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Development and Field Test of Residential SOFC Co-generation System with All-ceramics-segmented Cells

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ABSTRACT

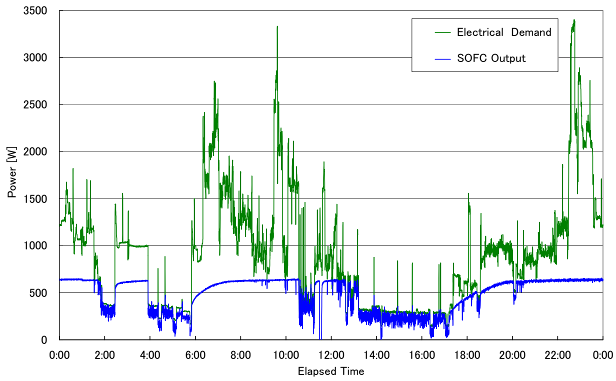
Tokyo Gas Co., Ltd., Kyocera corporation, Gastar Co., Ltd., and Rinnai corporation have collaboratively developed SOFC system with flat-tube segmented-cells. The segmented-cell stack is favorable in fabrication and assembling process because it is an integrated assembly of cells, which means we can eliminate difficult stacking process by a simple and efficient process of simultaneous co-firing of many cells and substrate. Generally, durability of metallic interconnecters used in planar SOFC cell-stack is one of the important challenges for commercializing SOFC systems from the point of long-term reliability and durability. To solve this critical issue, we have developed unique ceramics interconnecters and applied them to the developed cell stack. Finally, we have developed all-ceramics-segmented cell stack which is highly expected to offer both high performance and better durability. Specifications of developed SOFC co-generation systems are as the following table.

Electrical Power Output	0~700 W-AC
Electrical Conversion Efficiency	45%LHV (Target at rated operation)
Heat Recovery Efficiency	40%LHV (Target at rated operation)
Operation	Electric-load-following, continuous operation

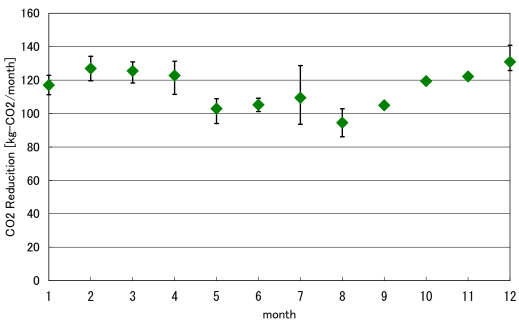
With developed SOFC co-generation system, we have performed both basic performance test and field test at a residence. Through the basic performance test, it is confirmed that the power generation efficiency at rated operation is around 41%LHVwith high heat recovery efficiency of 35%LHV. Through the field test at a resident, more than 50% of electricity power contribution and exhaust heat utilization against the demand of the household. Daily-average generation efficiency of 37.9%LHV and 34.1%LHV of heat recovery efficiency have also been recorded.

Thorough the field test, we also confirmed high CO2 emissions reduction effect of SOFCs. Thanks to the higher power generation efficiency of SOFCs and efficient exhaust heat utilization, the annual CO2 reduction reached 1,400kg. From these result, it has been confirmed that the developed SOFC system have environmentally-enhancing potentials in a wide range of environments.

Field test at a resident



Load-following operation at a resident



Monthly CO2 reduction through the field test

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Introduction

Tokyo Gas Co., Ltd., Kyocera Corporation, Gastar Co., Ltd., and Rinnai Corporation have collaboratively developed SOFC system with flat-tube segmented-cells [1, 2]. Figure 1 shows a cross-sectioon of a cell stack. Many single cells are fabricated on an electrically insulating flat-tube substrate and they are connected in-series using interconnectors. An assembly of cells fabricated on the substrate is called a cell-stack. The segmented-cell stack is favorable in fabrication and assembling process because it is an integrated assembly of cells, which means we can eliminate difficult stacking process by a simple and efficient process of simultaneous co-firing of many cells and substrate. Obtaining both electrical connection between each cell and gas sealing at the cell is also advantageous for durability and reliability of the cell-stack. Generally, durability of metallic interconnecters used in planar SOFC cell-stack is one of the important challenges for commercializing SOFC systems from the point of long-term reliability and durability. To solve this critical issue, we have developed unique ceramics interconnecters and applied them to the developed cell stack. Finally, we have developed all-ceramics-segmented cell stack which is highly expected to offer both high performance and better durability.

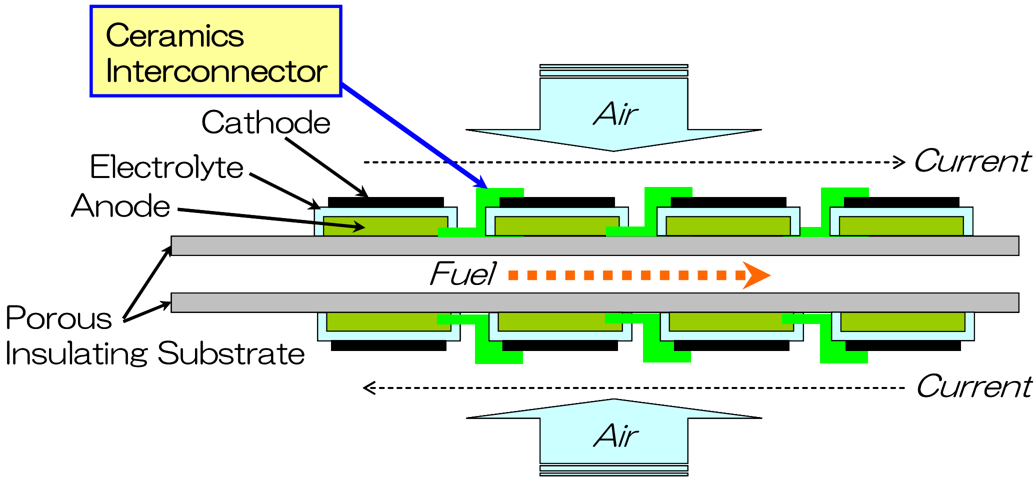


Figure 1. Sectional diagram of all-ceramics-segmented cell stack.

System Configuration and Specifications

SOFC Power Generation Unit

Figure 2 shows the assembling process of the SOFC power generation unit. Many cell-stacks are assembled in line and the assembly is called a bundle. Bundling cell stacks also enables the SOFC module compact and profitable for thermal-sustainability. Presently 36 cell-stacks are bundled and a typical power output of the bundle is around 400 W. For residential co-generation system, 2 bundles are mounted in a box of alloy with a fuel reformer and heat exchangers surrounded by insulators. The box is called a DC module, which role is optimizing circumstance of SOFC cell-stacks for power generation and fuel-reforming. An AC system consists of the DC module and other balance of plants (BOP) including pumps, blowers, a power conditioner and heat exchangers for exhaust heat recovery, etc. Regarding reduction of energy consumption by the BOP, the system has been assembled simply with reducing the amount of the BOP parts as much as possible. Thus, we have finished an AC 700 W system with exhaust heat recovery system for residential use. The system is operated automatically with various kinds of self-operation monitoring and safety systems including emergency shut-downs. Design and functions for environmental robustness for outdoor installation are also considered. Detailed specification of the SOFC unit is shown in Table 1.

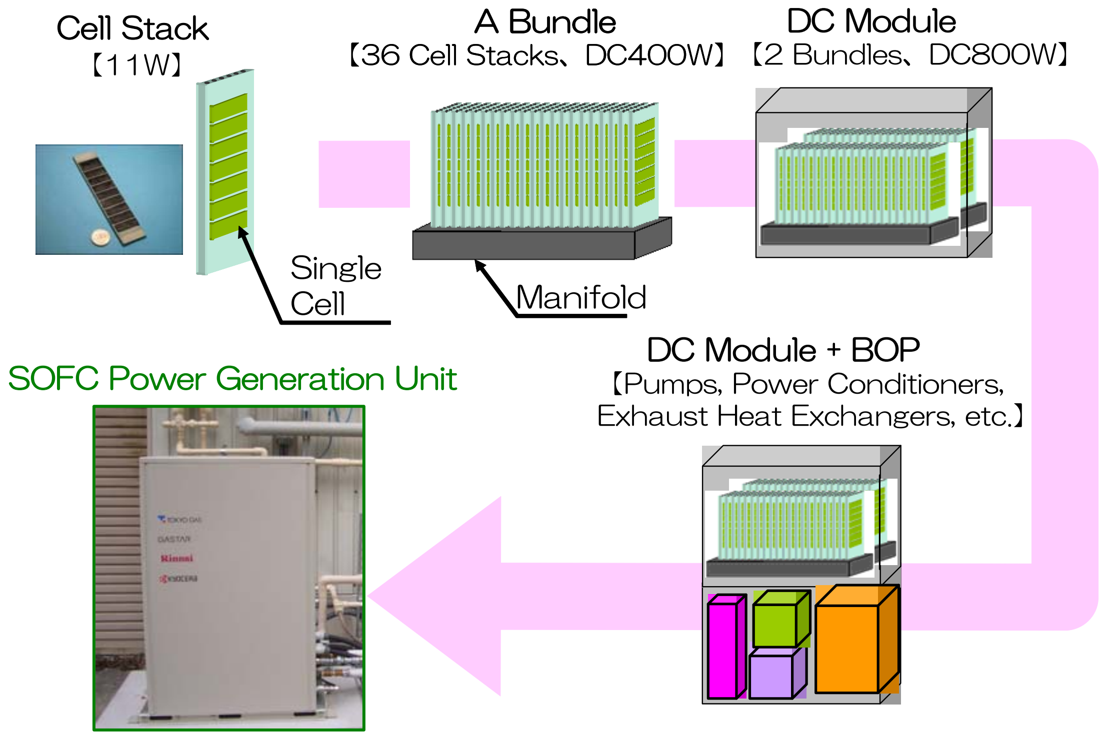


Figure 2. Procedure of assembling SOFC power generation unit.

Table 1. Specifications of SOFC power generation unit.

Manufacturer	Gastar Co. Ltd., and Rinnai Co. Ltd.,
Installation	Outdoor
Dimensions	W 650×D 350×H 1040 mm
Weight	125 kg (Dry)
Fuel	City Gas
Electrical Power Output	0~700 W-AC
Electrical Conversion Efficiency	45%LHV (Target at rated operation)
Temperature of Heat-Recovered Hot Water	75℃
Heat Recovery Efficiency	40%LHV (Target at rated operation)
Control	Automatic start-up, operation, and shut down
Operation	Electric-load-following, continuous operation

Hot-water Tank Unit and Co-generation System

The specification of a developed hot water tank unit is shown in Table 2. Hot water is generated using waste heat from the SOFC power generation system and accumulated little by little to the hot water tank. Hot water is accumulated all the day long according to the SOFC operation schedule. However, the timing and the amount of customer's hot-water-demand changes full of variety, and usually they do not match the amount of accumulated hot water. Then, it occurs both lack and left over of hot water in the tank. For lack of hot water, the unit has a high efficiency condensing boiler built in as a back up.

Figure 3 shows the appearance of the developed co-generation system. To enable the system installed even at narrow space, both units are designed as small as possible. Especially, minimization of the depth dimension is important for urban installation, therefore, both units are fabricated 350 mm in depth. The units are connected with remote controllers for operation and showing status of the system such as output power, amount of accumulated hot water in the tank, and alarm messages which support maintenance such as periodic replacement of component parts.

Table 2. Specifications of hot water tank unit.

Manufacturer	Gastar Co. Ltd., and Rinnai Co. Ltd.,
Installation	Outdoor
Dimensions	W 890×D 350×H 1620 mm
Weight	138 kg (Dry)
Volume of Hot Water Tank	80 L
Fuel	City Gas
Back-up Boiler	High efficient (95%HHV) condensing boiler
Other Features	Waste heat radiator installed
Control	Cooperating with SOFC Power generation unit by mutual unit-communication

Figure 3. Appearance of developed SOFC co-generation system

Experiments and Results

Basic Performance Test

Figure 4 shows the result of basic performance test of SOFC power generation unit. It is confirmed that the power generation efficiency at rated operation is around 41%LHV, which is higher than that of grid power supply efficiency at the households. It is also clear that the drop of the power efficiency in a partial output range over 500W is not so significant like conventional power generation units or other SOFC systems. Because of the optimum-designed DC module, the smaller temperature distribution and the higher heat sustainability led to the moderate performance drop especially to the extent of the half output power range. For heat recovery efficiency, high performance of more than 35%LHV is indicated with 75□ hot water recovery during the rated power operation.

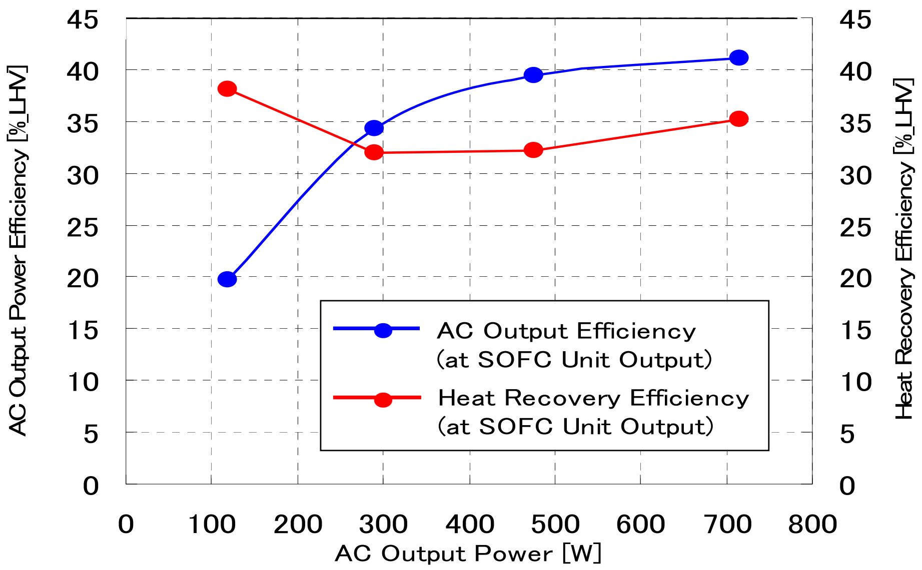


Figure 4. Basic performance of SOFC power generation unit.

Field Test at a Resident

Figure 5 is a photo during a field test. A result of one-day operational performance from the point of electrical load and supply of the developed SOFC system is shown in Fig. 6. The AC demand at the household and output of the SOFC unit have been measured simultaneously and plotted respectively with elapsed time. It is clear that the AC output power follows well according to the sharp-fluctuating load at the household. Through the field test, we obtained the following findings for the current SOFC system as residential power generation system. First, regarding the availability of electrical power output of the system, the daily-average output power is calculated as 482W against the average demand of 913W, which leads to 52.9% of power contribution by the SOFC system. The daily-average power generation efficiency of 37.9%LHV is also comparable to the partial load operation performance in the lab test.

Fig. 7 shows a result of heat demand in the house and heat supply from the hot water tank unit in the same day shown in Figure 6. The figure indicates that the accumulated hot water is effectively used corresponding to the demand of hot water through the day. The utilized amount of recovered heat through the one-day operation is 8.1kWh against the total daily demand of 15.1kWh, which leads to 53.7% of exhaust heat utilization. The daily change of heat recovery performance is shown in Fig. 8. Though the amount of heat recovery differs according to the load following operation of SOFC power generation unit, the heat recovery efficiency is kept relatively stable and high close to 35%LHV. As the daily average performance, 434 W of heat recover and 34.1%LHV of heat recovery efficiency have been recorded through this test.

Figure 5. Field test at a resident.

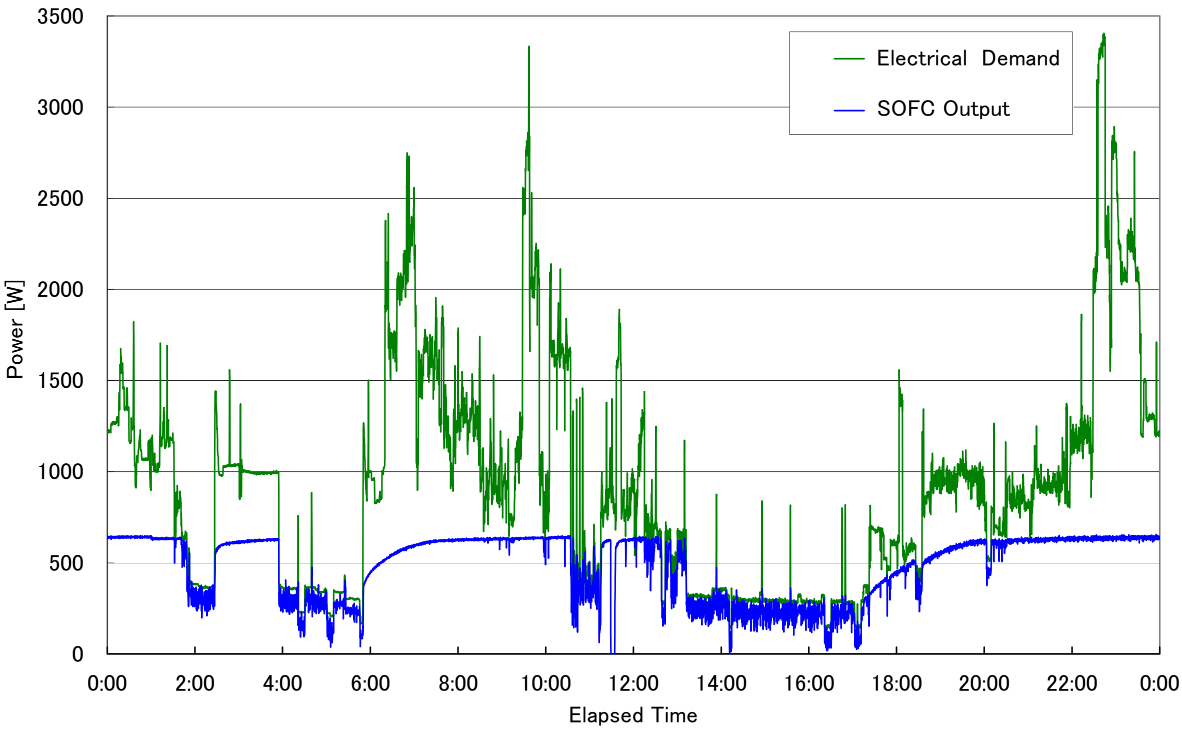


Figure 6. Load-following operations at a resident.

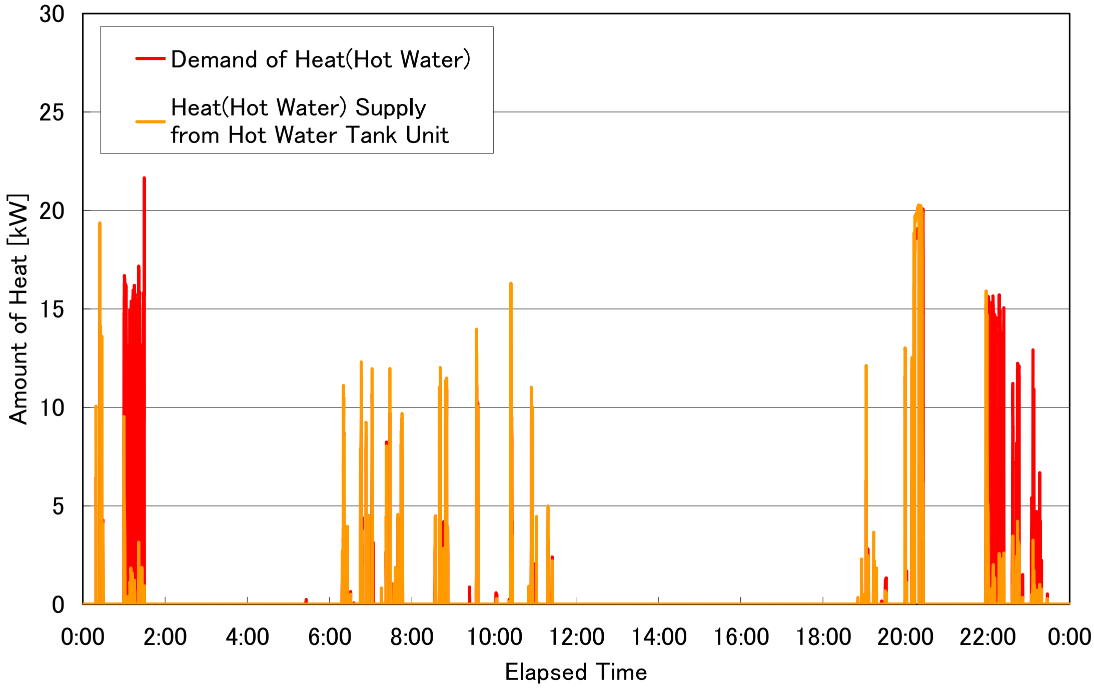


Figure 7. Demand and supply of heat (hot water) at a resident.

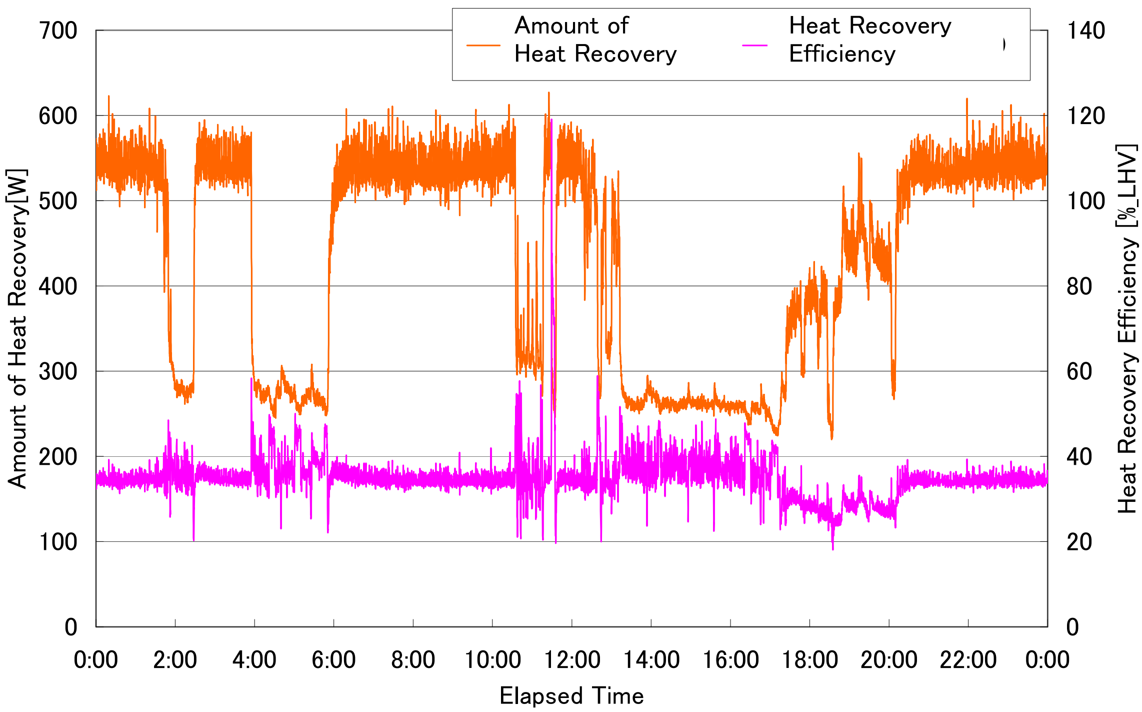


Figure 8. Heat recovery characteristics during one-day operation at a resident.

Figure 9 shows a monthly reduction effect of carbon-dioxide emissions through the field test. The filled diamond plots show the average reduced amount of carbon-dioxide emissions at the residence thanks to the developed SOFC system operation. The error bars show the distribution of reduced amount among the similar field test residences. The data indicate that the carbon-dioxide reduction effects are obtained constantly through the year. The figure also shows that the effect is relatively high in winter. The higher demand of heat leads more effective use of accumulated heat in the tank. Therefore, the effect of energy saving and carbon-dioxide reduction effect become much better. On the other hand, the emission reduction effect in summer is less than winter. However, we still have a certain level of carbon-dioxide reduction, thanks to the higher power generation efficiency of SOFCs. It has been found that the annual carbon-dioxide emission reduction reaches 1,400 kg, which corresponds to 20% reduction of the emission in the residence. From this result, it has been confirmed that the developed SOFC system have environmentally-enhancing potentials in a wide range of environments.

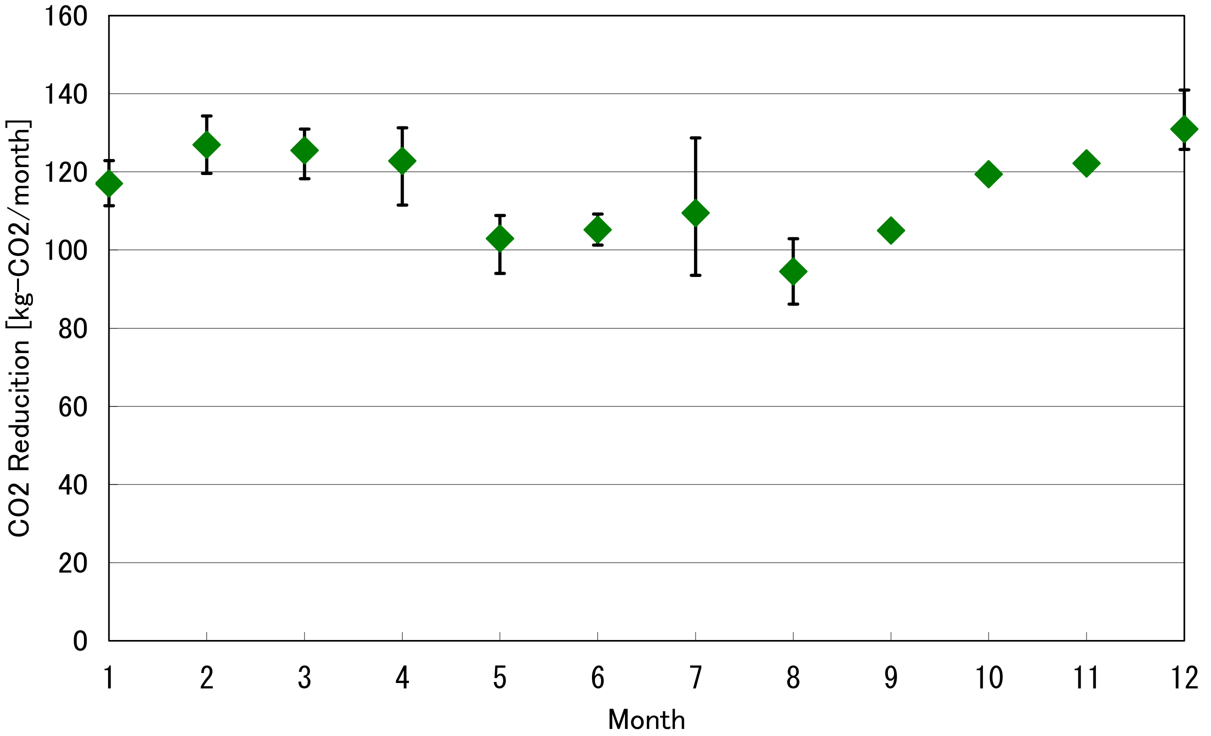
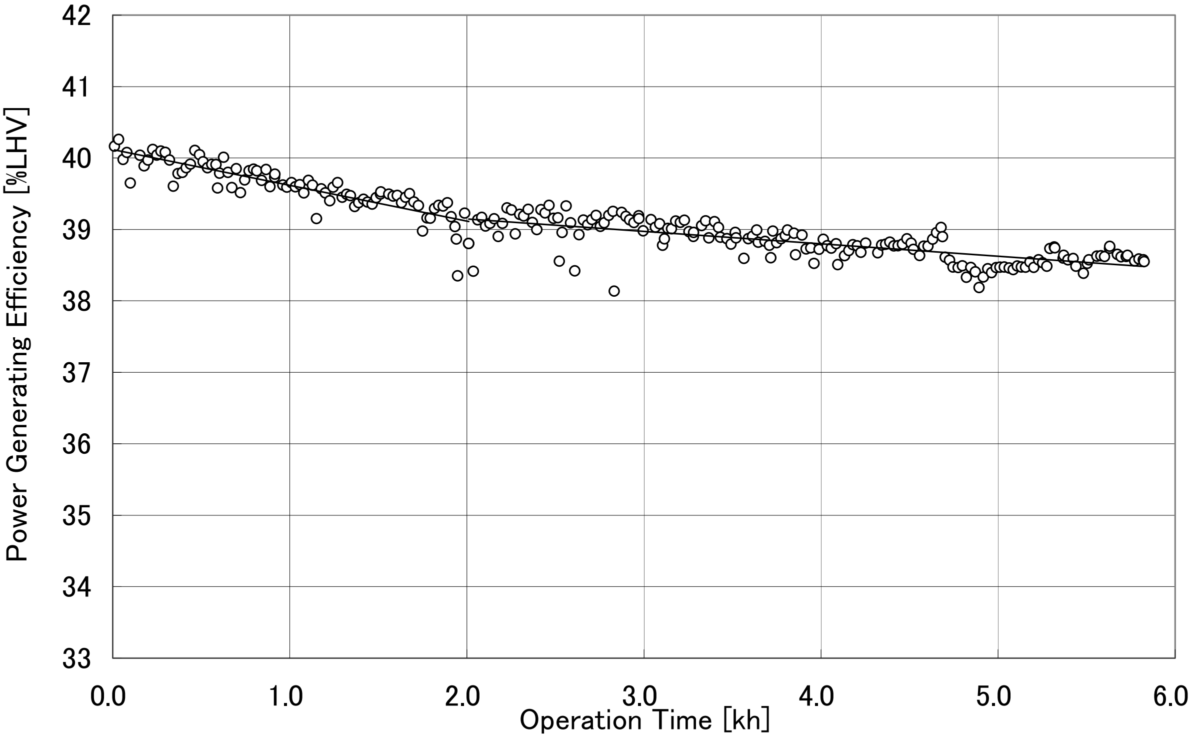


Figure 9. Monthly CO2 reduction through the field test.

Durability of the system is shown in Figure 10. In this graph, all plots are power generating efficiency under rated output conditions with operation time at the residence, which indicate system degradation trend through the field test. The degradation rate is decreased after 2,000 hours operation, which indicates the possibility for the long-term durability of the developed system. However, the durability has not been sufficient yet to bring the SOFC systems into the market. We believe that the performance durability will be improved by designing the heat flow in the DC module more adequately to decrease the temperature distribution of cell stacks.



Conclusions

A residential SOFC co-generation system with the all-ceramics-segmented cells has been developed and various performance tests have been conducted. By developing a design-optimized DC module, the high electric power output efficiency with effective exhaust heat recovery have been confirmed as basic performance. The SOFC power generation unit suitably operates as a residential co-generation system by connecting the developed hot water tank unit and the controlling system. Potentials for outdoor installation, availability as a residential co-generation system, and effectiveness of commercial utilization as an efficient and environmental-friendly energy system for households have also been verified through the field test at a resident.

References

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