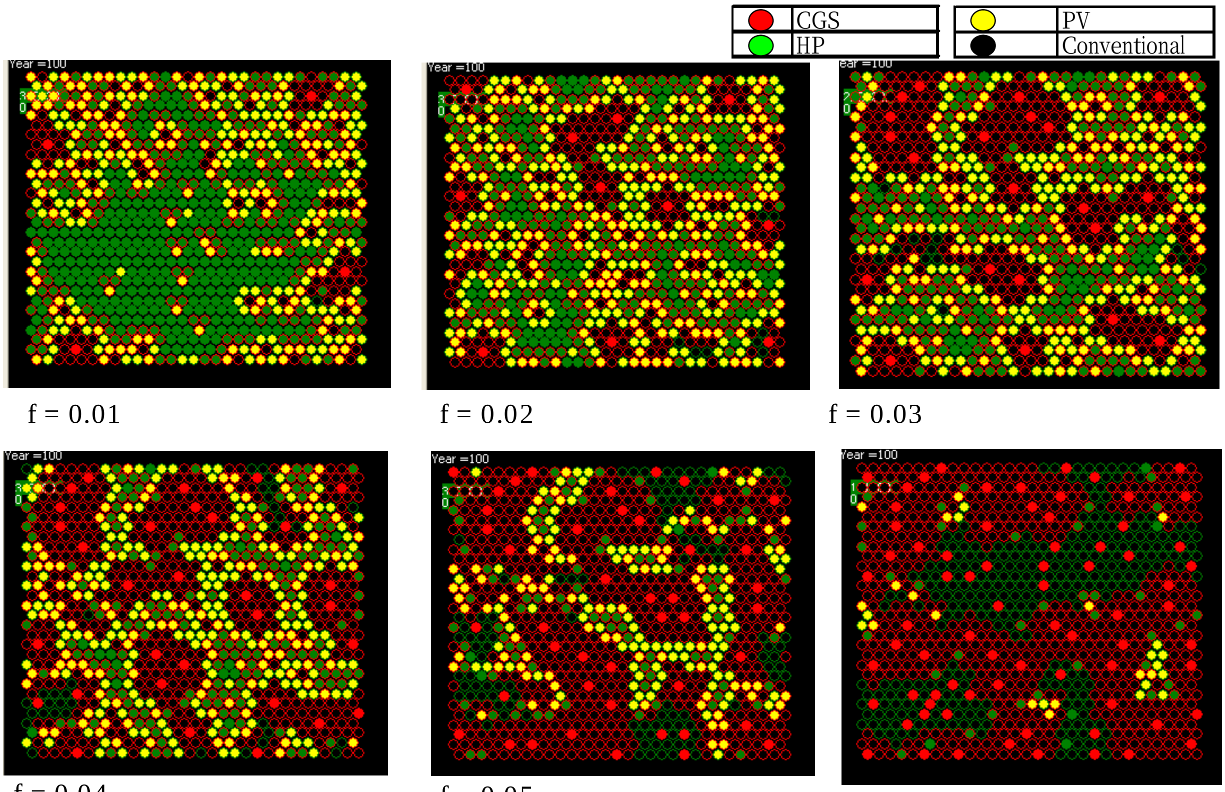
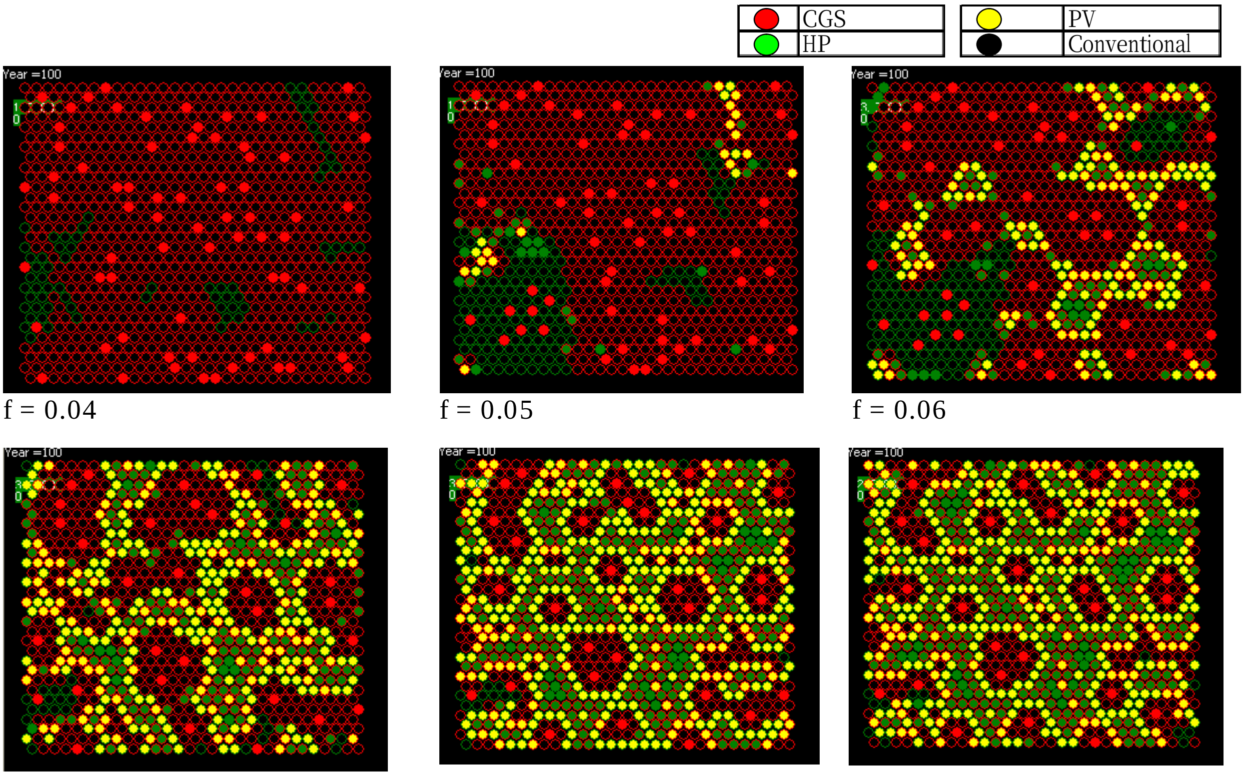


f = 0.01　f = 0.02　f = 0.03

f = 0.04　f = 0.05　f = 0.06

Fig.9. Result by parameter f of the electricity potential formula (at the time of 100 steps)



f = 0.04　f = 0.05　f = 0.06

f = 0.07　f = 0.08　f = 0.09

Fig.10. Result by parameter f of heat potential formula (at the time of 100 steps)