# Energy network designs and a hydrogen energy community growth scenario based on networking stationary fuel cells


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## Abstract

Almost all the hydrogen energy roadmaps of the IEA member countries are based on mainly disseminating hydrogen vehicles and stations. According to their roadmaps, it is necessary to deploy widespread hydrogen stations as road transport infrastructure. While in May 2009 in Japan, stationary fuel cells (residential CHP systems) were launched as commercial products and have been installed over ten thousands sets by the end of March 2011.

In this paper, the authors propose some energy network designs and a hydrogen energy community growth scenario based on networking stationary fuel cells in residential areas.

The first we propose a concept of energy network interconnected stationary fuel cells, and classify the types of Energy Community (EC) in which electricity, heat (hot water) and hydrogen are networked proportional to the residential areas. Focusing our scope on detached houses, we design some energy network models of Micro-scale EC through mathematical optimization, system simulation and acceleration experiment. The performance of the eight houses' network model indicates carbon dioxide mitigation is more than 6% and primary energy reduction is more than 15% as compared with single fuel cell installation in each house.

The second we make a hydrogen production and distribution model for Small-scale EC in residential areas and build up a hydrogen energy community growth scenario from Micro-scale ECs to Small-scale EC. At the final stage of this scenario, the performance prediction indicates the Small-scale EC achieves carbon dioxide mitigation over 3% as compared with single fuel cell installation.

## 1. Introduction

Almost all the hydrogen energy roadmaps of the International Energy Agency (IEA) member countries are based on mainly disseminating hydrogen vehicles and hydrogen stations [1-2]. According to these roadmaps, it is necessary to deploy widespread hydrogen stations as road transport infrastructure, such as 400 small H2 stations in EU Hyways countries [1], 50 H2 stations in California State of US [3], and 100 H2 stations in Japan [4] by 2015. While in May 2009 in Japan, stationary polymer electrolyte fuel cells (residential CHP systems) were launched as commercial products and have been installed over ten thousands sets by the end of March 2011 [5-6].

In this paper, the authors propose a concept of energy network interconnected stationary fuel cells, classify the types of energy network in residential areas as Energy Community (EC), and design some energy network models of Micro-scale EC through three research approaches. The performance of the Micro-scale EC is compared with single fuel cell installation in each house with regard to carbon dioxide mitigation and primary energy reduction.

Modeling hydrogen production and distribution of Small-scale EC in residential areas with its configuration, this paper indicates a hydrogen energy community growth scenario from Micro-scale ECs to Small-scale EC. At the final stage of this scenario, the performance prediction of the Small-scale EC is compared with single fuel cell installation.

## 2. Concept of energy network

The basic concept of energy network implies not only interconnecting stationary fuel cells but also aggregating energy demands in local residential area, and achieves load leveling from the point of external energy supply.

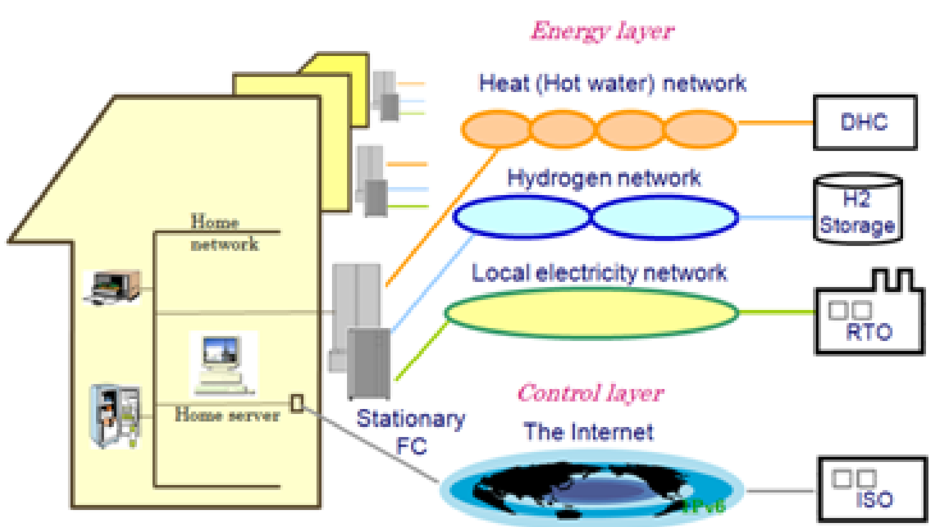


Fig. 1 Concept of energy network

### *2.1 Concept of energy network*

Energy network is composed of two layers, energy layer and control layer. The energy layer has local electricity, heat (hot water) and hydrogen network as energy carriers, and the control layer is the Internet connected to stationary fuel cells or home networks as shown in Fig. 1.

The local electricity network is a micro-grid connected to electrical grid, the heat network is hot water pipelines linked between adjacent houses, and the hydrogen network is gas distribution pipelines installed within Energy Community (described in chapter 3) with stationary fuel cells in residential areas.

### *2.2 Residential CHP system and energy demand*

A commercial stationary fuel cell is composed of reformer, fuel cell stack (polymer electrolyte fuel cell), waste heat recovery unit and hot water tank, therefore as a residential CHP system, there have been some serious problems between its specifications and residential energy demands as follows;

*Electric power output and average demand*

In the case of 1 kW-type fuel cell, the output power range is from 0.3 kW to 1.0 kW, but the average load of Japanese home is below 0.4 kW. The backward flow from residential fuel cell to electrical grid is inhibited in Japan. The commercial fuel cell is not capable of achieving its full capacity under Japanese regulation.

*Heat to electric power ratio*

The heat to electric power ratio of commercial stationary fuel cell is fixed 1.41 or 1.25 [7]. On the other hand, the ratio of most Japanese home demands varies from 0.3 in summer to 1.5 in winter drastically. It depends on mainly water temperature. The commercial fuel cell cannot work sufficiently throughout the year.

*Dynamic characteristics and power consumptions*

The output power of fuel cell stack can change 1 kW within a second, but that of commercial fuel cell varies only 1 W per second because of the dynamic characteristics of reformer. The commercial fuel cell cannot follow steep load fluctuations, such as the load of microwave oven.

As mentioned above, the dissemination of commercial stationary fuel cells in residential areas will be restricted inherently. From the point of distributed energy resources (DER), it is necessary to separate the functions of stationary fuel cell, such as reformer, fuel cell stack and hot water tank.

### *2.3 Aggregation effect of energy demand*

Main objective of energy network is aggregating energy demands in residential areas, and it means load leveling in local residential area.

In Japan, electricity and hot water demand account for more than 70% of household total energy demands. Fig 2 shows a part of residential energy survey of three homes and the average electricity and hot water demand of ten homes for three days in summer and winter.

The average demands indicate that aggregating energy demands of about ten homes is sufficient to level the electricity load and hot water load.

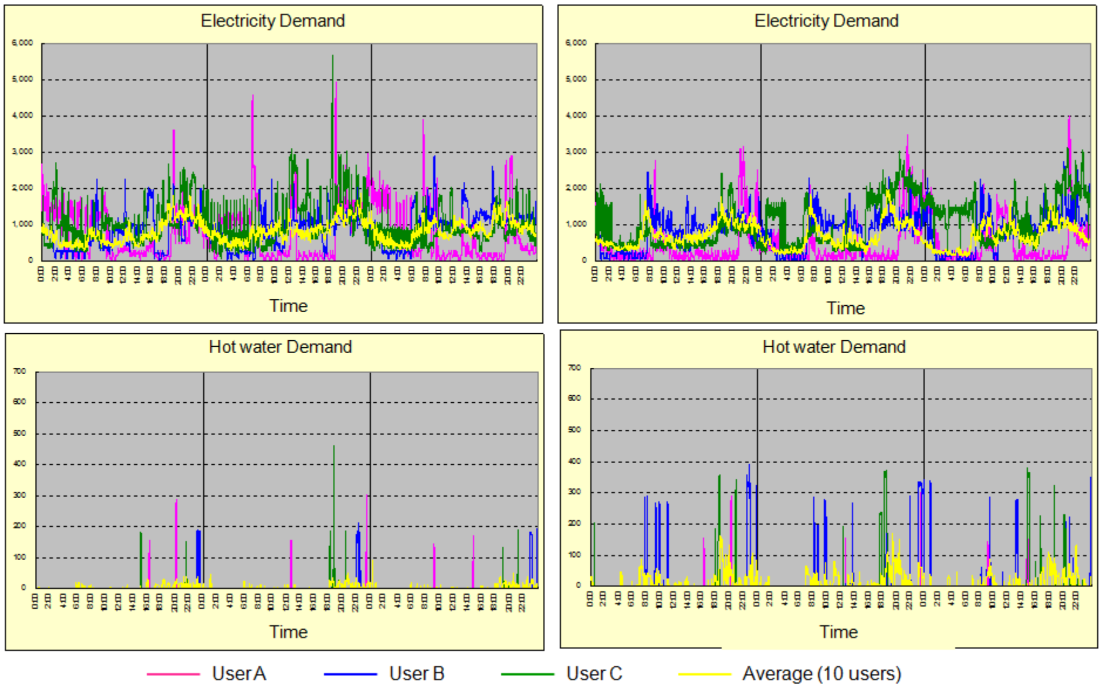


Fig 2 Average electricity demands and hot water demands for three days
(Left side in summer, Right side in winter)

## 3. Energy Community

Considering the characteristics of electricity, hydrogen and hot water as energy carriers, the authors classify the types of energy network in residential areas as Energy Community. Fig. 3 shows the classification of Energy Community, and is one of the results of our research.

### *3.1 Classification of Energy Community*

In terms of building structure, Energy Community is classified as detached house type and apartment house type, and is categorized as Micro-scale, Small-scale, and Residential Energy Community (EC) in terms of energy networking area.

Micro-scale EC, from three to eight detached houses or one floor in apartment building (up to ten homes), is networking all three energies, electricity power, hydrogen gas and hot water.

Small-scale EC, expanding in scale of Micro-scale EC, about two hundreds detached houses or one apartment building (up to one hundreds homes), is networking electricity power and hydrogen gas.

Residential EC, expanding Small-scale EC, combining detached houses with apartment buildings summing up about one thousand houses, is networking only electricity power under the same distribution line.

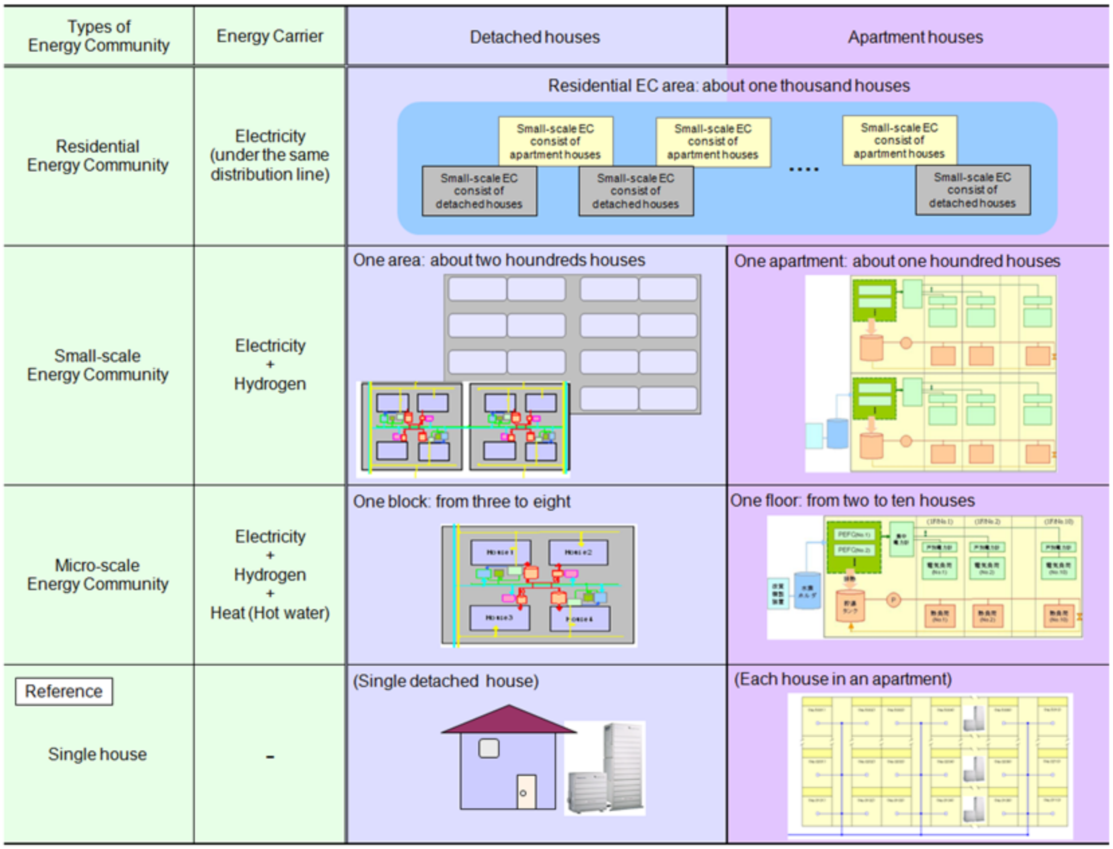


Fig. 3 Classification of Energy Community in residential areas

### *3.2 Scope of research*

In this paper, focusing research scope on Micro-scale EC and Small-scale EC of detached house type, the authors design some energy network models of Micro-scale EC through three research approaches, and build up a transition scenario from Micro-scale EC to Small-scale EC.

## 4. Research approaches for energy network design

To design the energy networks of Micro-scale EC, the authors take three research approaches, system simulation, acceleration experiment and mathematical optimization interactively [8-9].

### *4.1 Outline of research approaches*

The outlines of newly developed system simulator, experimental system and mathematical programming are described below.

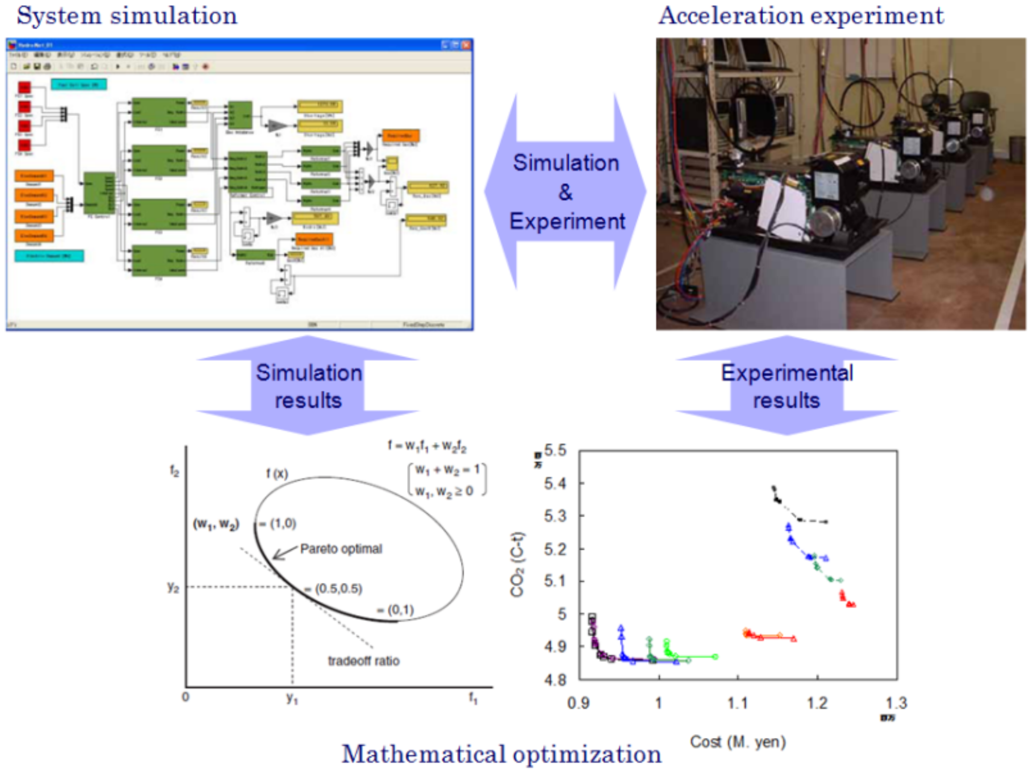


Fig. 4 Relationship among system simulation, acceleration experiment and mathematical optimization

*System simulator*

This is the computer simulator based on MATLAB and SIMULINK, modeling the energy networks of Micro-scale EC, interpolating each fuel cell's characteristics and operation algorithms, extrapolating electricity and heat demand data. Simulation results indicate the energy network performance and evaluate the operating algorithms.

*Experimental system*

This is the four fuel cells interconnected system with corresponding electronic load resistors for Micro-scale EC, interpolating network operation algorithms, extrapolating electricity and heat demand data. Experiment results verify the predictions of simulation partially.

*Mathematical programming*

This is the mathematical optimization modeling the energy networks of Micro-scale EC and setting the objective function under some constraints. The objective function is to minimize the total value of energy bills and carbon dioxide emissions for a year. The mathematical programming results give optimum numbers of fuel cell and reformer for Micro-scale EC.

*4.2 Interactive approaches*

Using the mathematical optimization results, various system simulations and acceleration experiments are performed alternately for specifying energy network design and operation algorithm of Micro-scale EC.

Fig 4 shows the relationship among system simulation, acceleration experiment and mathematical optimization.

## 5. Micro-scale Energy Community

Based on the results of three approaches, the authors design the two types of energy network model of Micro-scale EC, four houses' network model and eight houses' model.

*5.1 Four houses' network model*

In the case of four detached houses, the results of three research approaches indicate;

- Optimum number of fuel cell is two sets, and that of reformer is one and a half set with a hydrogen tank.
- Surplus electricity of fuel cells should be shared equally among the other houses by the load balancing algorithm, and surplus heat of storage tanks should be shared with adjacent houses.

Fig 5 shows a design example of four detached houses' network model.

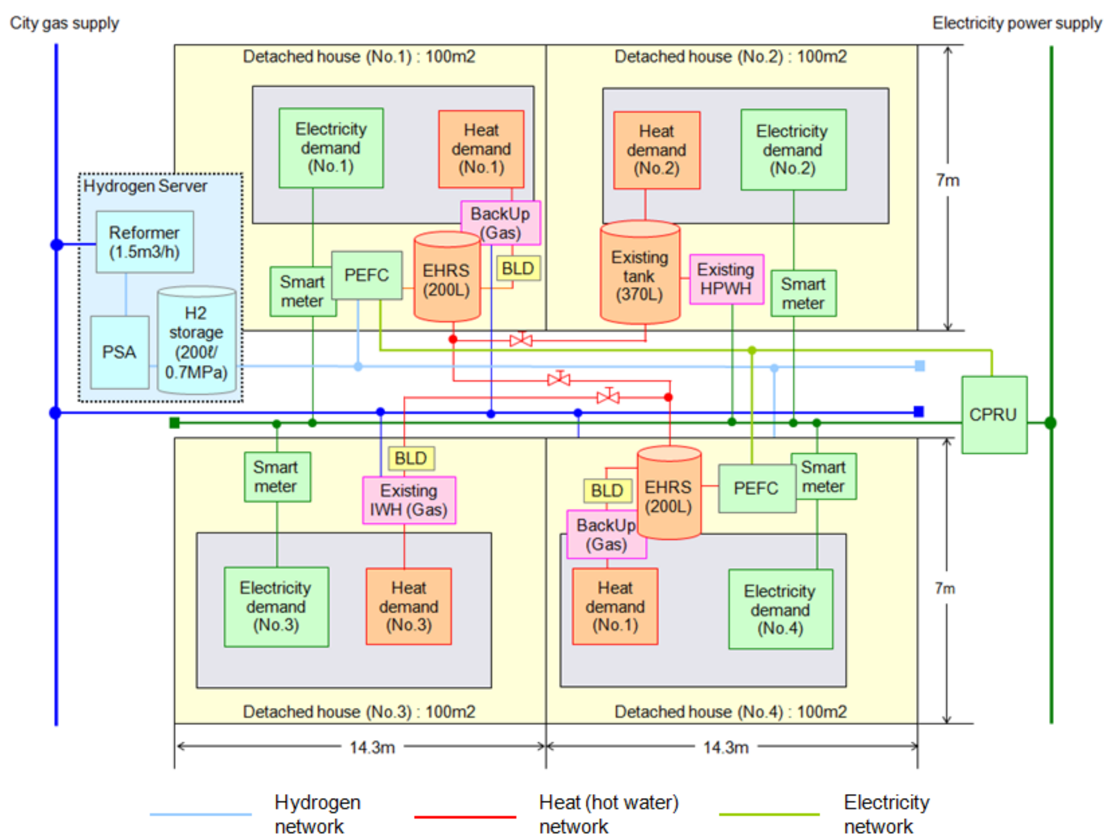


Fig. 5 Design example of four houses' network model

The specifications of energy network are as follows,

- For all four houses, the electricity network forms local area distribution network connected grid power line.
- The reformers are aggregated in one place (total capacity is 1.5 m3/h) with a hydrogen storage tank (storage capacity is less than 200 l, pressure is 0.7 MPa) as a hydrogen server. The hydrogen network is connected all fuel cells (PEFC and 1.0 kW-type), and the other houses can be easy to access hydrogen network.
- The fuel cell cogenerates hot water and keeps it in the storage tank (storage capacity is 200 l). The hot water pipeline is connected from the storage tank to adjacent water heater via water mixer.

*5.2 Eight houses' network model*

In the case of eight detached houses, a design example is shown in Fig. 6.

This energy network design looks like the same four houses' network model in two, but the specifications of hot water network is different as follows,

- The electricity network forms local area distribution network for all eight houses.
- The reformers are aggregated in one place (total capacity is 3.0 m3/h) with a hydrogen storage tank (storage capacity is less than 400 l) and hydrogen network is connected all four fuel cells.
- The hot water network is closed in four houses' area, left side four houses or right side.

In eight houses' network model, three research approaches verify carbon dioxide mitigation is more than 6% and primary energy reduction is more than 15% as compared with single fuel cell installation in each house. The formation of eight houses' model, installing four fuel cells in eight detached houses, introducing energy networks, leads to better performance than single fuel cell installation in all houses.

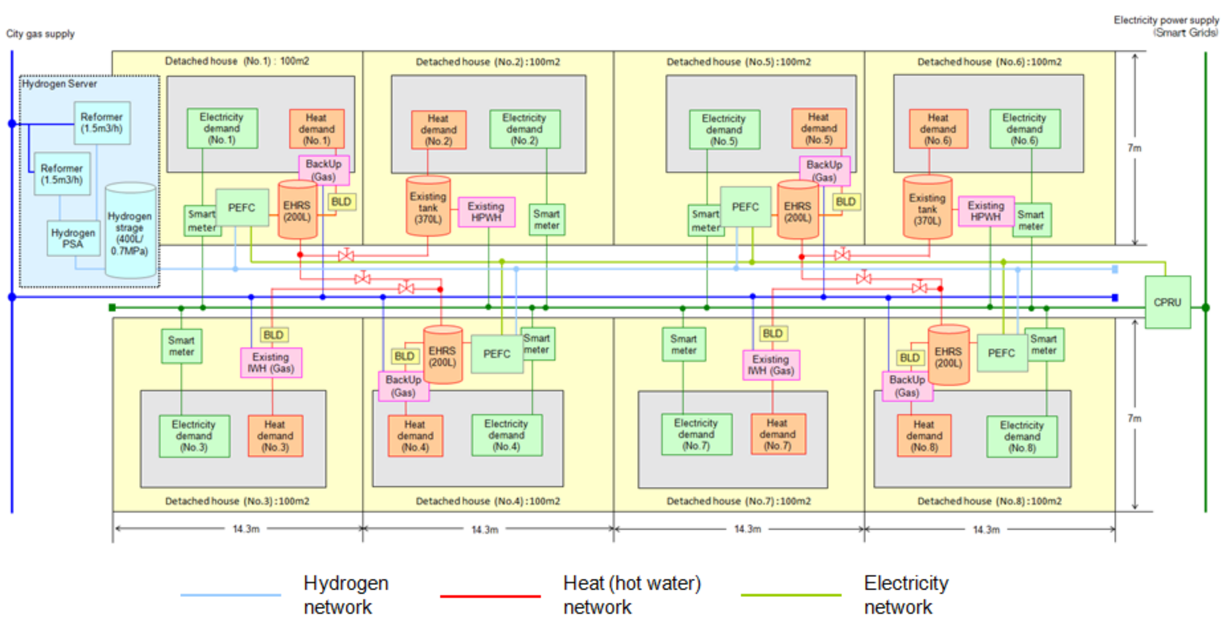


Fig. 6 Design example of eight houses' network model

## 6. Small-scale Energy Community

Small-scale EC is the expanding case of Micro-scale EC and is networking electricity power and hydrogen gas. Considering hydrogen distribution condition (i.e. no need to additional boosting), the maximum area of Small-scale EC assumes about one hundred and eighty meters square, and it has thirty Micro-scale ECs, about two hundred and forty detached houses.

Fig 7 shows the configuration of Small-scale EC and the relationship between Small-scale EC and Micro-scale EC.

In Small-scale EC, it is necessary to install a specific hydrogen station, supplying hydrogen to each Micro-scale EC through newly distribution pipelines. This hydrogen station is not for hydrogen vehicles but for stationary fuel cells, and it has some different specifications as follows,

- The hydrogen station for Small-scale EC is a backup fueling station to hydrogen servers of Micro-scale EC through distribution pipelines.
- The station generates hydrogen from city gas and/or from renewable energies, such as photovoltaic and small wind power, but the hydrogen gas is not so pure, its concentration is sufficient for 90 % to 98 %.
- The hydrogen storage tank is only a buffer, because each hydrogen server of Micro-scale EC has already installed a suitable hydrogen tank.

Thus at the beginning stage, there is no need to be equipped with full capacity of hydrogen station for Small-scale EC.

The diagram of hydrogen station for Small-scale EC is shown in Fig. 8.

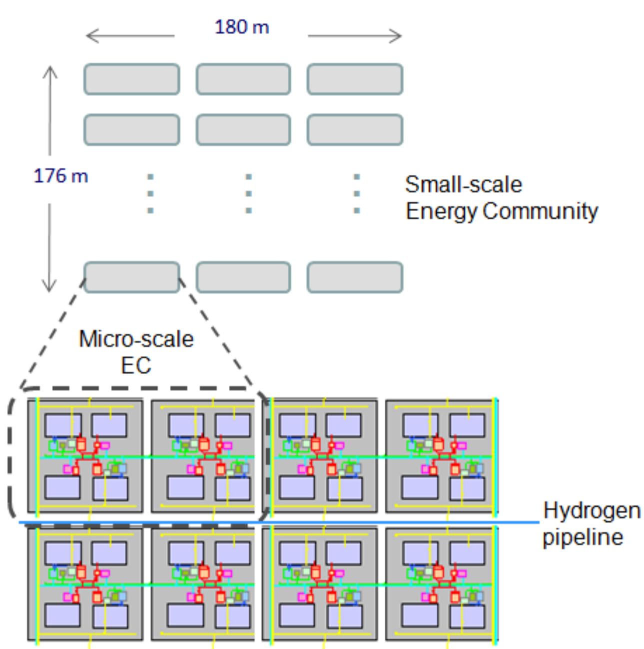


Fig. 7 Configuration of Small-scale Energy Community

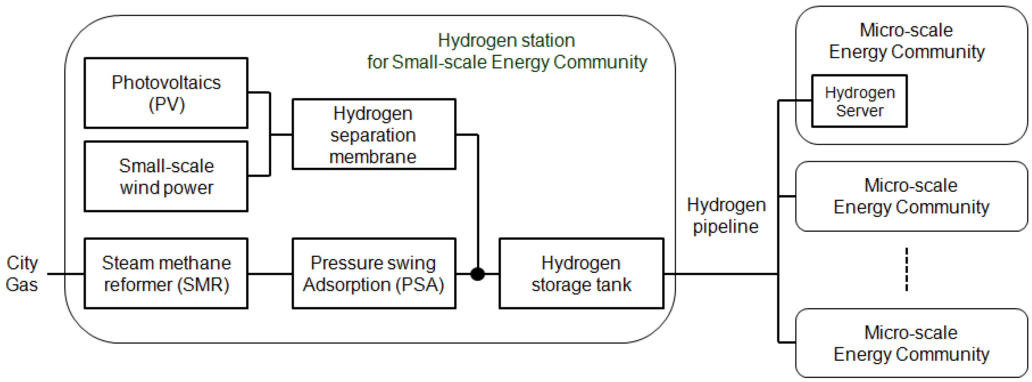


Fig. 8 Diagram of hydrogen station for Small-scale Energy Community

## 7. Hydrogen energy community growth scenario

Using Small-scale EC model and specific hydrogen station, the authors propose a scenario to build up hydrogen energy community based on networking stationary fuel cells. Specifically the growth process from Micro-scale EC to Small-scale EC is referred to the stationary fuel cells diffusion plan in Japan [10] and Diffusion of innovations [11]. The growth process involves incubation phase, expansion phase, maturity phase of Micro-scale ECs and migration phase, build-up phase of Small-scale EC.

Fig 9 shows the outline of hydrogen energy community growth scenario.

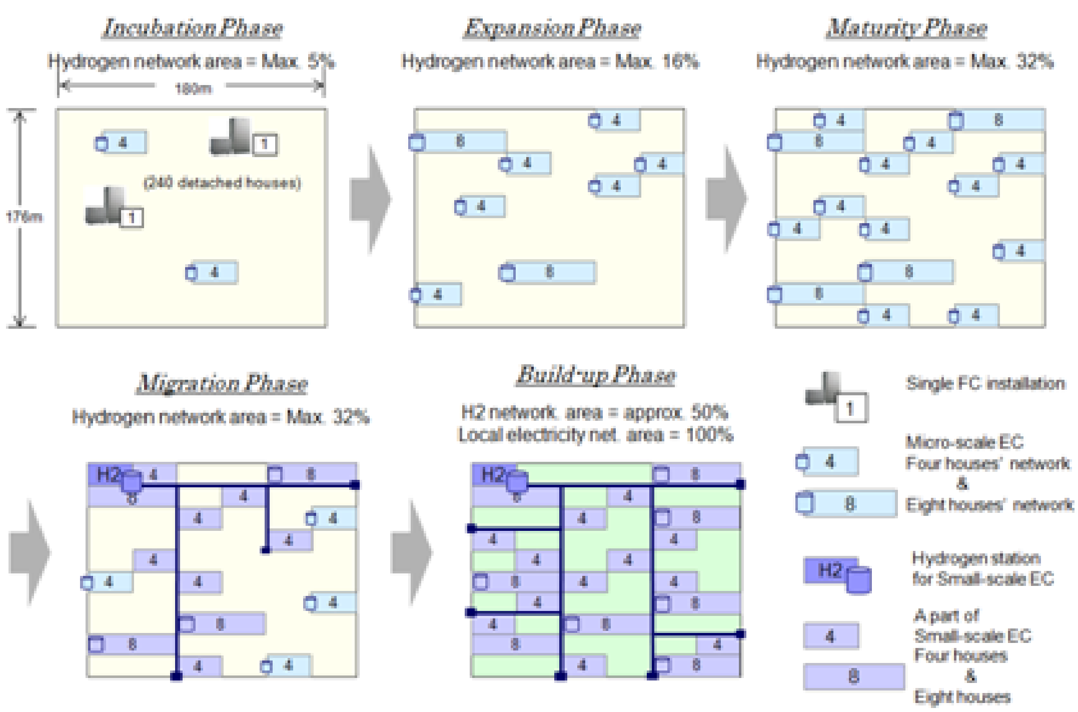


Fig. 9 Outline of Hydrogen energy community growth scenario

*Incubation phase*

The first stage is Micro-scale EC incubation phase. In this phase, installing single fuel cell in each house (i.e. commercial product specification) is normal setting, additionally a group of users whose heat demand is relatively high throughout the year introduces Micro-scale EC, such as four houses' type, for experimental purposes. This stage continues until the fuel cells diffusion rate 2.5 % as Innovators.

*Expanding phase*

The former innovating experiments accelerate installing Micro-scale EC for the second user group, whose electricity and heat demand is relatively high but heat to electric power ratio varies depending on the seasons. Therefore four houses' type of Micro-scale EC increases and additionally existing Micro-scale ECs expand four houses' type into eight houses' type. This stage continues until the fuel cells diffusion rate 8 %[1)] as Japan's plan.

1) According to Japan' plan, residential fuel cells will be introduced 2.5 million sets by 2030. At that time, there will be 30 million detached houses in Japan. Accordingly the fuel cells diffusion rate is calculated about 8 %.

*Maturity phase*

In this stage, installing Micro-scale EC (i.e. four hoses' type and/or eight houses' type) is normal setting, and Micro-scale EC penetrates into the large user group whose electricity and heat demand are a little higher than the average in Japan. This stage continues until the fuel cells diffusion rate 16 % as Early Adopters. Consequently at the end of this stage, the hydrogen network area accounts for 32 %[2)] of total.

2) The hydrogen network area is the rate of detached houses belonging to Micro-scale ECs in total area. According to four and eight houses' network model, this rate is about twice the fuel cells diffusion rate.

*Migration phase*

As the hydrogen network area exceeds one third, shifting the phase from Micro-scale EC to Small-scale EC, Energy Service Providers (ESP) emerges, and ESP equips a hydrogen station and distribution pipelines for Small-scale EC. ESP supplies not only hydrogen gas but electricity power to the Micro-scale ECs connected to the hydrogen station.

The fuel cells diffusion rate is 16 %, the same of maturity phase, but the formation of energy supply and asset management changes in this stage.

*Build-up phase*

The final stage is Small-scale EC build-up phase. In this stage, the role of ESP is not only supplying Small-scale EC with suitable energies (i.e. hydrogen and electric power) but managing various assets (e.g. hydrogen station, distribution pipelines, local electricity networks and fuel cells). ESP promotes disseminating fuel cells and expanding hydrogen network in Small-scale EC, and the fuel cells diffusion rate reaches 25 %, the hydrogen network area accounts for 50 % of total.

At the end of this scenario, Small-scale EC grows up hydrogen energy community, and the carbon dioxide mitigates more than 3 % and the primary energy reduces more than 7.5 % as compared with single fuel cell installation in each house.

## 7. Conclusion

This study proposed a concept of energy network interconnected stationary fuel cells and classified the types of energy network in residential areas as Energy Community. Through the system simulation, the acceleration experiment and the mathematical optimization, this study indicated the two types of energy network model of Micro-scale EC and its performance.

Modeling the configurations of Small-scale EC, this study made up a hydrogen energy community growth scenario from Micro-scale ECs to Small-scale EC, and indicated Small-scale EC had better performance as compared with single fuel cell installation in each house throughout the scenario.

## Reference


[1] EC HyWays, HyWays - The European Hydrogen Energy Roadmap, Feb. 2008.

[2] U.S. DOE, Hydrogen Posture Plan - An Integrated RD and Demonstration Plan, Dec. 2008.

[3] U.S. California, California Hydrogen Blueprint Plan, May 2005.

[4] Japan Minister of Economy, Trade and Industry, Press release on Jan. 13, 2011. http://www.meti.go.jp/press/20110113003/20110113003.html (Access on 3 July 2011)

[5] Tokyo Gas Co., Ltd., Press release on Jan. 28, 2009. http://www.tokyo-gas.co.jp/Press/20090128-03.html (Access on 3 July 2011)

[6] Japan Fuel Cell Association, "Grant data of Enefarm". http://www.fca-enefarm.org/subsidy/data/index.html (Access on 3 July 2011)

[7] Tokyo Gas Co., Ltd., Press release on Feb. 9, 2011. http://www.tokyo-gas.co.jp/Press/20110209-01.html (Access on 3 July 2011)

[8] H. Aki, S. Yamamoto, et al., Operational Strategies of Networked Fuel Cells in Residential Homes, IEEE Transaction on Power Systems, Vol.21, No.3, Aug. 2006.

[9] H. Aki, S. Yamamoto, et al., Fuel cells and energy networks of electricity, heat, and hydrogen in residential areas, International Journal of Hydrogen Energy, Vol.31, No.8, 2006.

[10] Japan Minister of Economy, Trade and Industry, Press release (in Japanese) on May 23, 2008. http://www.enecho.meti.go.jp/topics/080523b.pdf (Access on 23 July 2011)

[11] Everett M. Rogers, Diffusion of Innovations, Fifth Edition, Free Press, 2003.


## Curriculum Vitae


**Ichiro Sugimoto** received the B.S. and M.S. degrees in communicational engineering from Osaka University, Osaka, Japan, in 1980 and 1982, respectively. He has been a research scientist with Osaka Gas Co., Ltd. since 1982. He has been an energy analyst with the Center for Promotion of Natural Gas on loan since 2009.

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