

The Operation Result of the Demonstration of Energy Networks of Electricity, Heat, and Hydrogen at an Apartment Building in 2007

*Hirohisa Aki, Yukinobu Taniguchi, and Junji Kondoh,
National Institute of Advanced Industrial Science and Technology
Itaru Tamura and Akeshi Kegasa, Osaka Gas Co., Ltd.
Yoshiro Ishikawa, Shigeo Yamamoto, and Ichiro Sugimoto, KRI Inc.*

ABSTRACT

The demonstration project on energy networks of electricity, heat, and hydrogen in an existing apartment building has been initiated to evaluate authors' proposal. The authors proposed the setting up of an energy system by fuel cells and energy networks of electricity, hot water, and hydrogen in residential areas. In such networks, some homes are equipped with fuel cell stacks, fuel processors, hydrogen storage devices, and large storage tanks for hot water. The energy network enables the flexible operation of the fuel cell stacks and fuel processors.

A demonstration has been started since April 2007. The demonstration is presented in a small apartment building, which was constructed for experimental purpose in Osaka City. Two homes on the 3rd floor and four homes on the 4th floor, total six homes are involved in the demonstration. The six families are spending their completely normal daily life using the system.

Three small PEM fuel cells have been installed, and the electricity and hot water from the fuel cells are shared via an internal electricity grid and a hot water pipe. Hydrogen production facility, a small storage and a hydrogen pipe have been installed as an infrastructure to supply hydrogen to the fuel cells. The energy flow process from hydrogen production to consumption in the homes is demonstrated.

The operation results including the performance of each system component such as fuel cell and lessons learned are reported.

Introduction

The residential fuel cells that are commercially available in Japan are PEMFCs at present.¹ The Japanese government has initiated a large-scale deployment for the project of the residential fuel cell systems in 2005. More than 2,000 units have been installed by 2007. However, the systems have challenges against the penetration such as energy demand characteristics of homes and built-in fuel processor, which make hydrogen from natural gas/kerosene.

The concept of interconnecting a group of residential homes by energy networks involving electricity, heat (hot water), and hydrogen, with some of these homes possessing fuel cells, has previously been proposed as the solution (Aki et al. 2006a, 2006b) The networks connect fuel cell stacks, fuel processors, and other equipment, and are expected to contribute to the mitigation of the associated environmental impacts through the flexible and efficient utilization of the equipments. Starting with small-scale systems, a gradual expansion to larger

¹ Residential fuel cell systems using solid oxide fuel cells are also under research and development by Osaka Gas Co., Ltd in Japan.

systems can be achieved by consistently using conventional energy systems; this can also help to avoid a large initial investment.

The energy interchange system has also been proposed for apartment houses. The combination of two different types of distributed generations (DGs)—proton ex-change membrane fuel cells (PEMFC, or polymer electrolyte fuel cells [PEFC]) and gas engines/solid-oxide fuel cells (SOFC)—allows variations in the ratio of heat to electricity supply and enables load matching, which is necessary for the homes. We have developed mathematical models, a PC-based simulator, and an experimental system to evaluate the proposal (Aki et al. 2006b). The effects of the systems were analyzed and verified by the simulator and experimental systems.

As the next step towards a practical application, a demonstration has been started in existing residential homes to evaluate the proposal since April 2007. The demonstration is presented in a small apartment building with 18 apartments, which was constructed for experimental purpose in Osaka City. Two homes on the 3rd floor and four homes on the 4th floor, total six homes are involved to the demonstration. The six families are spending their completely normal daily life using the system. Three small PEM fuel cells with hot water tanks have been installed, and the electricity and hot water from the fuel cells are shared via an internal electricity grid and a hot water pipe. Hydrogen production facility, a small storage and a hydrogen pipe have been installed as an infrastructure to supply hydrogen to the fuel cells. The energy flow process from hydrogen production to consumption in the homes is demonstrated. The operation results in fall of 2007 and lessons learned are reported in this paper.

Proposed Systems

The first challenge of the commercialized residential fuel cells is the demand characteristics of residential homes. The installation of fuel cells with capacities that equal or exceed the peak demand is not economically justified. Therefore, the capacity of the commercialized residential fuel cells is 700–1000 W, and they are operated in a grid-dependent mode and are not intended to supply the peak demand.

Residential homes have a varying energy demand in general. The electricity base load of Japanese homes is usually 250 to 500 W, and their peak load is 3 to 5 kW. Their electricity demands have “demand spikes”, which is a large load in a short period, such as that is caused by the use of microwaves. The load factors of the electricity demands are usually low because of the demand spikes. The demand spikes usually occur at different times for different homes. The maximum load of the combined load of all the homes is considerably smaller than the sum of the peak load values of each home. For a group of homes, combining the electricity load of all the homes and considering them as a single consumer reduces the required total capacity of the equipment including fuel cells. The implementation of the energy networks for the group enables connects the equipment and the energy demand of the homes. Thus, a coordinated and flexible operation of the equipment can be provided.

The fuel processors, which produce hydrogen from natural gas (methane) or kerosene, are equipped to the fuel cell systems so that any hydrogen infrastructure is not necessary. However, the shortcoming of that scheme is slow response to demand. The fuel processors use chemical process and have four different catalyses that must be kept different temperatures. They can not respond to changes in the load quickly, while the fuel cell stacks can respond quickly and without delay, i.e., the fuel cells have the ability to respond to the spike in electricity demand. Addition to the slow response, the fuel processors provide lower efficiency at partial load

operation and require 1 hour or longer preheating of catalyses at start-up. These shortcomings spoil the advantages of the fuel cell stacks.

Based on the above discussions, the authors have designed and proposed typical system configurations for detached houses and apartment buildings.

An example of the system configurations for a group of eight detached houses is shown in Figure 1. The electricity generated from the fuel cells, which are installed in residential homes, can be shared via a grid because the fuel cells are interconnected with the grid. This means that the homes virtually share all the fuel cells.

It is better to install small fuel cells in each home than to install a single large fuel cell in only one of them. The exhaust heat from the fuel cells should be recovered and used to increase the total energy efficiency. Hot water from the heat exchangers of the fuel cells should primarily be used in homes where fuel cells are installed; otherwise, the hot water has to be wasted or transported to other homes, and the total efficiency will be decreased.

Figure 1. Example of the Proposed System for 8 Detached Houses

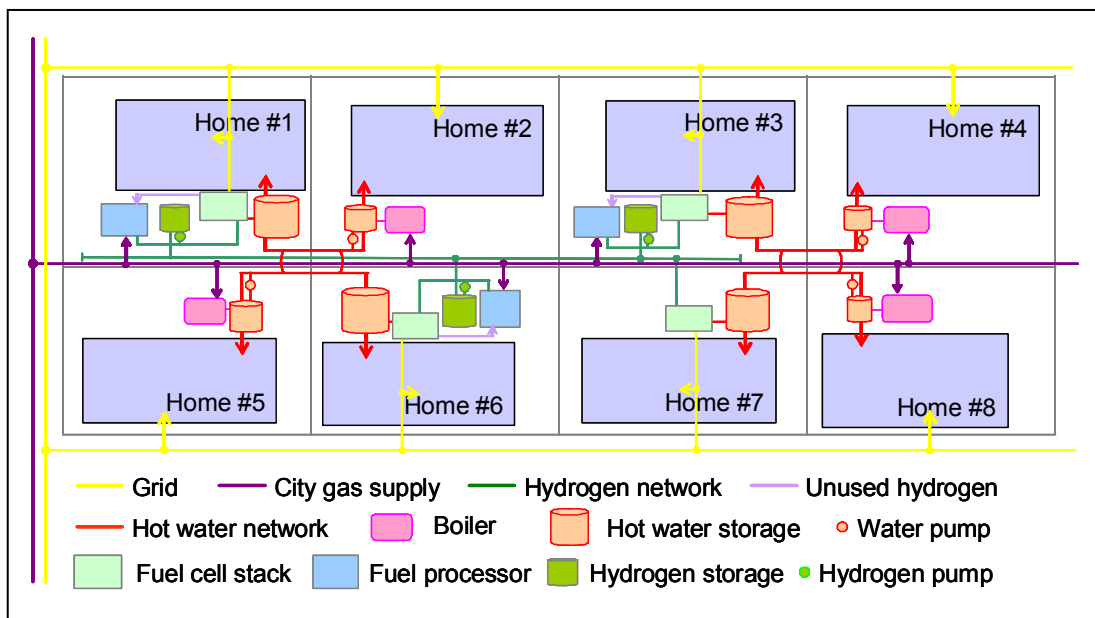


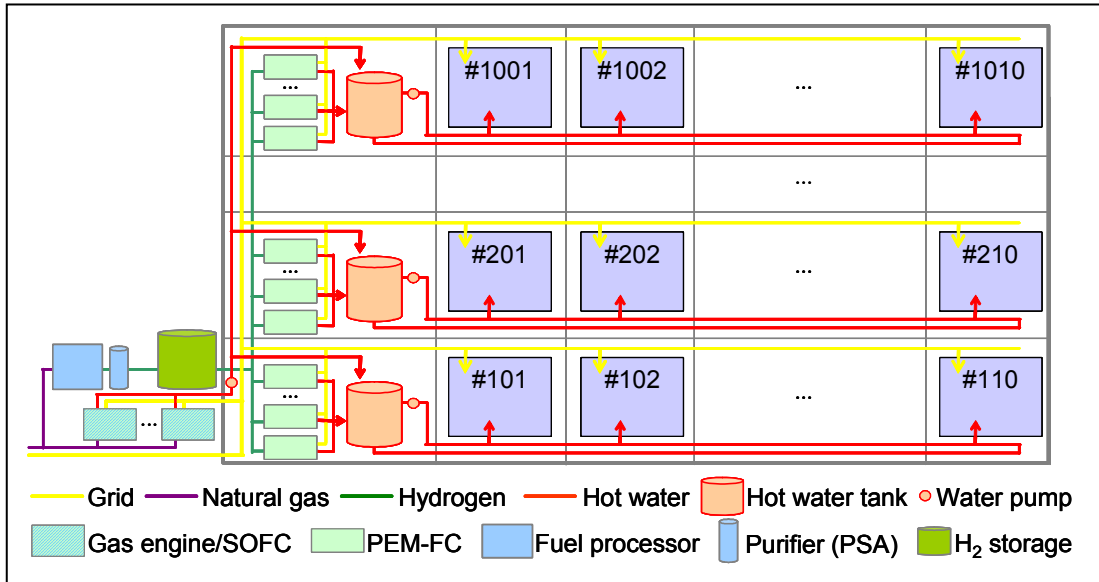
Figure 2 shows an example of an apartment building which has 100 apartments (10 x10). In the case of an apartment building, it is possible to install larger systems into public rooms such as the electric room of an apartment building. A hybrid generation system, which combines two or more types of generation systems, e.g., PEMFCs and SOFCs, enables variations in the ratio of heat to electricity supply depending on the demand. The authors propose the installation of PEMFCs into some of the homes along with the installation of gas engines or SOFCs.

Centralized hydrogen production with purifiers (pressure swing adsorption [PSA] units) will be chosen for the apartment buildings. It can provide pure hydrogen and is better suited for fuel cell stack operation; however, it is unavailable for detached houses due to technical constraints in PSA production. The minimum capacity of a PSA unit is 5–10 Nm³/h, which is equivalent to 5–10 kW capacity of fuel cell stacks.

In these apartment buildings, the hot water will be circulated horizontally and will be shared between all apartments on the same floor. Sharing the hot water between all the

apartments would be another option; this would depend on the trade-off between the electricity consumption involved in pumping up the water and its utilization.

Figure 2. Example of the Proposed System for an Apartment Building (10 x 10 = 100)



Demonstration Project

Outlines

A demonstration project was initiated to evaluate the previous proposal. The purpose of the demonstration is as follows: 1) to evaluate the technological feasibility of hydrogen based system, 2) to improve operational algorithms to adapt to more practical applications, and 3) to verify the effect of the proposed systems on the reduction of primary energy consumption and CO₂ emission.

The demonstration is being conducted at the Experimental Complex NEXT21 (Figure 3) in Osaka, Japan. NEXT21 is an apartment building which various experimentation and demonstration can be conducted (Shiba 2007). The building has seven storeys including a basement and 18 families are living on 3rd – 6th floors. The allocated rooms are completely separated from each other to simulate also detached houses. Each floor has a large space for the installation of pipes for hot water and gas supply and for electric cables beneath the floor. The large space enables complete modifications of those pipes if necessary.

Figure 3. Demonstration Site



System Configuration

Two homes on 3rd floor and four homes on 4th floors are involved in the demonstration project. A hydrogen production facility (three sets of reformer and PSA, 1.5 Nm³/h each) and a small storage tank are installed on the roof of the building. Hydrogen pipes are installed for the entire area involved in the demonstration; hydrogen is supplied as part of the basic infrastructure such as electricity and water. Therefore, the operation of the hydrogen production facility may be beyond the scope of the evaluation in this demonstration. A PEMFC and two PEMFCs are installed on 3rd and 4th floors, respectively. Hot water tanks are installed adjacent to the fuel cell stacks to use the recovered heat for production of hot water. The hot water will be transported through a pipe. Auxiliary boilers are provided to all six homes as a backup.

Two types of demonstrations are performed as follows. Figure 4 represents the implemented energy systems.

- Detached house case: A simulation of the system for a group of detached homes. Four homes on 4th floor are involved. Two of four homes have PEMFCs. Electricity and hot water are interchanged or shared. The interchange of hot water is available between two tanks.
- Apartment building case: A simulation of the system for an apartment building. The PEMFCs and hot water tanks are shared. Two hot water tanks on the 4th floor are connected sequentially and used as single tank. Electricity is shared with all six homes and hot water is circulated and shared with two/four homes on each floor.

The major specifications of the fuel cells and the hot water tanks are shown in Table 1. The design efficiencies of the fuel cells are 40% for electricity and 30% for heat recovery as shown in the table, but both of them are approximately 40% according to our measurement. Note that the electricity generation efficiencies depend not only on fuel cell stack characteristic but also on inverter performance.

Figure 4. Energy Systems of the Demonstration

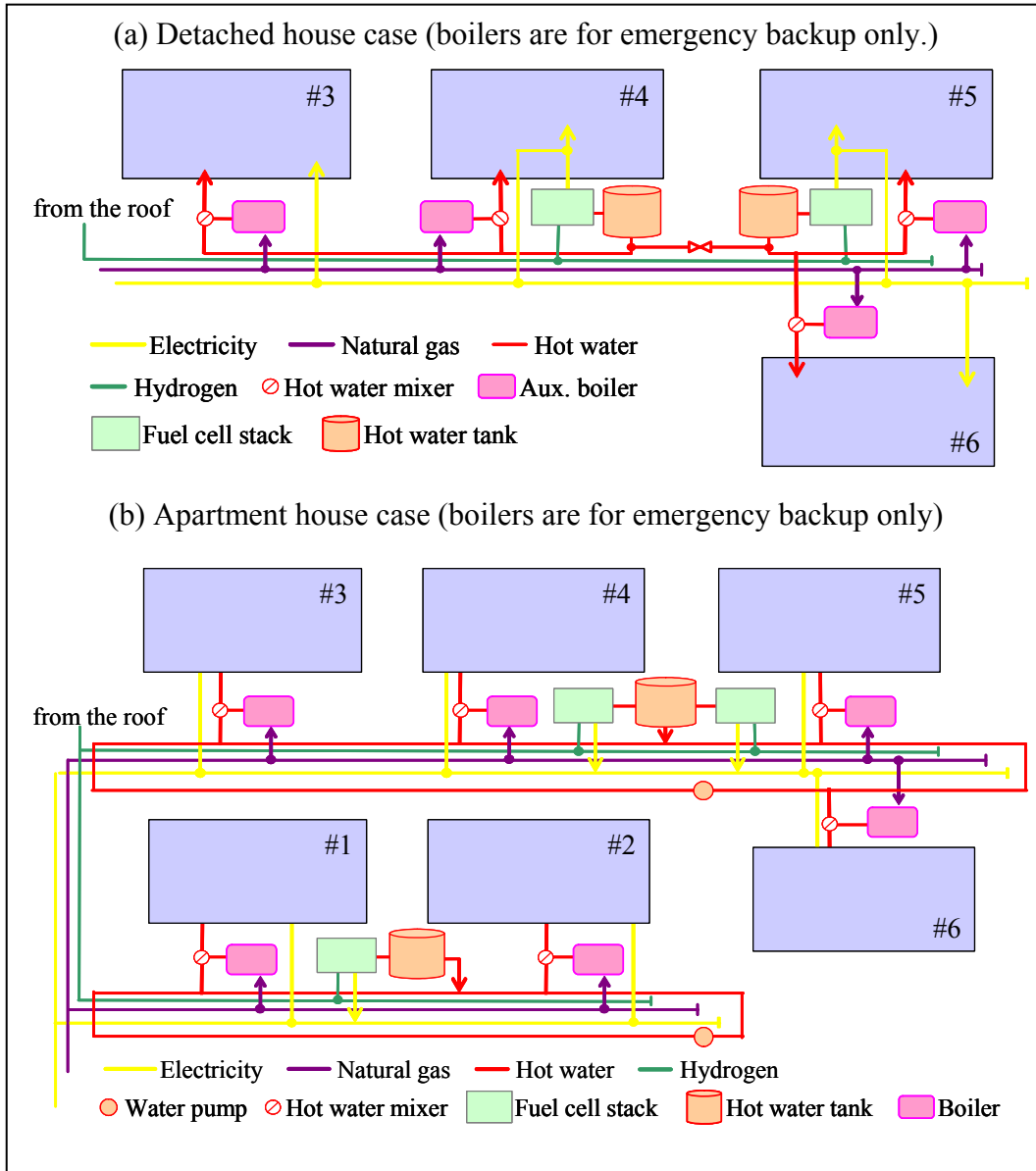


Table 1. Design Specification of Fuel Cells and Hot Water Tanks

| Item | Design specification |
|-----------------|--|
| Type | Polymer Electrolyte Membrane fuel cell (PEM-FC) |
| Fuel | 99.99% hydrogen |
| Electric output | Rated output: 700 W, Output: AC 200 V Efficiency at rated operation: 40% (HHV) |
| Heat recovery | Temperature: 60-70°C, Efficiency at rated operation: 30% (HHV) |
| Dimensions | Generation units: 300 W x 1250 H x 440 D (m) Hot water tanks: 370 L x 1 (3 rd floor), 200L x 2 (4 th floor) |

Figure 5 shows the hot water system of each apartment. The mixers always regulate the flows of the tap water and the hot water from the tanks to maintain the temperature of the hot water which is supplied to the apartments. The auxiliary boilers are equipped to the apartments for backup, and are automatically turned-on when the hot water temperature is low.

The energy demand of the homes that includes electricity consumption for air conditioning and lighting, hot water consumption for bathing etc., as well as the states of the equipment and energy flow are measured by every two seconds and stored on a server via Ethernet. The major measurement points are summarized in Table 2. The accurate measurement on hot water system is challenging. The flow always varies and often causes errors, and small error, e.g., 2–3°C on temperature measurement may critical to evaluate the hot water system efficiency. The complex state-of-the-art boiler (Figure 5) provides more comfort to habitant but also provides difficulties to us.

The demonstration is conducted for three weeks in every season (spring, summer, fall, winter) by following order: 1) energy demand measurement without fuel cells as evaluation standards, 2) detached house case, 3) apartment building case.

Figure 5. Details of Hot Water System of each Apartment and Measurement System

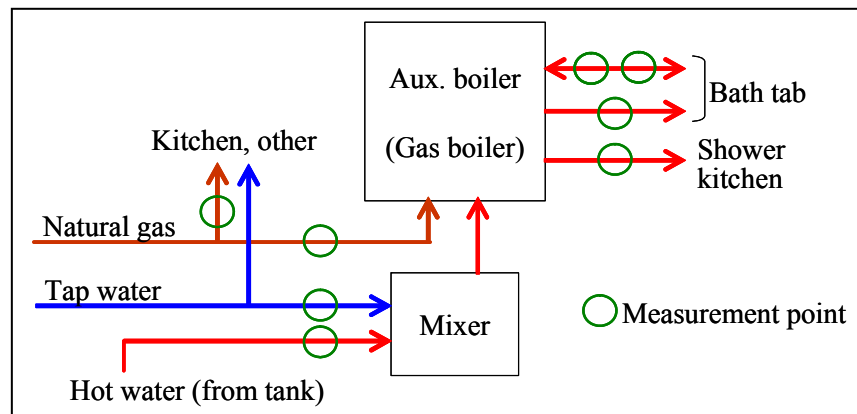


Table 2. Measurement Points

| Fuel cells, hot water tanks, other | Apartments |
|--|---|
| Hydrogen consumption | Electricity consumption |
| Electricity generation (AC) | Electricity consumption of air conditioner |
| Recovered heat (hot water) temperature | Natural gas consumption |
| Hot water tank level | Natural gas consumption of aux. boiler |
| Hot water flow and temperature | Cold/hot water flow & temperature to/from aux. boiler |
| | Hot water flow & temperature from hot water tank |

Results

The entire system has functioned well; no major fault or trouble has been happened since the demonstration started. This means that the hydrogen based system is technological available to residential homes at present. The result of the fall of 2007 has been analyzed by present and reported in this paper.

The operation results are summarized in Table 3. The conditions of each column are not same, e.g., people's behavior and their energy demands vary day by day. The hot water demand of the apartment building case was significantly larger than that of the detached house case, since the ambient temperature when the apartment building case was conducted was low. The hot water from fuel cells is in almost proportion to electricity from the fuel cells, and was not enough to cover all hot water demand in apartment building case. The auxiliary boilers compensated the shortage and supplied half of hot water demand.

80–85% and 50–60% of external energy supply was hydrogen, i.e. the apartments depended most of their end-use energy on hydrogen. Therefore, CO₂ emission, energy cost, and other performance depend on hydrogen production in hydrogen energy systems.

The heat losses of hot water were not small in all cases. They were caused in tanks, circulation, and branch pipes between main circulation pipe and each home. Additional efforts for improvement are necessary to reduce the losses.

CO₂ emissions are reduced 12% and 6% in weekdays of detached house case and apartment building case from conventional system which use grid power and gas boiler, but no clear energy savings were shown in both cases.² Note that above is tentative information since the results of whole year (four seasons) are not available at this time though the CO₂ emission and the energy savings should be evaluated with the whole year data.

Table 3. Operational Result in Fall 2007: Average Energy Supply and Demand (MJ/day)

| | Detached house case | | Apartment bldg. case | |
|---------------------------------------|---------------------|----------|----------------------|----------|
| | Weekdays | Weekends | Weekdays | Weekends |
| Electricity | | | | |
| 1 Demand | 127.7 | 144.8 | 256.5 | 290.0 |
| 2 Fuel cells | 103.9 | 111.6 | 170.1 | 163.5 |
| 3 Grid | 23.9 | 33.2 | 86.6 | 126.7 |
| 4 Fuel cells contributed, (1-3)/1 | 81.3% | 77.1% | 66.2% | 56.3% |
| Hot water | | | | |
| 5 Demand | 72.3 | 59.7 | 192.0 | 234.5 |
| 6 Fuel cells | 104.9 | 109.3 | 162.4 | 160.0 |
| 7 Loss | 45.4 | 60.0 | 96.8 | 106.6 |
| 8 Aux. boilers | 16.8 | 14.7 | 128.2 | 171.3 |
| 9 Fuel cells contributed, (5-8)/5 | 76.8% | 75.4% | 33.2% | 26.9% |
| External energy supply | | | | |
| 10 Electricity (secondary energy) | 23.9 | 33.2 | 86.6 | 126.7 |
| 11 Natural gas (primary energy) | 22.4 | 19.6 | 171.0 | 228.4 |
| 12 Hydrogen (secondary energy) | 262.1 | 276.0 | 424.7 | 411.7 |
| 13 Hydrogen covered, 12/(10+11+12) | 85.0% | 83.9% | 62.2% | 53.7% |

² The calculations are base on following assumptions: CO₂ emission intensities are 0.555 kg-CO₂/kWh and 51 g-CO₂/MJ for grid power and natural gas, efficiencies are 80%, 75%, and 40% for hydrogen production, gas boiler, and grid power.

The supply and demand of electricity and hot water including the operation of equipment of two cases of three weekdays are shown in Figures 6 and 7. Note that only four homes are involved to detached house case and all six homes are involved to apartment building case. Majority of electricity demand was supplied by PEMFCs in both cases. The PEMFCs followed to the demand variations in low demand hours, and kept rated output in other hours. The fuel cells did not keep rated output in Figure 7(a) because of minor trouble. The hot water storage capacity and heat from PEMFCs could not cover the whole hot water demand, and auxiliary boilers assisted especially in the apartment building case.

Figure 6. Operational Result of 3 Weekdays in Fall 2007 – Detached House Case

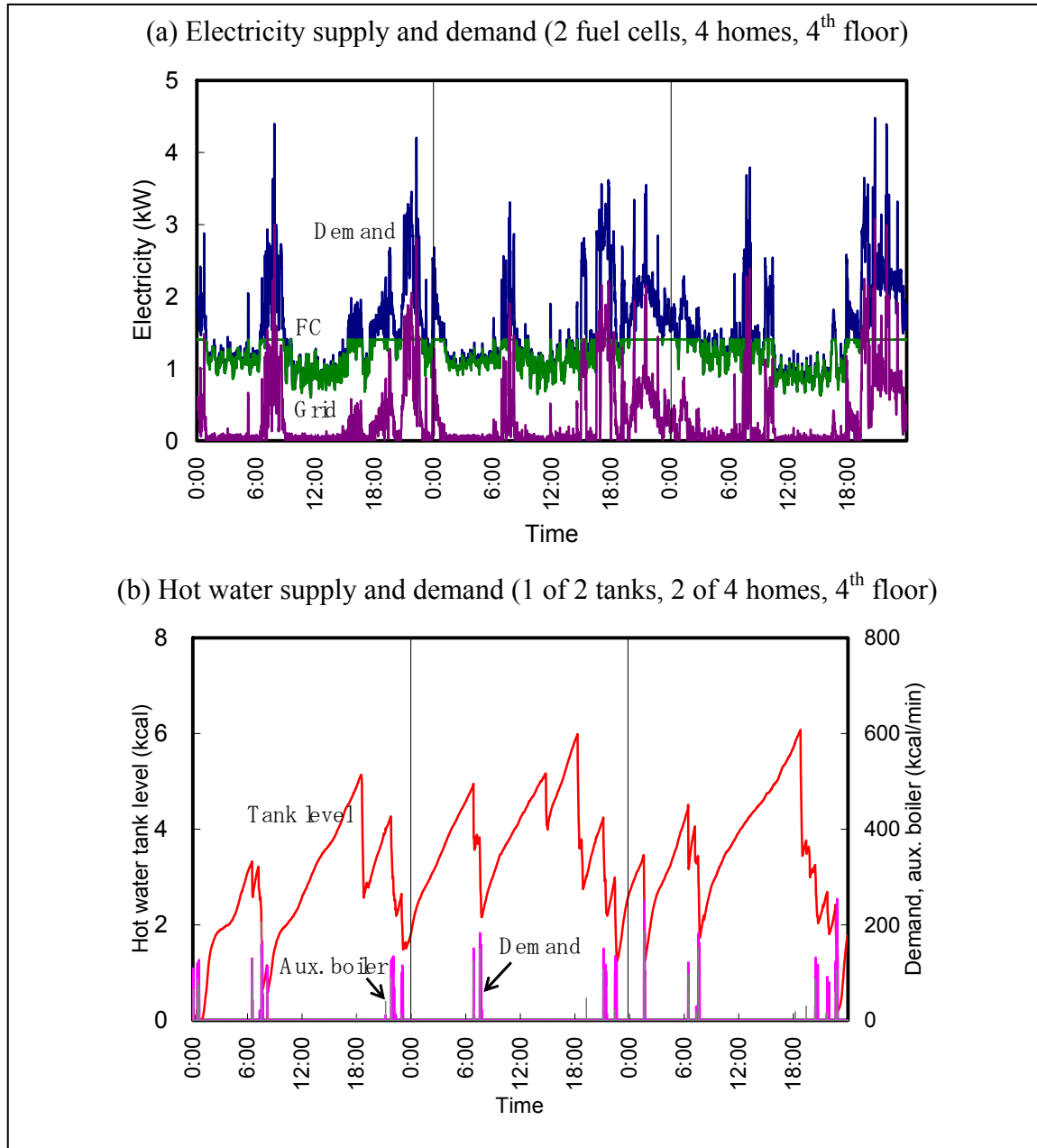
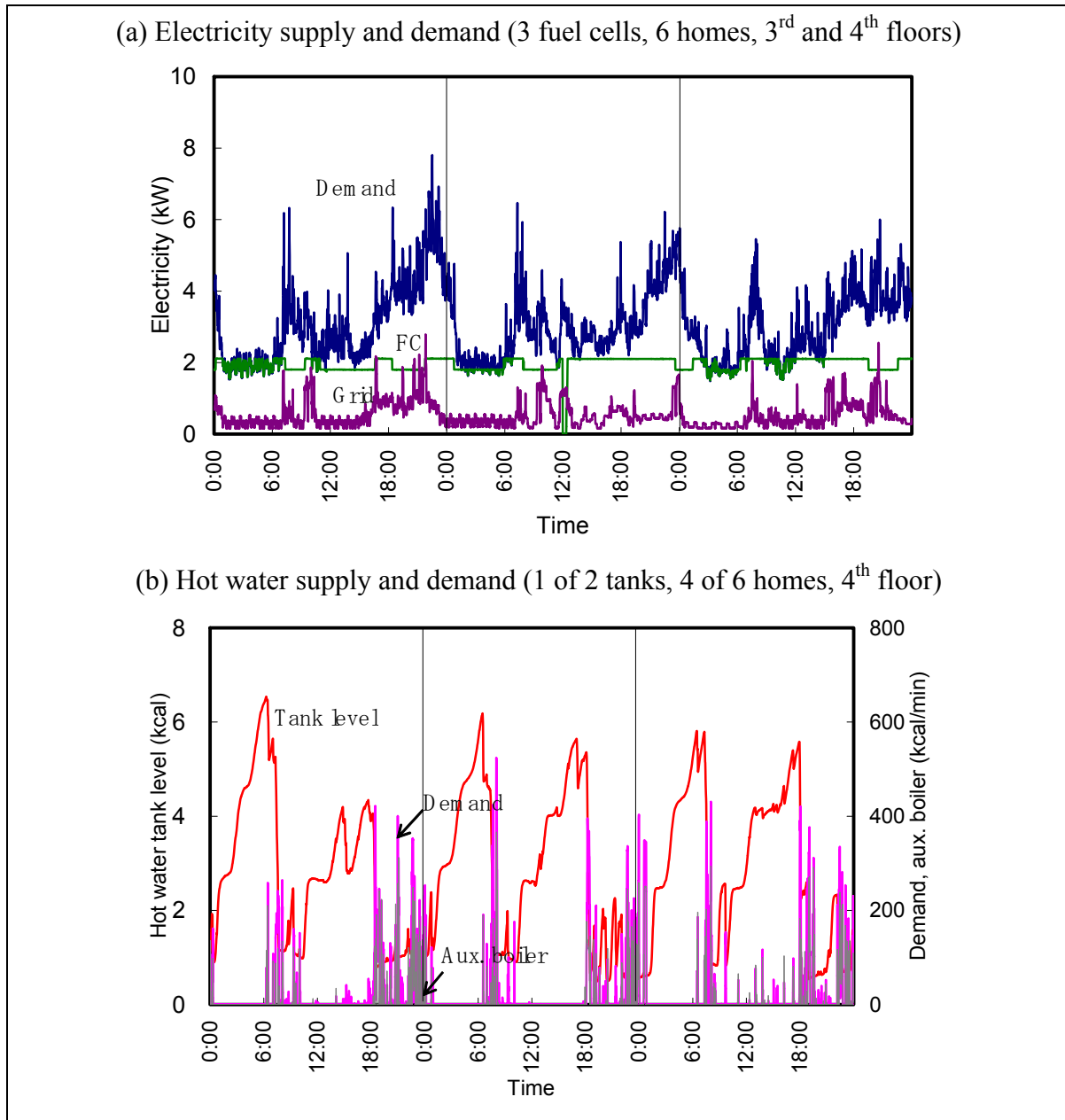


Figure 7. Operational Result of 3 Weekdays – Apartment House Case



Conclusion

The concepts of the proposed systems and the outline and present state of the demonstration project at an apartment building that hydrogen energy system is installed are presented in this paper. Hydrogen production facility is installed on the roof and hydrogen is supplied as a basic energy infrastructure in the building. Three PEMFCs are installed and supply electricity and hot water to six apartments.

The system is successfully running well. This demonstration shows that hydrogen based energy systems for residential homes are technological available at present; most of end-use energy is supplied from hydrogen. However, they still have lifetime and cost issues.

The demonstration will be continued also in 2008 and is expected to provide more valuable data and lessons learned.

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