Development of PEFC Co-generation system for Japanese Residential Market

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ABSTRACT

Tokyo Gas has been conducting R&D on natural gas fuelled PEFC co-gen aiming at the commercialization especially for residential application. Towards the market introduction of residential PEFC co-gen in early 2005, various R&D activities have been carried out, such as developments of the integrated fuel processor and desulfurizer agent, examination of specification, optimization of operation control system, performance evaluation tests of prototypes at laboratory, and the field trial at actual houses etc.

As for integrated fuel processor, efficiency at 30% load was successfully improved by 5 points and weight was reduced by half, as compared with the former type. Sulfur removal capability of the newly-developed desulfurizer dramatically increased as compared with the commercialized one.

Performance evaluation at laboratory showed the efficiency at low load of latest prototype PEFC system was especially improved, and electrical efficiency was over 30% even at 50% load.

By the optimization of operation control system, generated power and recovered hot water could be used effectively, for PEFC systems were operated based on automatic demand forecasting.

Results of field trials of prototypes showed that average of generating hours per one operation mostly doubled in FY2003 compared with FY2002. This is partly due to improvement of the operation control system.

Tokyo Gas will continue R&D activities on PEFC co-gen furthermore to achieve further energy-saving, CO_2 reduction, economical efficiency and reliability to cultivate the way to efficient use of the energy.

INTRODUCTION

Tokyo Gas has been conducting intensive research and developments of fuel cells including polymer electrolyte fuel cell (PEFC). PEFC has desirable characteristics, such as easy start-up and shutdown, compactness and light-weight etc., for a small scale co-generation system (co-gen). Counting on them, R&D on natural gas fuelled PEFC co-gen for residential application in Japan has been conducted. Our activities relating to residential PEFC co-gen include establishment of a specification of PEFC co-gen fitting market requirements, development of integrated fuel processors, and evaluation of the performance through operation tests and field trials. In this paper, these activities towards the first market introduction will be reported.

RESIDENTIAL PEFC CO-GENERATION SYSTEM

In a conventional Japanese house, electricity is supplied by the commercial power grid, and hot water is mainly supplied by a gas-fired water heater. On introducing of a natural gas fuelled PEFC co-gen to the house, the efficient use of both electricity and hot water from the PEFC co-gen is essential to achieve high energy efficiency. An image of a residential PEFC co-gen is schematically shown in Figure 1. Generated electricity is connected to the commercial power grid and consumed by electrical appliances in the house, while hot water is stored in a storage tank and supplies the demand.

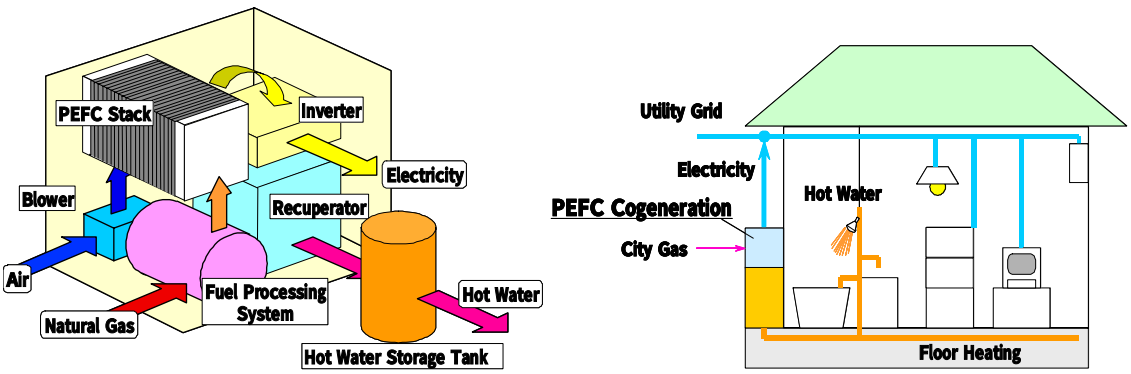


Figure 1. Schematic Configuration of Residential PEFC Co-gen.

In the typical energy demand of a Japanese household, an amount of electricity demand is usually greater than that of hot water. On the other hand, the PEFC co-gen supplies more energy in hot water than in electricity. Therefore it is difficult to meet all the electricity demand only by the PEFC co-gen system without any surplus of hot water. In order to achieve the maximum energy saving with avoiding generation of excess amount of hot water, it is desirable to operate the residential PEFC co-gen just so as to fulfill the hot water storage tank and to utilize all of the generated hot water. In this case, grid connection of the residential PEFC co-gen is essential because the commercial power grid is necessary to supply the shortage of electricity. The operation concept of the residential PEFC co-gen system is schematically shown in Figure 2.

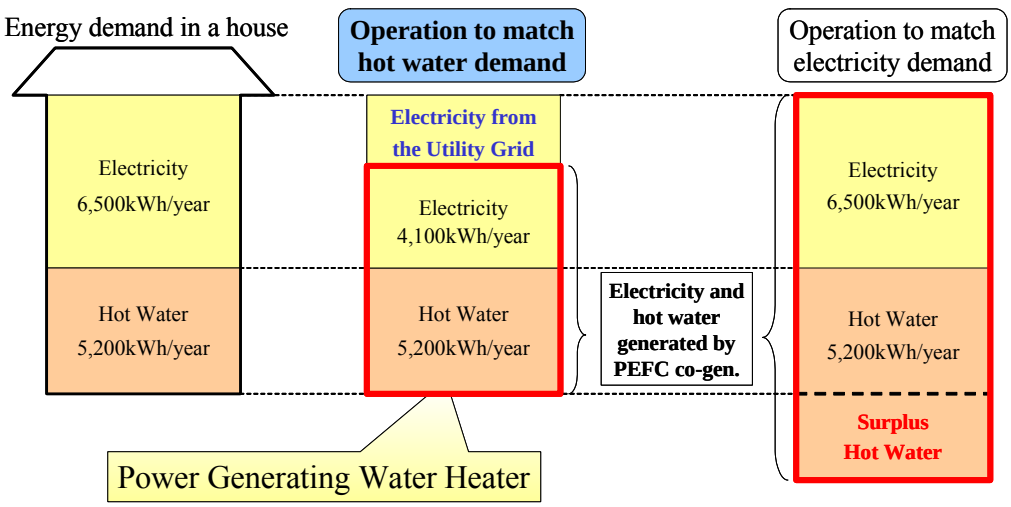


Figure 2. Operation Concept of the Residential PEFC Co-gen.

In consideration of primary energy saving and customer's economic merits by saving utility expenses, the optimum scale of the residential PEFC co-gen for a typical Japanese household was estimated at 1 kWe class. In addition, it is desirable to shutdown a system when demands, either hot-water or electricity, become or be expected small.

On condition that there is no surplus of hot water, 16 % of primary energy and 27 % of CO_2 emission are estimated to be reduced compared with using energy from conventional energy system in Japan, as shown in Figure 3. In this estimation, efficiencies of PEFC co-gen are assumed to be 31 % (HHV) for electricity and 40 % (HHV) for hot water, based on our conceptual design.

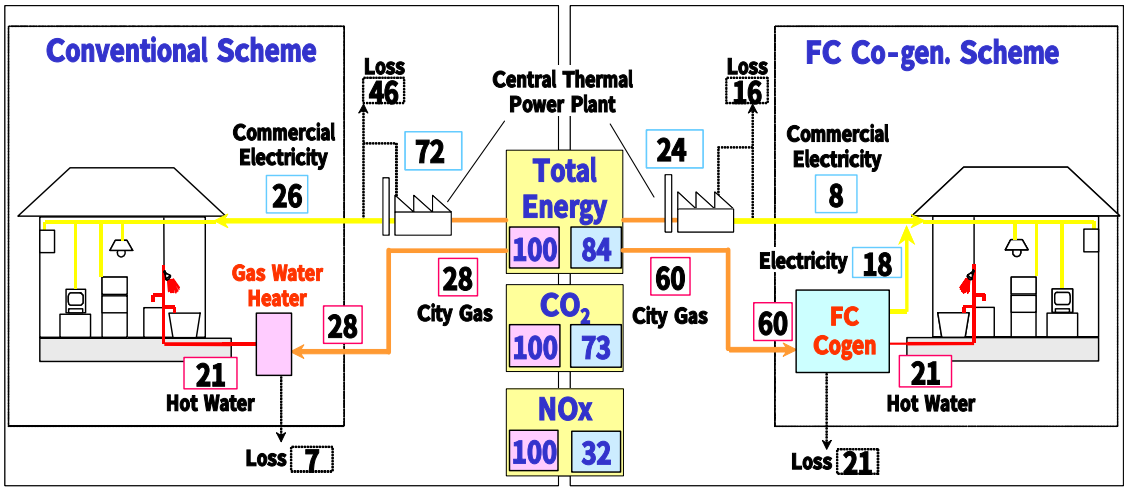


Figure 3. Estimated Merit of Japanese Residences (Example)

IMPROVEMENT OF THE INTEGRATED FUEL PROCESSOR

Fuel processing technologies are very important for a natural gas fuelled PEFC co-gen to achieve high performance. General fuel processing process from natural gas to hydrogen is shown in Figure 4.

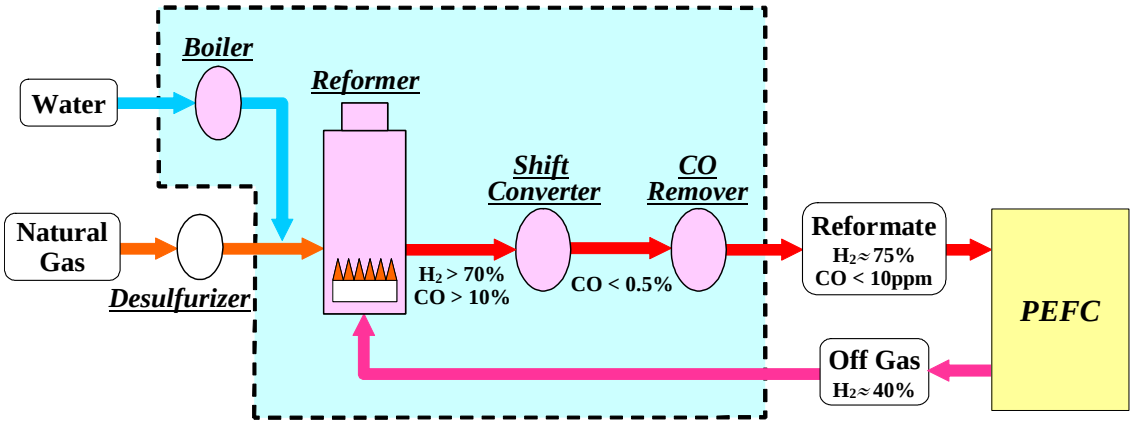
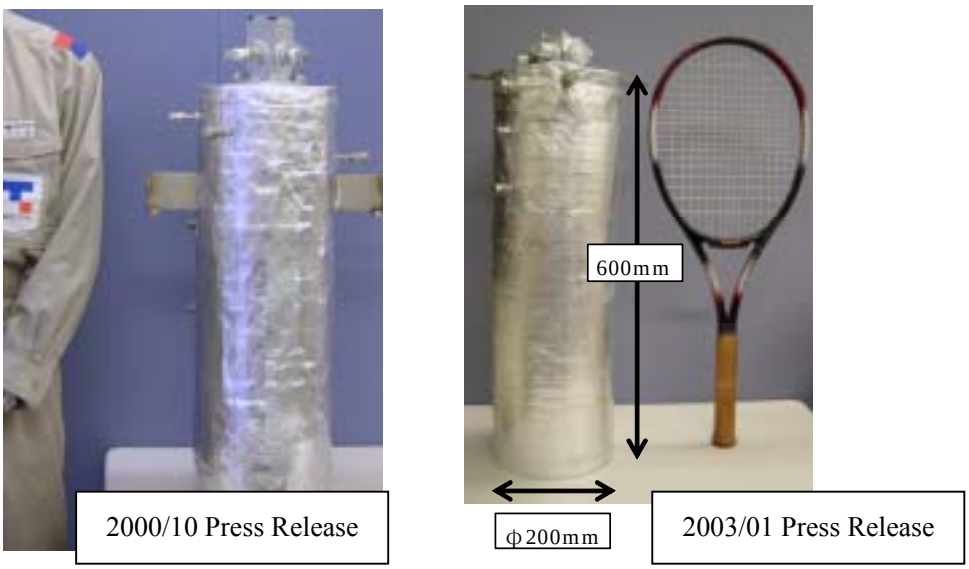


Figure 4. Fuel Processing

Tokyo Gas has been developing a fuel processor designed to supply natural gas reformate for 1 kWe class residential PEFC co-gen. The processor features integrated structure of steam reformer, CO shift converter, CO remover, steam boiler and other necessary functions, and provides compactness in size and high efficiency.

In 2000, the developed fuel processor demonstrated world-highest level fuel processor efficiency of 83% (HHV) and small size of φ200mm x 600mm (19 liters). Based on this technology, advanced-type fuel processor successfully achieved improvement of partial load efficiency, reduction of weight and simplification of internal structure (10-folded tube to 4-folded tube), which will lead to cost reduction. Photographs of an external view of the former and advanced integrated fuel processors are shown in Figure 5.



a) Former b) Advanced

Figure 5. External View of the Integrated Fuel Processor

Efficiency at 30% load of an advanced integrated fuel processor successfully improved by 5 points and its weight was reduced by half (17kg including thermal insulation), as compared with the former one. These improvements owe to optimization of the heat flow design inside of a fuel processor and realization of the optimal catalyst combination. Furthermore, heat capacity of fuel processor was reduced by half with its weight, so start-up time of system also can be expected to be reduced. The comparison of low load efficiency and characteristic between the former and new integrated fuel processors (FPS) are shown in Table 1 and Figure 6.

Table 1. Comparison of the Characteristic between the Former and New Integrated FPS

		Former Integrated FPS	New Integrated FPS
Class		1kWe	1kWe
FPS Efficiency* (HHV Base)	100% Load	83%	83%
	30% Load	71%	76%
Volume		19L	19L
Weight	Including Thermal Insulators	30kg	17kg
	Excluding Thermal Insulators	27kg	13kg

* FPS Efficiency = Heat Value of Hydrogen used in PEFC / Heat Value of Input Fuel

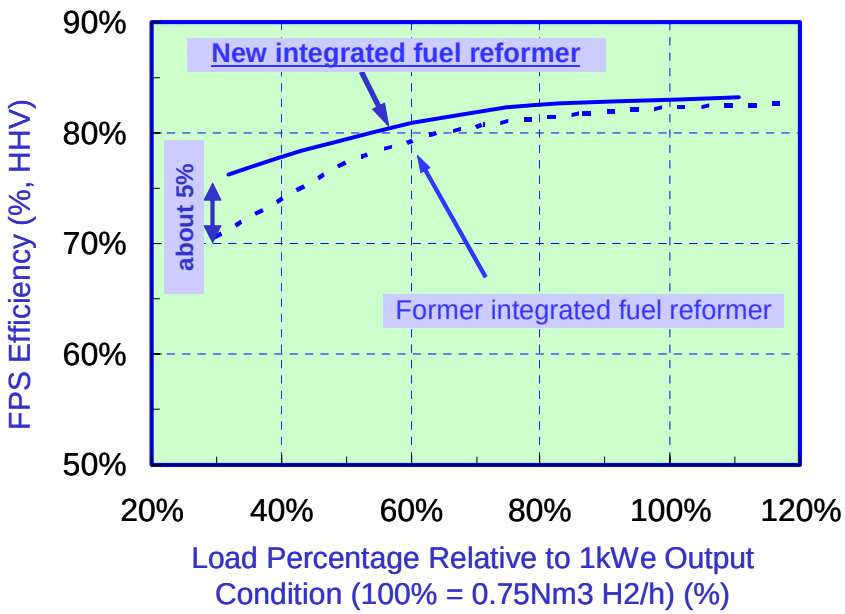


Figure 6. Comparison of Efficiency between the Former and the New FPS

NEW DESULFURIZER AGENT

Sulfur compounds in natural gas and LPG have to be removed before introduction to fuel processors, because they degrade the activity of catalysts used in the fuel processors. Tokyo Gas has developed a high-performance desulfurizer using a zeolite-base material that can easily remove trace amount of sulfur compounds at ambient temperature. For residential PEFC systems, which require quick and easy start-up and simple operation, it is important to use a desulfurizer functioning at ambient temperature. Materials based on activated carbon (AC) and zeolite are commercially available for desulfurization

adsorbents working at ambient temperature, but their sulfur removal capabilities are insufficient. Sulfur removal capability of the newly-developed desulfurizer dramatically increased compared with the commercialized one, as shown in Figure 7. Furthermore, Figure 8 shows that newly-developed desulfurizer was found out not to be easily influenced by the impurities, such as water in fuel. Therefore, when this newly-developed desulfurizer is applied for 1kW residential PEFC co-gen, required quantity is estimated to be only about 200 cc per year in typical conditions in Japan.

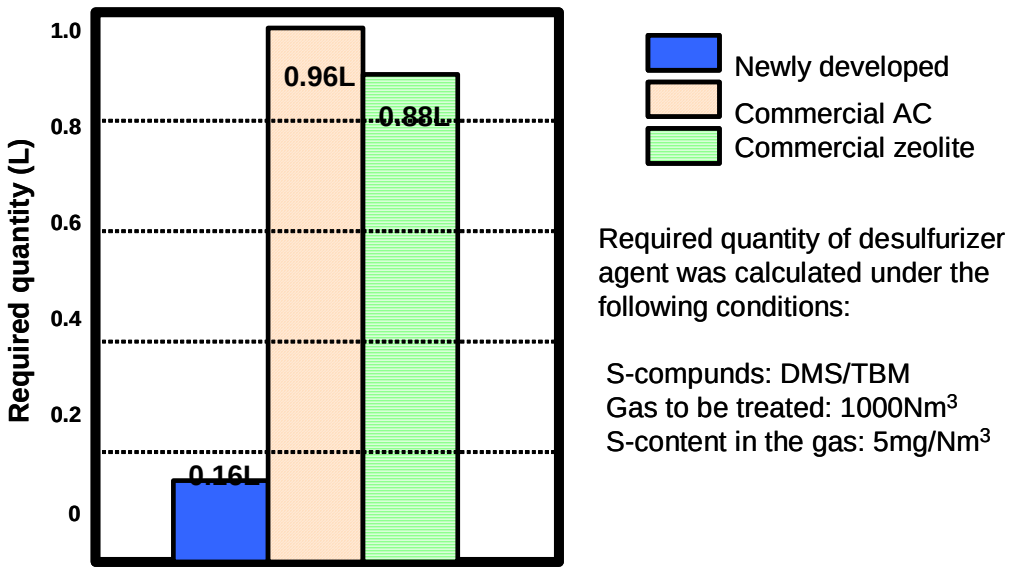


Figure 7. Required Quantity of Desulfurizer Agent

In addition, this desulfurizer has two excellent characteristic features. Firstly, it requires no pretreatments and can remove sulfer compounds only by passing the fuels through it at ambient temperature, offering quick start-up characteristics and easy operation. Secondly, the desulfurizer agent changes its color from white to orange as desulfurization reaction proceeds, shown in Figure 9. This offers an indicator function by which users can easily know the time for replacement.

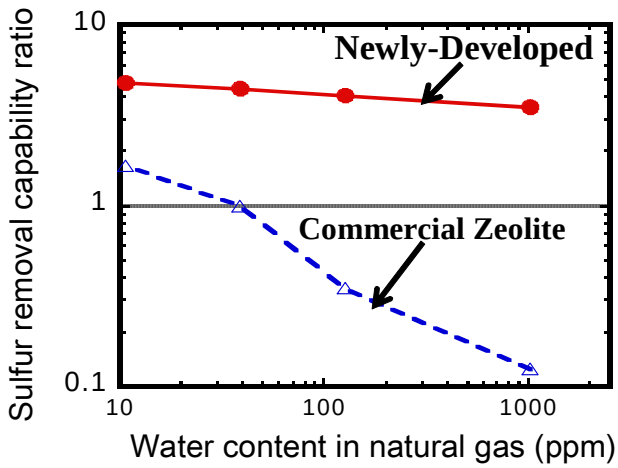


Figure 8. Comparison of Sulfur Adsorption Capability (Water Resistance)

Figure 9. Desulfurization Reaction Proceeds

PERFOEMANCE EVALUATION (OPERATION TEST)

Optimum Specification of PEFC Co-gen

Specification examination of PEFC Co-gen has been conducted towards the market introduction in Japan. The target specifications of our company are shown in Figure 10.

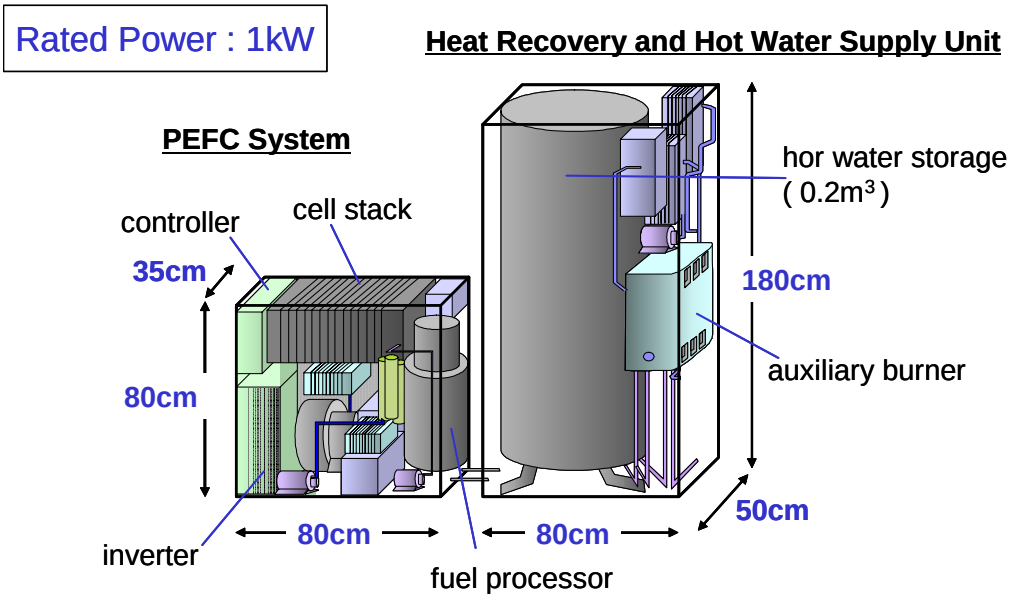
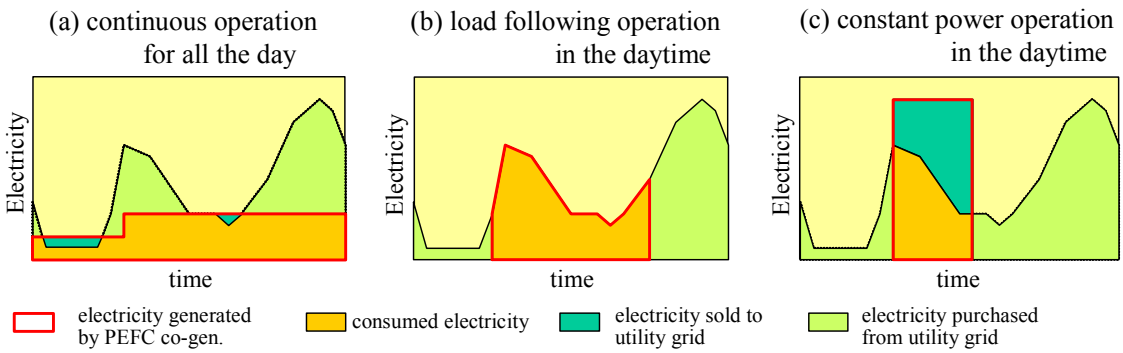


Figure 10. Optimum Specification of PEFC Co-gen

The operation method is basically DSS (Dairy Start-up and Shutdown) and load following operation to avoid hot water surplus, described in Figure 11 (b).



Operation Patten	(a)	(b)	(c)
Rated Power	Small (500W)	Medium (1kW)	Large (over 1kW)
Technical Hurdle	Longer Life High efficiency	Load Following operation, Frequent start-up and shutdown	Frequent start-up and shutdown
Peak Cut Effect for Utility Grid	Small	Medium	Large
Reverse Power to Utility Grid	Small	None	Large

Figure 11. Operation Patterns of Residential PEFC Co-gen.

Initial market is assumed to be newly constructed independent houses. Using N_2 at start-up and shutdown procedures is not practical from a viewpoint of the installation space for N_2 cylinders, refilling frequency, and economical efficiency etc., so N_2-less start-up and shutdown procedures is needed for commercialization.

Operation Tests

Tokyo Gas has been evaluating the PEFC co-gen prototypes through operation tests regarding the fundamental performances. In this activity, the PEFC co-gen prototypes which incorporated with Tokyo Gas's advanced integrated fuel processor technology, "Pre-commercial 1 (former), and Pre-commercial 2 (advanced)", were evaluated. The specifications and photographs of the systems are shown in Table 2 and Figure 12.

Table 2. Specifications of the PEFC Co-gen System for Operation Test

	Pre-commercial 1	Pre-commercial 2
Rated Power	1.0 kW	1.0kW
Heat Recovery Temp.	60 °C	60 °C
Power Range	0.3 – 1.0 kW (11 step)	0.3 – 1.0 kW (11 step)
Dimensions	900W x 280D x 900H mm	840W x 350D x 900H mm
Weight	174 kg	190 kg
Start-up and Shutdown gas	N_2	N_2 less

Figure 12. Photographs of Pre-commercial 1 (left) and 2 (right)

Figure 13 shows electrical efficiency of Pre-commercial 1 (PCME1) and Pre-commercial 2 (PCME2). These systems are manufactured by Ebara Ballard Corporation. Compared with PCME1, electrical efficiency of PCME2 at low load was especially improved, and it reached over 30% even at 50% load. This result owed largely to the improvements of integrated fuel processor developed by Tokyo Gas. Moreover, PCME2 can be operated with N_2-less start-up and shutdown procedure and the good results were obtained with the examination using this procedure.

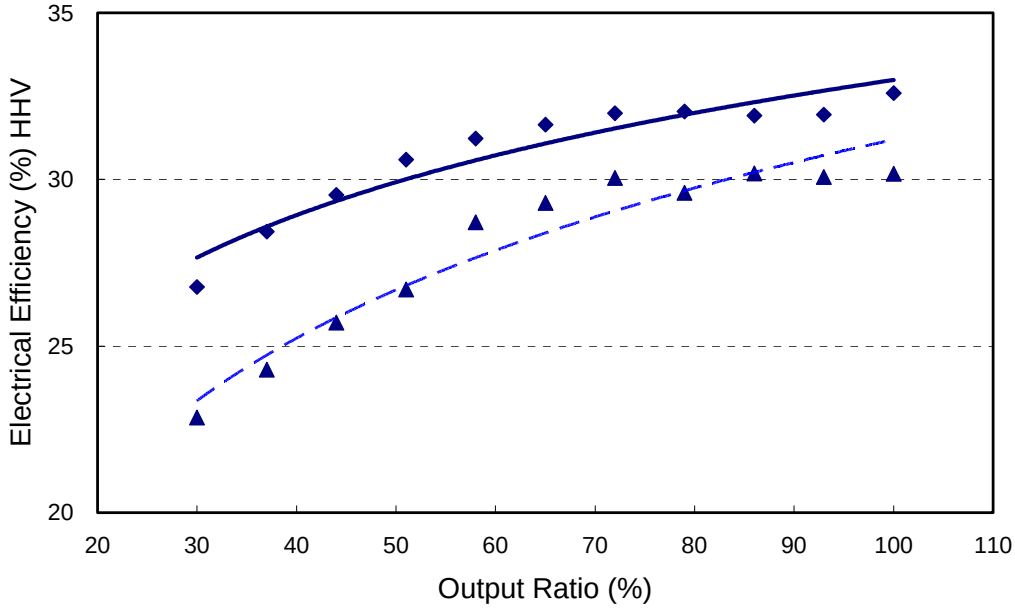


Figure13. Electrical Efficiency of PCME1 (dotted line) and PCME2 (solid line)

DEVELOPMENT OF AN OPERATION CONTROL SYSTEM

If the PEFC co-gen is operated only according to the demand, it is difficult to achieve large effect for energy saving, for a) low load operation at low electrical demand such as during the midnight hours, b) heat loss because of the large gap of time between demand and heat recovery, c) energy loss by frequent start-up and shutdown, etc. Therefore, to achieve the high energy saving and reduction of CO_2 emission by introducing the PEFC co-gen, the operation control system has been developed in Tokyo Gas. This system daily predicts demand based on past data, for example, it predicts the time when hot water storage shall be 100% for large demand of hot water, such as taking a bath. The control system optimize the operation plans with minimizing start-up and shutdown times for durability and energy saving.

FIELD TRIAL

Tokyo Gas has carried out field trials since March 2002. Two PEFC co-gen prototypes are installed in Tokyo area in order to verify our original technologies such as

operation control, evaluate the performance and reliability of system, confirm the energy saving and obtain the know-how of installation and maintenance. The field trial system is schematically shown in Figure 14 and the photographs are in Figure 15.

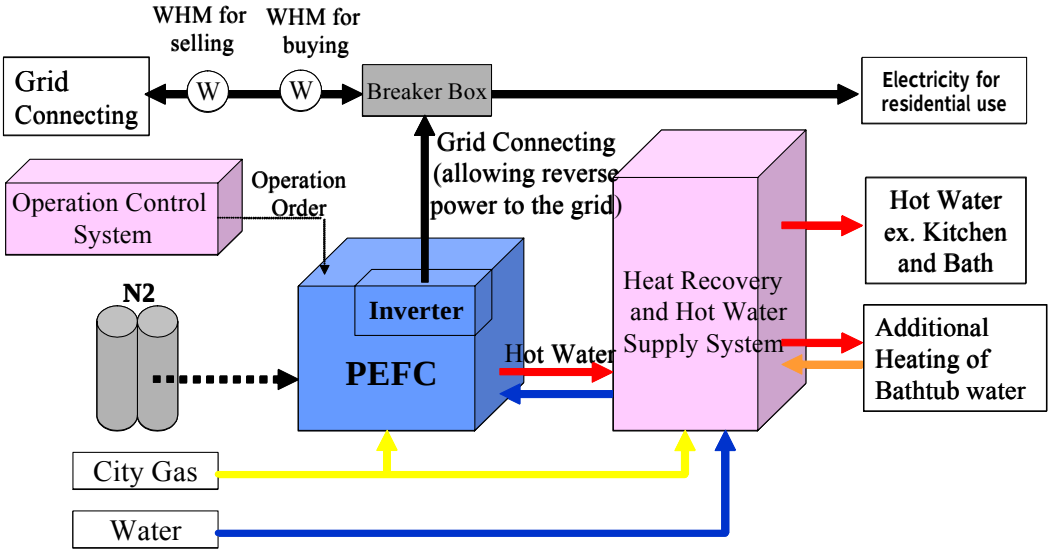


Figure 14. Schematic of Field Trial

Figure 15. External Views of Field Trial

Operation results of field trial with prototypes are shown in table 3. Test machines were replaced to the new type at the end of FY2002, but were not the newest one. Table 3 shows that the average of generating hours for each operation has almost doubled in FY2003 compared with FY2002. This is partly due to improvement of an optimal operation control system.

Table 3. The Results of Field Trial

	Test Site A		Test Site B	
Test Period	02/03 - 03/02	03/03 – **	02/03 – 02/12	03/03 – 04/06
Trial Times	305	304	264	340
Generation Times	271	291	226	278
Generating hours (average at once)	1304 hr (4.8 hr/once)	1940 hr (6.7 hr/once)	909 hr (4.0 hr/once)	2751 hr (9.9 hr/once)
Amount of Generated Power	1081 kWh	1338 kWh	872 kWh	2219 kWh
Amount of Heat Recovery	1673 kWh	2644 kWh	1796 kWh	3524 kWh

**As end of 2004/06

In the field trial of FY2003, the relation between the amount of primary energy reduction per day and the average of electric efficiency which includes all start-up and standby energy is shown in Figure 16. The amount of primary energy reduction was calculated by the difference of the primary energy between the actual results of using PEFC co-gen and assumption of being provided by conventional system (thermal power plants and gas-fired water heater). Each dot shows calculated result from 7 days continuous data.

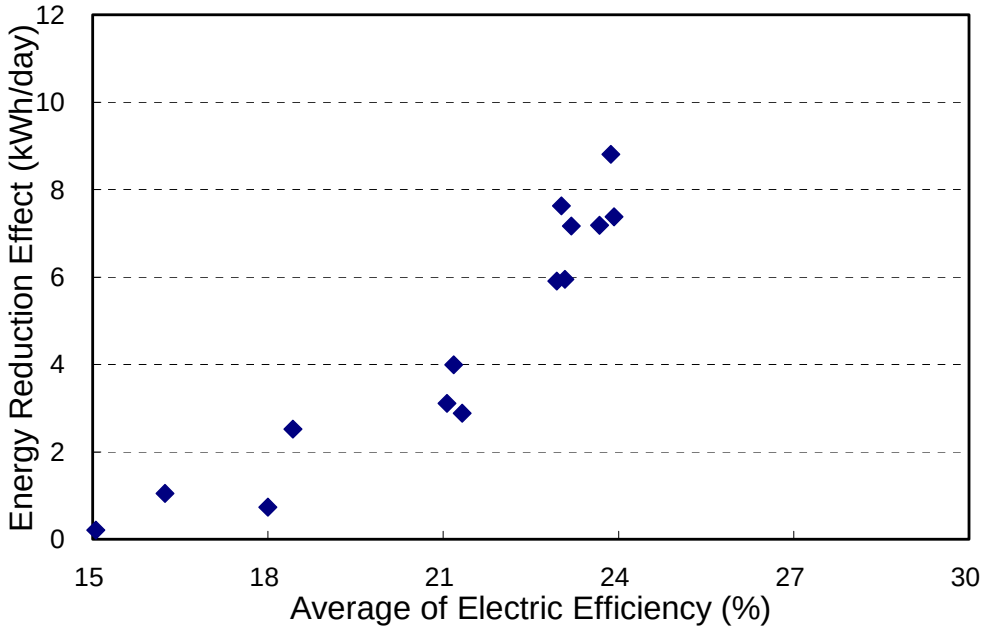


Figure 16. Amount of Energy Reduction (FY2003 Field Trial)

It turns out that the average of electric efficiency and the amount of primary energy reduction have strong correlation. When the amount of reduction for one month (30 days) is calculated by using actual data which showed the best reduction effect, the amount of primary energy reduction is equivalent to about 950 MJ per month.

In order to improve energy saving effect, it is necessary to improve the average of electrical efficiency. To realize that, reduction of start-up and standby energy, an improvement of electrical efficiency including partial load, and optimization of operation control such as the reduction of start-stop numbers into 1 time per day as many as possible, are needed.

With advanced PEFC co-gen for FY2004 field trial, the electrical efficiency at the low load was so sharply improved that electrical efficiency reached over 30% even at half load. Moreover, standby energy was also reduced almost by half as compared with the PEFC co-gen for FY2003 field trials. When this machine is applied to a field trial, therefore, the further improvement of the average electrical efficiency can be expected, and much more improvement for the market introduction product.

From April 2004, new field trials using FY2004 machines started. Site locations of field trial (including previous sites) are shown in Figure 17. The operation results of these sites will be reported when evaluations with annual data can be performed.

Figure 17. Locations of Field Trial Sites

GOVERNMENT PROGRAM

Tokyo Gas has been participating in the Japanese government programs relating to stationary PEFC, such as establishment of codes and standards, and field trials, as a member of Japan Gas Association.

FUTURE PROSPECTS

Aiming at initial market introduction of the residential PEFC co-gen in early 2005, Tokyo Gas started joint development with two of PEFC system manufacturer groups, Ebara Ballard group (Ebara Ballard Corporation, Ebara Corporation, and Ballard Power Systems Inc.) and Matsushita Electric Industrial Co., Ltd. In our company, related sections such as sale and maintenance etc. have been organized to prepare for the market introduction. Tokyo Gas will continue the intensive R&D activities on PEFC co-gen to achieve further energy-saving, CO_2 reduction, economical efficiency, and reliability, and to cultivate the way to efficient use of the energy through the spread of residential PEFC co-gen.

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