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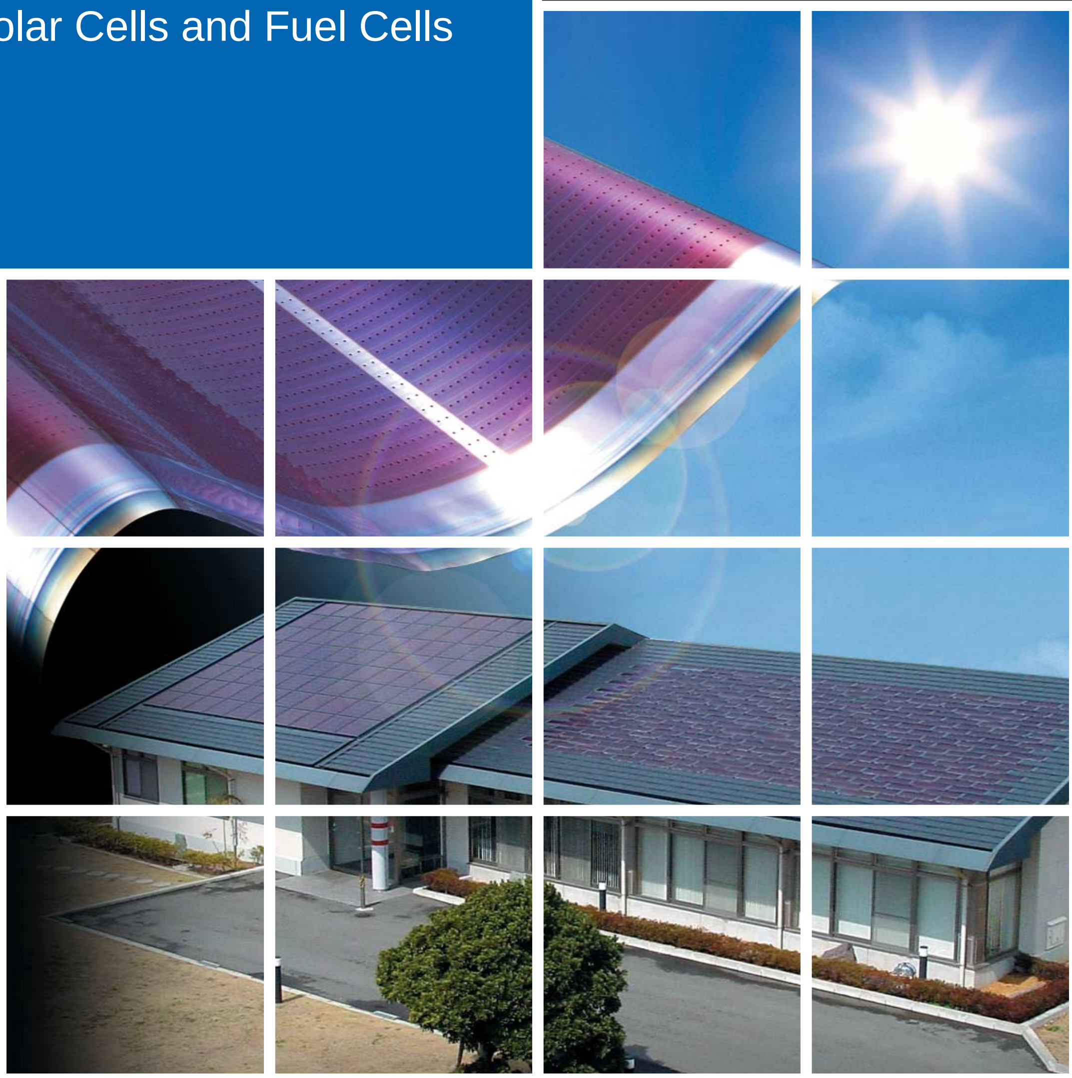
Solar Cells and Fuel Cells



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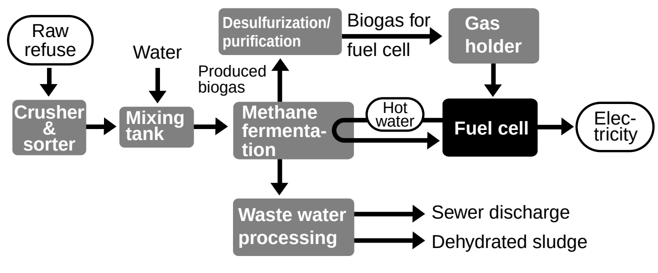
The technology has arrived.

Biogas fuel cells convert raw refuse into energy to provide electrical power generation.

Raw refuse or other organic waste is fermented to release methane, and this methane gas is used as fuel for the fuel cells in a biogas power generating system. Fuel cells generate electrical and thermal energy by chemically reacting hydrogen, which has been extracted from the methane gas, with oxygen in the atmosphere. This promising technology is expected to lead to reduced CO_2 emissions and to the effective utilization of natural resources.


100 kW
Phosphoric-acid fuel cell

Mechanism of the fuel cell power generation system for converting raw refuse into biogas



Biogas Fuel Cell Power Generation System

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REVIEW

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Solar Cells and Fuel Cells

CONTENTS

Cover photo:

The production of solar cells worldwide is supported by various national governments and is growing by nearly 40 % annually, and expectations for photovoltaic generation are increasing. The future promotion and popularization of this technology requires the development of techniques capable of realizing broad based cost reductions.

Fuji Electric is engaged in the development of amorphous solar cells, which are fabricated on a low-cost substrate of plastic film, are lightweight and well suited for mass production.

The cover photo shows the Health Promotion Center at Fuji Electric Corporate Research and Development Ltd. Film-substrate amorphous solar cells have been mounted on the roof of this building and are undergoing verification testing. The solar cells on the left half of the roof are conventional cells encapsulated by a glass substrate, and the cells on the right half are integrated with building material and are attached to tiles. The solar cells complement the design of the building and create a subdued atmosphere.

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Present Status and Prospects for New Energy

Norio Kanie
Noriyuki Nakajima

1. Introduction

The situation regarding energy in Japan is changing dramatically. This change stems from efforts to protect the global environment beginning with the 3rd session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3), held in 1997 in Kyoto, Japan, and is also due to the liberalization of the electric power market in Japan.

Ever since the first and second oil crises, the research and use of alternative energy has been promoted in Japan. Examples of alternative energies include coal liquefaction, photovoltaic generation, utilization of solar heat, and geothermal power generation. A typical household had a solar-powered water heater installed on the house roof to supply hot water for a bathtub, for example. At one time, 800 thousand of these solar-powered water heaters were installed annually, contributing to a reduction in demand for crude oil. However, as the supply of crude oil stabilized, solar-powered water heaters gradually slipped from public awareness.

The subsequent deterioration of the global environment due to global warming, acid rain, ozone depletion, reduction of tropical forests, etc. has become critical issue for the international community. Sulfur oxides (SOx) and nitrogen oxides (NOx) emissions are regulated, and statutory regulations have mandated the discontinuation of carbofluorocarbon gas production. In order to combat global warming, we must reduce those substances that contribute to the warming problem. Carbon dioxide (CO_2), one of the substances contributing to global warming, is generated mainly by the combustion of fossil fuels, and therefore the usage of fossil fuels must be curtailed. The introduction of new alternative energy sources will lead to a reduction in CO_2 usage.

2. Present Status and Issues of New Energy

2.1 Definition

New energy is prescribed under the Special Law for Promoting New Energy Utilization as "resources for the production, creation and utilization of alternative energy, which are not yet in widespread use due to economic reasons, but are expected to contribute significantly to accelerating the adoption of alternative energy." The resources specifically mentioned include photovoltaic generation, wind power, utilization of solar heat, ocean thermal energy conversion, waste power generation, thermal utilization of waste, waste-derived fuel production, electric (and hybrid) powered vehicles, natural gas-fueled vehicles, methanol-fueled vehicles, natural gas cogeneration, and fuel cells. Figure 1 shows the technical levels of these new types of energy.

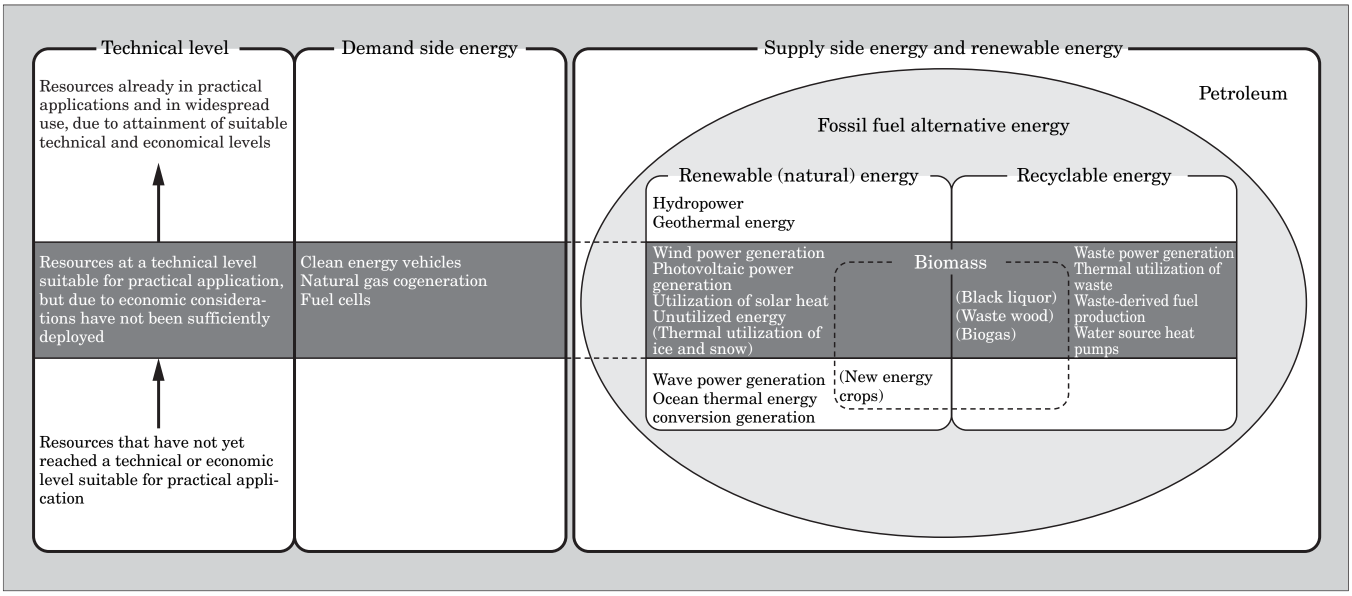
2.2 Present status

In December 1999, a New Energy Subcommittee was formed within the Ministry of International Trade and Industry's (presently the Ministry of Economy, Trade and Industry) Advisory Committee for Energy, and this subcommittee began studying the future course of Japan's energy policy. After a total of 18 meetings, the subcommittee released a written report in June 2001, the contents of which specified the quantity of new energy presently in use, the expected adoption and target levels for new energy by 2010 (see Table 1). New energy accounted for 1.2 % of the total supply of primary energy (equivalent to 6,930 ML of crude oil) in 1999, and 3 % of the total supply (equivalent to 19,100 ML of crude oil) is targeted by 2010.

The widespread adoption of new energy hinges upon the ability to achieve economic efficiency. Table 2 lists examples of estimated unit prices for power generation by various types of new energy resources.

Sufficient technical capability for practical application of new energy resources has been achieved and ongoing technical development is concentrating on finding ways to lower costs. Various measures are being studied in order to achieve the targets for 2010. One such measure under consideration is a bill requiring electric companies to provide a certain minimum quantity of power from new energy sources.

Fig.1 Technical level of new energy resources



2.3 Targeted adoption levels

Table 1 shows the targeted levels of new energy adoption by 2010, as set forth by the New Energy Subcommittee. The table shows both the case of continuation of the current policy and the target case, which implements additional measures. Policies aimed at the target cases were considered. New energy can be classified according to the supply-side and the demand-side. The supply-side includes photovoltaic generation, wind power generation and waste generation, and has a target value of the equivalent of 19.1 billion liters of crude oil. The demand-side includes clean energy vehicles, natural gas cogeneration, and fuel cells.

Renewable energy resources include new energy, hydropower (general waterpower) and geothermal energy, and as shown in Table 1 (b), the 2010 estimate and target is 40 billion liters, or approximately 7 % of the primary energy supply. This target value is 10 billion liters greater than the of 30 billion liters estimate according to existing policy, and that differential will be made up from new energy.

The target values in Table 1 are based upon values in the 1998 interim report by the Supply and Demand Subcommittee of the Advisory Committee on Energy, and significant differences between figures contained therein and 2010 target values are listed below.

(1) Wind power generation is increased from 300 MW to 3,000 MW
(2) Biomass power generation is added to the power generation field
(3) Unutilized energy is considered a group and includes the addition of ice energy
(4) Targeted capacity for cogeneration is halved from 10,020 MW to 4,640 MW.

The targeted adoption for all types of new energy is at the same level as approximately 3 % of the primary energy supply. Policy emphasizes solar power generation, power generation from waste, wind power generation and utilization of solar heat.

2.4 Issues

Issues concerning the adoption of new energy resources include economic efficiency, output stability and utilization factor. The resolution of these issues will accelerate the adoption of new energy.

(1) Economic efficiency

For each type of new energy resource, technical development is vigorously pursuing various techniques to reduce equipment cost. For example, wind power generation aims to reduce costs by increasing equipment capacity, and a 2,500 kW capacity windmill has been developed. Sixty percent of the cost of a photovoltaic power generation system is attributed to the expense of solar cell modules. To decrease the solar cell module cost, module efficiency is being enhanced, modules are being fabricated with larger surface area, and module production is being implemented on a large scale. However, at present, photovoltaic power generation remains approximately three times as expensive as the cost of residential use electricity.

With fuel cells, if waste heat is completely utilized, the power generation cost will approach the cost of commercially purchased electricity. However, battery cells have a lifespan of approximately 5 years (40,000 hours) and reduction of their replacement cost remains a challenge. Experimental studies are underway to extend the lifespan of existing cells, and in the near future, achievement of life spans on the order of 60,000 hours is expected.

Table 1 Share of new energy will grow to about 3 % by 2010

(a) Trends and targets of new energy (supply side) Units: 1,000 kL (1,000 kW)

		1999 results		2010 estimate & target				2010/ 1999
				Estimate according to existing policy		Target		
		Crude oil equivalent	Equipment capacity	Crude oil equivalent	Equipment capacity	Crude oil equivalent	Equipment capacity	
		(10 ML)	(10 MW)	(10 ML)	(10 MW)	(10 ML)	(10 MW)	
Power generation field	Solar power generation	5.3	20.9	62	254	118	482	Approx. 23 times
	Wind power generation	3.5	8.3	32	78	134	300	Approx. 38 times
	Power generation from waste (resources)	115	90	208	175	552	417	Approx. 5 times
	Biomass power generation	5.4	8.0	13	16	34	33	Approx. 6 times
Heat utilization field	Solar heat	98	–	72	–	439	–	Approx. 4 times
	Unutilized energy (including ice energy)	4.1	–	9.3	–	58	–	Approx. 14 times
	Waste thermal energy	4.4	–	4.4	–	14	–	Approx. 3 times
	Biomass heat	–	–	–	–	67	–	–
	Black liquor, waste wood, etc. (∗1)	457	–	479	–	494	–	Approx. 1.1 times
Total for new energy (Percentage of the total supply of primary energy)		693 (1.2 %)	–	878 (1.4 %)	–	1,910 (approx. 3 %)	–	Approx. 3 times

(∗1): Grouped as one type of biomass. Includes portion used for power generation.

(b) Trends and targets of renewable energy Units: 1,000 kL

	1999 results	2010 estimate & target		2010/1999
		Estimate according to existing policy	Target	
Total new energy supply	7	9	19	Approx. 2.7 times
Hydropower	21	20	20	Approx. 1 times
Geothermal energy	1	1	1	Approx. 1 times
Total renewable energy supply (Primary energy supply/ component percent)	29 (4.9 %)	30 (4.8 %)	40 (7 %)	Approx. 1.4 times
Primary energy supply	593	622	Approx. 602	

(c) Trends and targets of new energy (demand side)

	1999 results	2010 estimate & target		2010/1999
		Estimate according to existing policy	Target	
Clean energy vehicles (∗2)	65,000 vehicles	890,000 vehicles	3,480 M vehicles	Approx. 53.5 times
Natural gas cogeneration (∗3)	1,520 MW	3,440 MW	4,640 MW	Approx. 3.1 times
Fuel cells	12 MW	40 MW	2,200 MW	Approx. 183 times

(∗2): Includes the demand-side new energy vehicles of electric vehicles, fuel cell vehicles, hybrid inverter controlled motor and retarder vehicles, natural gas-power vehicles, methanol-power vehicles, and liquefied petroleum gas-powered vehicles.
(∗3): Includes fuel cell-derived power

(2) Output stability

Because wind power generation and photovoltaic power generation are dependent upon environmental conditions, their output is unstable. In Northern Europe, wind power is able to provide stable electric power because the average wind speed is large and the

Table 2 Comparison of new energy costs

Type of new energy		Energy cost	New energy/ comparative energy	Comparative energy cost
Solar power generation	Household use	Avg: 66 yen/kWh	Approx. 3.0 times Approx. 16.5 times	Household-use electric rate: 23.3 yen/kWh Equivalent fuel cost: 4.0 yen/kWh (∗2)
		Max: 46 yen/kWh	Approx. 2.0 times Approx. 11.5 times	Household-use electric rate: 23.3 yen/kWh Equivalent fuel cost: 4.0 yen/kWh
	Non-household use	Avg: 73 yen/kWh	Approx. 3.5 times Approx. 18.3 times	Commercial electric rate: 20.0 yen/kWh Equivalent fuel cost: 4.0 yen/kWh
Wind power		Large-scale: 10 to 14 yen/kWh	Approx. 1.4 to 2 times Approx. 2.5 to 3.5 times	Rate for electricity from thermal power plant: 7.3 yen/kWh Equivalent fuel cost: 4.0 yen/kWh
		Small-scale: 18 to 24 yen/kWh	Approx. 2.5 to 3 times Approx. 4.5 to 6 times	Rate for electricity from thermal power plant: 7.3 yen/kWh Equivalent fuel cost: 4.0 yen/kWh
Waste power generation		Large-scale: 9 to 11 yen/kWh	Approx. 1.2 to 1.5 times	Rate for electricity from thermal power plant: 7.3 yen/kWh
		Small-scale: 11 to 12 yen/kWh	Approx. 1.5 times	Rate for electricity from thermal power plant: 7.3 yen/kWh
Phosphoric acid fuel cells		22 yen/kWh (∗1)	Approx. 1.1 times	Commercial electric rate: 20.0 yen/kWh
Utilization of solar heat		28 yen/Mcal	Approx. 1 to 3 times	9.0 to 27.3 yen/Mcal (∗3)
Water source heat pumps & Thermal utilization of waste		10 yen/MJ	Approx. 1.1 times	Heat supply cost (assuming use of city gas): 90 yen/MJ

(∗1): Figure includes waste heat recovery
(∗2): The equivalent fuel cost (4.0 yen/kWh) is set as a discretionary cost for the power company when installing solar power or wind power generation equipment, for which output will vary depending upon weather conditions.
(∗3): The comparative energy cost for a solar heat system is the heat utilization unit price, which reflects the efficiency of a kerosene, city gas or LPG based hot-water supply. The respective energy costs are 9.0 yen/Mcal for kerosene, 18.5 yen/Mcal for city gas, and 27.3 yen/Mcal for LPG.
Note: These examples were computed using uniform assumptions and were chiefly based on the average cost of equipment for business operations introduced in 1999.

wind blows in a steady direction. In Japan, however, there are few places where the wind speed and direction are steady, and even if a steady wind could be obtained, because the electric power lines in many regions are weak, connecting wind power generation equipment to those lines would ultimately degrade electric power quality and negatively affect general household customers. When connecting wind power generation equipment to a weak electrical power system, equipment (such as a fly wheel system or storage battery system) capable of supplementing a fluctuating quantity of power generation must be installed on the wind power generation-side to ensure the electrical power quality.

(3) Utilization factor

Utilization factor is typically expressed as (actual annual electricity generated)/(standard capacity × 8,760 h) and is a value that represents the annual power generation of a facility operating at rated (standard) capacity. The utilization factor varies according to the location of the facility, but average values are 65 %, 22 % and 12 % for waste power generation, wind power generation and photovoltaic power generation, respectively. As can be seen from these figures, the utilization factor for new energy generating facilities is extremely low compared to that of conventional thermal power generating facilities. This low utilization factor is a major reason for the higher power generation cost of new energy resources. Photovoltaic power generation has an especially low value of 12 %. Of course, the utilization factor would improve if the facility were located at a site that received direct sunlight and had mostly clear weather conditions. Japan, unlike the desert regions of the Middle East, does not have any place where sunlight irradiation is excellent, and therefore it is not possible to improve this value to a large degree. Moreover, installing wind power facilities at sites where wind conditions are favorable can boost the utilization factor for wind power generation, but even in Europe's region of favorable wind conditions, the utilization factor is only about 35 %.

3. Fuji Electric's Approach to New Energy

Rather than considering each type of new energy as an individual power generation resource, Fuji Electric aims to provide comprehensive energy solutions that include conventional power generation from diesel and gas engines, as well as energy saving measures, and is proposing optimal energy supply systems to its customers. So as to be better equipped to provide total energy solutions to its customers, Fuji has established an energy solutions office and is expanding its energy solutions business.

In the field of energy savings, Fuji Electric-an early developer of high efficiency devices — is also providing energy saving devices such as inverters and energy saving equipment, in addition to energy saving systems such as heat storage system and cogeneration.

Fuji Electric has also entered the ESCO (Energy Service Company) business and performs equipment diagnosis and proposes energy saving measures. The establishment of a plan for energy savings requires detailed data about the power used by each facility. Should additional measurements be required, Fuji also supplies Ecopassion and Ecoarrow wireless measurement systems that simplify the task of wiring.

Fuji Electric, an early developer of technology for solar cells and fuel cells, has also been providing systems that utilize a wide range of renewable energy resources including geothermal, small-scale hydropower, wave power, and wind power resources. Details of Fuji's solar cells and fuel cells are described below.

3.1 Photovoltaic power generation

Leveraging its core technology of inverters, Fuji Electric has standardized power conditioners (inverters for photovoltaic power generation use) and is selling photovoltaic power systems.

At present, the majority of solar cells used worldwide for power generation are crystalline-type solar cells. Fuji Electric is working to develop amorphous (non-crystalline) solar cells. Although amorphous solar cells are less efficient than crystalline solar cells, there is no need to be concerned about the limited supply of crystalline silicon material, and amorphous solar cells can be mass-produced, leading to lower costs. Moreover, the solar cells being developed by Fuji Electric are deposited on plastic film instead of a conventional glass substrate, and since a roll-to-roll process is utilized in which film that had been wound on a roll is rewound onto another roll after the solar cell film deposition, and this process is believed to lead to lower costs. Presently, Fuji Electric is concentrating on verifying reliability and lowering costs of these amorphous solar cells. Fuji Electric is also promoting the development of integrated roofing material that leverages the characteristics of Fuji Electric's amorphous solar cells, and is working to make this material commercial feasible.

3.2 Fuel cells

Many various types of fuel cells have been developed. Fuji Electric began developing phosphoric acid fuel cells in 1973, after performing collaborative research with electric power companies and gas companies and implementing field-testing to ensure reliability and performance, has been shipping commercial devices since 1998. Presently, Fuji is concentrating on expanding sales of phosphoric acid fuel cells and on developing polymer electrolyte fuel cells. The main use for phosphoric acid fuel cells has been in cogeneration systems that use town gas (13A, natural gas) as fuel to generate electricity or to pre-heat feed water. Recently, Fuji has also delivered fuel cells that use biogas, having methane gas as its main component and created as a byproduct from the decomposition of raw garbage or sewage sludge, as fuel for the purpose of generating electricity or heating fermentation processes. By generating energy from energy resources that were previously incinerated or otherwise unused, these types of systems will contribute to the preservation of the environment.

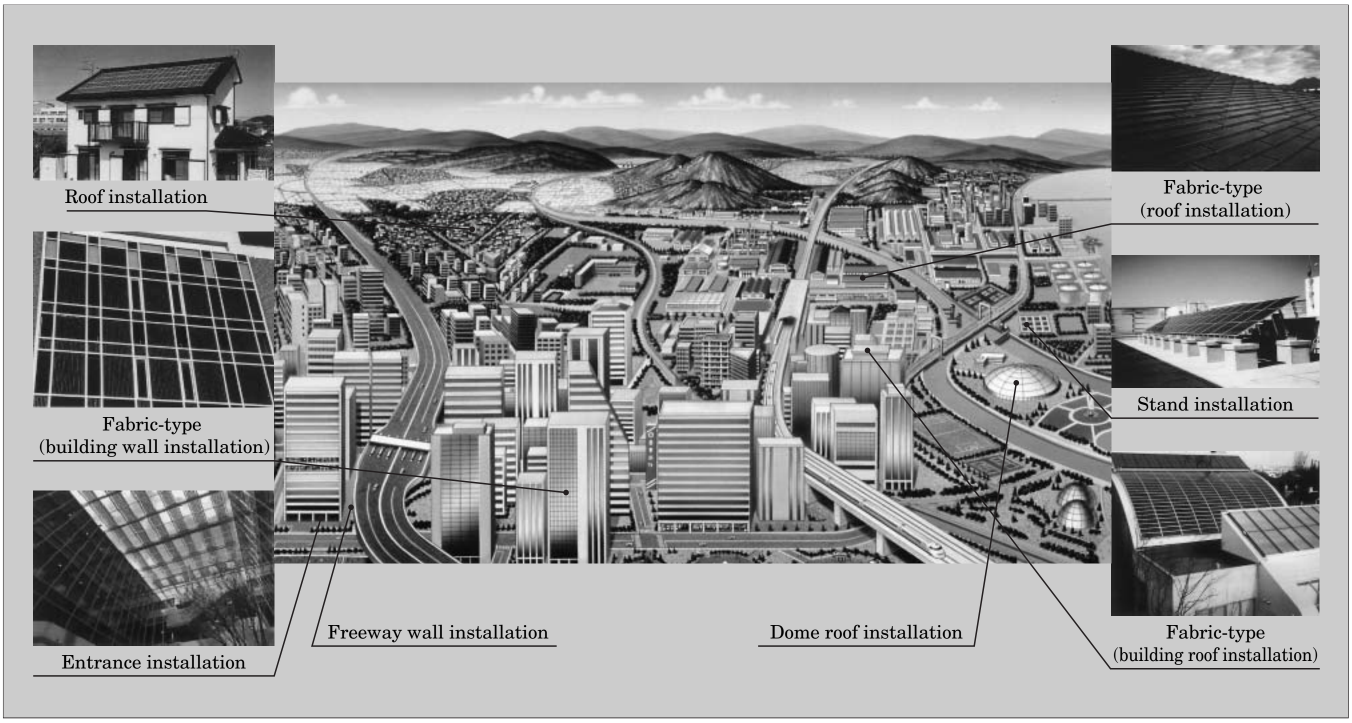
4. Future Prospects

The year 2010 targets outlined by the New Energy Subcommittee form the guidelines for promoting the adoption and widespread usage of new energy. New facilities will be brought online for photovoltaic power generation, waste power generation, and wind power generation, with the largest new capacity for photovoltaic power generation, followed by waste power generation, and wind power generation. In terms of the equivalent quantity of crude oil, however, this order becomes inverted as 5,520 ML for waste power generation, 1,340 ML for wind power generation and 1,180 ML for photovoltaic power generation. This discrepancy is due to differing values of the utilization factor as described above. Waste power generation is more efficient and is therefore a more economical means for generating electricity. If the cost of electricity generation is the most important factor affecting the adoption and widespread use of new energy, then we should concentrate efforts on promoting waste power generation.

Some people have the opinion that wind power generation is ill suited for Japan, where unlike Northern Europe there are few places favored by a steady wind speed and direction. However, relatively stable wind can be obtained at sea, and the introduction of offshore wind power generation — which has also begun in Northern Europe — is believed to be the key to achieving targeted adoption levels in Japan. Wind power generation will be advanced as small-scale power generation facilities having capacities of less than 2,000 kW and large-scale power generation facilities such as a wind farm having capacities of several tens of megawatts.

The major disadvantages of photovoltaic power generation are that the sunlight which reaches the earth has a low energy density and that the utilization factor is small. Its advantage, however, is that photovoltaic power generation equipment of large or small capacity can be installed in any suitably sized area that receives sunlight, and this makes it possible for even an individual to contribute to clean power generation according to his or her own finances. Other types of new energies do not have this advantage. Figure 2 illustrates example installations of photovoltaic power generation systems in a city. The opportunities for installation are limitless and include conventional roof installations, stand mounted installations, integration with building material (roof, wall, and window installations), and installations in the sound

Fig.2 Photovoltaic power generation example for city use



barriers along freeways. The cost of photovoltaic power generation is predicted with near certainty to drop to the same level as that of residential use electricity by 2010. Due to impending environmental issues, applications of photovoltaic power generation are expected to increase dramatically and become more widespread. The amorphous solar cells being developed by Fuji Electric have an approximately 10 % higher annual power output than crystalline solar cells. This is because photovoltaic power modules reach elevated temperatures during the summer months and amorphous solar cells, compared to crystalline solar cells, only exhibit slight degradation of efficiency due to high temperatures. Consequently amorphous solar cells are able to achieve higher efficiency. By leveraging this advantage, Fuji Electric plans to make significant contributions to photovoltaic power generation.

To lower the cost of fuel cells, polymer electrolyte fuel cells are expected to become the mainstream, and applications are predicted to center on fuel cells for automobiles and stationary fuel cells for home use. If the application of fuel cells to automobiles becomes practical, mass production will be necessary and subsequent cost reductions are anticipated. To promote the widespread usage of fuel cells, a fuel supply infrastructure must be built out and supporting maintenance work will also be necessary. Meanwhile, phosphoric acid fuel cells, which have a high operating temperature, are well suited for use in cogeneration systems that utilize exhaust heat. In the future, applications for phosphoric acid fuel cells will be segregated from those for polymer electrolyte fuel cells.

5. Conclusion

Separate from but concurrent with the New Energy Subcommittee, the Ministry of Economy, Trade and Industry organized an Energy-Saving Subcommittee to study Japan's future policy regarding energy saving. According to the report issued by this Energy-Saving Subcommittee, the target for year 2010 is the equivalent of 57 billion liters of crude oil, which is approximately three times the total new energy target. Based on these figures, to curtail CO_2 emissions and protect the environment it is important to reduce consumption of existing energy resources and also to incorporate a well-balanced percentage of new energy.

Fuji Electric will continue to contribute to society by providing energy solutions that include new energy resources as well as energy saving measures.

Reference

(1) NEDO Activities to Promote the Introduction of New Energy.

New Energy Generation System for Fuji Electric Human Resources Development Center

Yoshimi Horiuchi
Hironori Nishihara
Takashi Ujiie

1. Introduction

Ever since the 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3) held in December 1997 in Kyoto, Japan, there has been greater concern and interest in reducing burdens on the environment. The training institute at Fuji Electric Human Resources Development Center has introduced an energy management system for integrated management of an amorphous solar cell system, a phosphoric acid fuel cell system and a micro gas turbine. This paper presents a general description of Fuji Electric's energy management system.

2. Overview

Table 1 lists a summary of the training institute's facilities and specifications.

The training institute, containing both training facilities and accommodation facilities, requires both electrical power and heat. With the goal of reducing CO_2, NOx and other burdens on the environment and of enhancing energy utilization efficiency, this institute has installed a 10 kW photovoltaic system, a 100 kW environmentally friendly fuel cell system, and a 26 kW micro gas turbine. Figure 1 shows an overview of the entire system. For the purpose of enhancing energy utilization efficiency, we estimated the demand for electric power and heat based on the number of reservations for training and accommodations. An energy management system has been constructed using high efficiency fuel cells, having high electric power generating efficiency, to handle the electric power demand and a micro gas turbine, having high waste heat collection efficiency, to handle the heat demand.

The introduction of photovoltaic power generation, fuel cells and other new energy generation equipment is expected to result in reduction of the following burdens on the environment.

- ○ CO_2 reduction: Approximately 28 t-C/year (17 % reduction)
  169 t-C/year before introduction is reduced to 141 t-C/year after introduction
- ○ NOx reduction: Approximately 84 kg/year (33 % reduction)
  253 kg/year before introduction is reduced to 169 kg/year after introduction

Table 1 Training institute's facilities and specifications

Large training room	1 room
Mid-size training room	3 rooms
Small training room	12 rooms
Open training room	2 rooms
Accommodation floor	Floors 4 to 6 (equipped with bath and toilet)
Total floor space	6 floors and approx. 6,000 m^2

3. Power Generation System Specifications

3.1 Photovoltaic system

With the goal of commercial feasibility, present day photovoltaic systems use amorphous-silicon solar cells, and the development of these amorphous-silicon solar cells is being advanced. This system is configured from amorphous-silicon solar cells, a 10 kW power conditioner, and measuring equipment (including weather monitoring equipment), and has grid-connected operation. The solar cells are mounted on a stand angled at 30° on the roof of the training institute. Table 2 lists the specifications of the solar cells and the power conditioner.

3.1.1 Photovoltaic module

Figure 2 shows the external view of the type of amorphous-silicon solar cell module that is installed on the institute's roof. The basic module structure utilizes the same glass module structure commonly used in crystal-silicon solar cells. Figure 3 shows the onsite solar cell installation.

3.1.2 Power conditioner

The power conditioner installed in this system has a 10 kW inverter unit, and extra capacity can be added in increments of 10 kW. In addition to the inverter unit, the power condition also has a display unit equipped with control functions and an I/O unit. The power condition is a rack-mounted type.

Fig.1 Overview of entire system

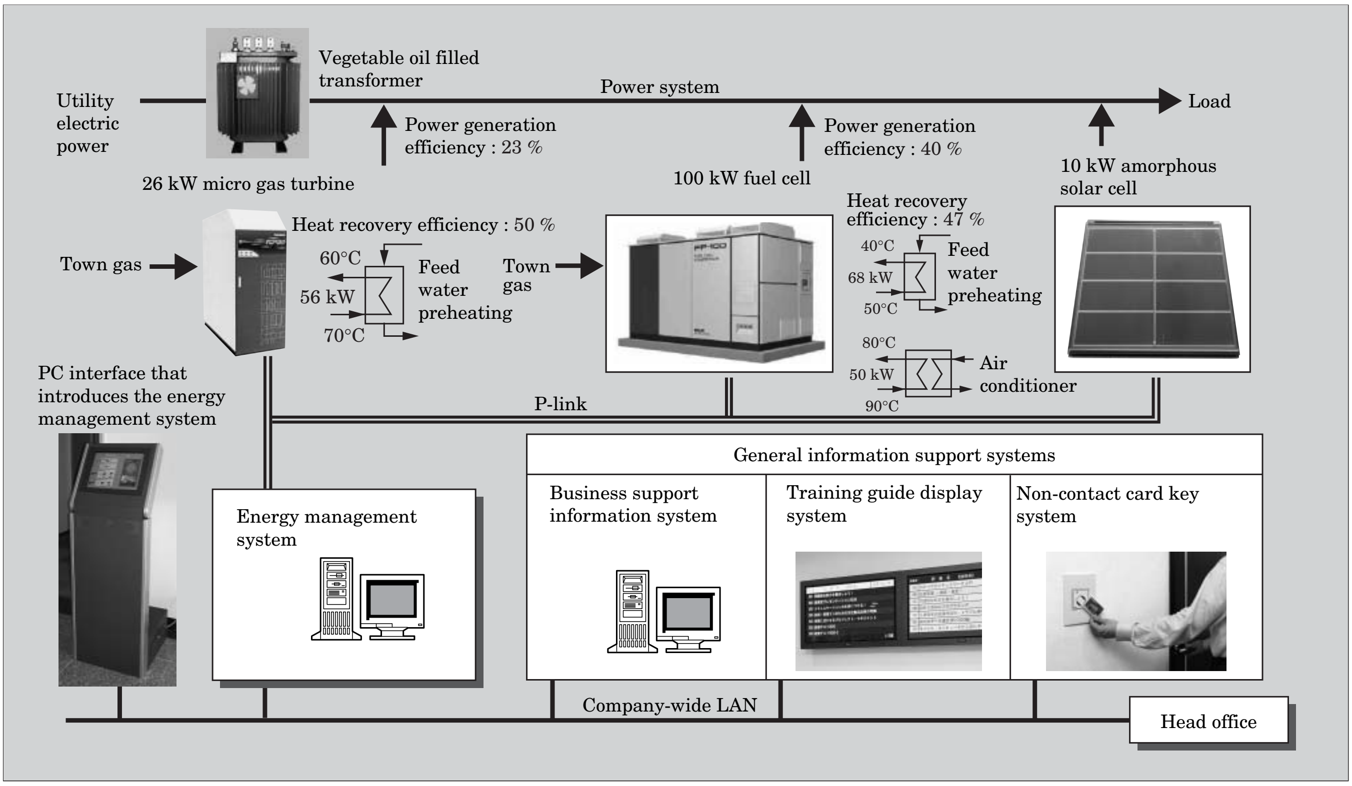


Table 2 Solar cell & power conditioner specifications

Solar cell	Type	Glass encapsulated amorphous-silicon solar cell
	Max. power of module	48 W
	No. of modules	210 (3 series × 70 parallel)
	Total installed capacity	10.08 kW
	Angle of installation	30° facing South
Power condi-tioner	Type	PVI plus10
	Rated input voltage	300 V DC
	Operating voltage range	190 to 450 V DC
	System condition	3-phase 3-line 210 V 50 Hz
	AC output power	10 kW
	Effective energy efficiency	94 % or greater
	Power factor	95 %
	Current distortion factor	Total: 5 % or less Each of the following degrees: 3 % or less

3.1.3 Measurement

One objective of the installed photovoltaic system is to verify operation of the amorphous-silicon solar cells currently being researched and developed. Therefore, in addition to measurements of output power and meteorological data, the solar cells were subdivided into small units (sub-arrays) and measurement points were determined so that a performance evaluation of the amorphous-silicon solar cells could be carried out. The measured items are listed in Table 3. This measurement system transmits the measured data via an intranet.

Fig.2 External view of solar cell module

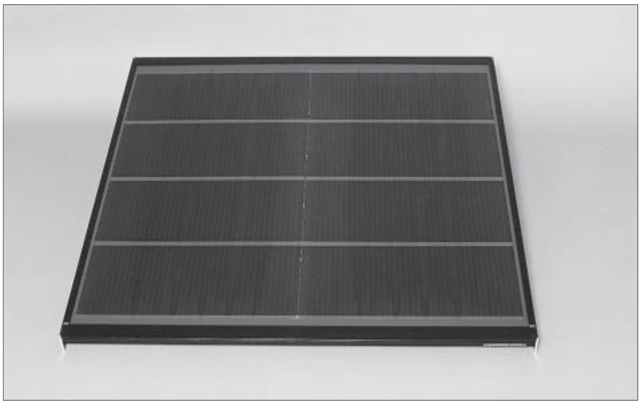


Fig.3 Onsite installation of solar cells

Table 3   Measurement items

Measurement group	Measurement item	Signal classification	No. of measure-ment points
Solar cell	Solar irradiation (horizontal)	0 to 1 kW/m^2	2
	Cell temperature	−20 to +100°C	9
	Cell output current	0 to 3 A	24
	Cell output voltage	0 to 400 V	2
Inverter	Line voltage (3 phase)	0 to 300 V	3
	Line current (3 phase)	0 to 50 A	3
	Electric power output	0 to 15 kW	1
	Electric power energy	0.1 kWh/Puls	1
Weather	Ambient temperature	Pt100 Ω	1
	Humidity	0 to 100 %RH	1
	Rainfall	0.5 mm/Puls	1
Status monitoring	Inverter failure	On/Off	1
	Inverter operation, shutdown	On/Off	1
	UPS abnormality	On/Off	1

Table 4   Phosphoric acid fuel cell specifications

Rated output	100 kW (power transmitting side)
System condition	3-phase 3-line 210 V 50 Hz
Power generation efficiency	40 % (for rated output, LHV)
Heat recovery efficiency	47 % (for rated output, LHV)
Total energy efficiency	87 % (for rated output, LHV)
Exhaust gas properties	NOx : 5 ppm or less (O_2 = 7 % conversion) SOx, dust concentration : below detectable limit
Fuel consumption	22 Nm^3/h (town gas 13A)
Operating system, mode	Fully automated, linked to the utility system
Main dimensions	2.2 m (W) × 3.8 m (L) × 2.5 m (H)
Mass	10 t

3.2 Phosphoric acid fuel cell system

3.2.1 Specifications and features of 100 kW phosphoric acid fuel cells

Table 4 lists the fuel cell specifications. The power generation efficiency is 40 %, and this value is highly efficient compared to other types of 100 kW generating equipment. Use of recovered waste heat boosts the total energy efficiency to 87 %. The ratio of electric output to waste heat output is approximately 1:1 and this is well suited for cogeneration that mainly uses electricity. Waste heat becomes largest when the power generation load is at its rated value. One advantage of fuel cells is that their power generation efficiency does not decrease for partial loads of even 50 %. This is a huge advantage compared to other cogeneration devices that experience significantly lower efficiency for partial loads.

Fig.4   Fuel cell power unit installed onsite

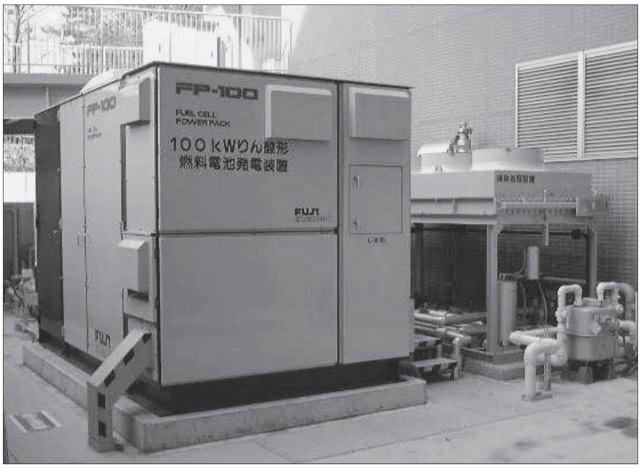


Table 5   Micro gas turbine specifications

Rated output	26 kW (power transmitting side)
System condition	3-phase 3-line 210 V 50 Hz
Power generation efficiency	23 % (for rated output, LHV)
Heat recovery efficiency	50 % (for rated output, LHV)
Total energy efficiency	73 % (for rated output, LHV)
Exhaust gas properties	NOx : 15 ppm or less
Fuel consumption	9.7 Nm^3/h (town gas 13A)
Operating system, mode	Fully automated, linked to the utility system
Main dimensions	0.79 m (W) × 1.9 m (L) × 2.1 m (H)
Mass	1.2 t

3.2.2 Fuel cell power system

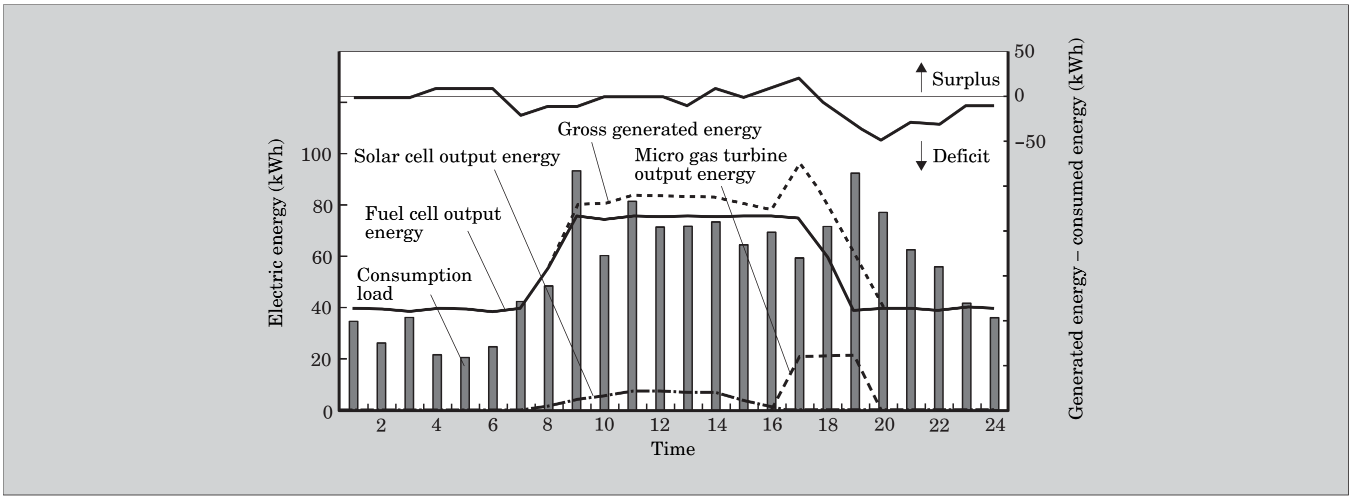
This system is comprised of a fuel cell power unit, waste heat treatment equipment, water treatment equipment, nitrogen equipment, and a water-fired chiller; it is linked to the utility system and operates continuously. Figure 4 shows a photograph of the fuel cell power unit.

High temperature water (90°C) is used as the heat source for a water-fired chiller (10RT) and can be used for the air conditioning in an institutional kitchen or elsewhere. Lower temperature water (50°C) is fed through a heat exchanger and is used for feed water preheating.

The operational load is estimated based on the number of reservations for training and accommodations, and a pattern upon which to base the operational control can be selected by the energy management system.

Moreover, this system is able to supply electricity during an outage of the utility power. Specifically, when a power outage occurs, the load feeder that is not supplying power is cut off. Meanwhile, the fuel cell system halts the inverter output by means of a power outage detector, and after a certain amount of time has elapsed, performs a soft start by gradually increasing voltage so that restart is implemented with suppressed

Fig.5 Example of electric power generation and consumption



rush current. The system then performs load feeding as a stand-alone operation. Furthermore, during stand-alone fuel cell operation, so that there is no abrupt spike in the load, the system takes into consideration the specific load selected and the application of the load.

3.3 Micro gas turbine

Specifications of the micro gas turbine are listed in Table 5. This cogeneration system is configured from a Capstone turbine main unit, a 26 kW micro gas turbine with an attached waste heat recovery unit, a town gas pressure blower, air-fin coolers, etc. This system is linked to the utility system and uses waste heat for feed water preheating. The ratio of electric output to waste heat recovery output is approximately 1:2 and this is well suited for cogeneration that mainly uses waste heat. The energy management system operates the micro gas turbine in the evening when the demand for heat is greatest.

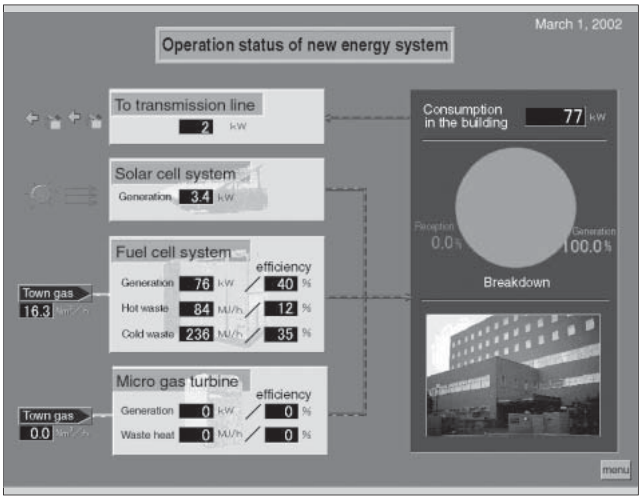
4. Energy Management System

The energy management system controls operation of the power generating equipment in order to maximize the energy utilization efficiency of the electric power and heat consumed by the training institute. The energy management system is equipped with the following three functions.

(1) Operating pattern selection function

The energy usage quantity (estimated demand) is calculated based on training that has been registered in the work support system and the number of reservations for accommodations. An optimal operating pattern for the fuel cells and micro gas turbine is determined and control is performed accordingly. Because there is no database of energy demand data for the institute, estimated demand is calculated commensurate with the probable usage for the reserved

Fig.6 Example monitor screen showing status of new energy generation system



training and accommodation floors based on the energy usage of a typical office building or hotel. The energy utilization efficiency is enhanced by operating the fuel cell system, which has high power generating efficiency, in response to the power demand and a micro gas turbine, which has high waste heat recovery efficiency, in response to heat demand. Since continuous operation of the fuel cells is desired, the fuel cells are operated at minimum output power during nighttime hours and on holidays when demand for power is low. The present operating pattern outputs 75 % of the rated power during daytime hours and 40 % of the rated power during nighttime hours. Figure 5 shows an example of the generation and consumption of electric power. It can be seen that the generated power roughly satisfies the demand for power consumption.

We will continue to accumulate and analyze data of the training institute's energy usage and will conduct verification testing of operation patterns so that the demand estimate is optimized and is commensurate with the energy usage of this institute.

(2) Logging function

The energy generation status of fuel cells, solar cells and the micro gas turbine and the energy consumption status of the building are logged and daily, monthly and annual reports can be generated.

(3) Monitor display

The energy generation and consumption statuses can be monitored from the lobby of the training institute. In consideration of the lobby design, this function is implemented with a station-type LCD monitor. Figure 6 shows an example display of the status of the new energy generation system.

5. Conclusion

Fuji Electric will construct a database of energy consumption status and other data, and plans to verify the behavior of environmentally friendly operation that enhances the energy utilization efficiency. Moreover, based on the knowledge and experience acquired through the construction and operation of this system, Fuji intends to intensify its ongoing efforts to provide optimal energy solutions.

Solar Cell Development Trends and Future Prospects

Takashi Yoshida
Shinji Fujikake

1. Introduction

The development of solar cells began with the invention of single crystal silicon solar cells in 1954 at Bell Labs. Thereafter, research continued to make progress, and during the era spanning the latter half of the 1950s through the beginning of the 1960s, this technology began to be utilized in high value added applications such as the power supply for a man-made satellite.

With the 1974 oil crisis as an impetus, major research projects in Japan [including the Sunshine Program sponsored by the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry)] were initiated for power applications.

In the latter half of the 1980s, concern heightened for environmental issues such as global warming. It is thought that approximately 60 % of the greenhouse effect is attributable to CO_2 and of that amount, 80 % is attributable to the consumption of fossil fuels. Solar cells are promising not only because they represent a new energy resource that is maintenance-free and does not generate CO_2, but also because they will potentially provide a solution to global environmental problems.

The Kyoto Protocol intended to curb global warming was adopted at The 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3) held in Kyoto, Japan in December 1997. This protocol sets forth compulsory numerical targets for the reduction of greenhouse gas emissions by each advanced nation by the year 2010. Subsequently, at COP6, basic agreement was also reached regarding the year 2002 enactment of the Kyoto Protocol. Hereafter, momentum is expected to increase for the introduction of new energy, which does not have a deleterious effect on the environment.

The majority of solar cells currently in use are crystal silicon solar cells. Under standard test conditions (in the vicinity of room temperature), these solar cells have a high conversion efficiency of 14 % to 16 %. However, because they have a thick substrate of several hundred micrometers, procurement of a sufficient supply of high-purity silicon material is a problem.

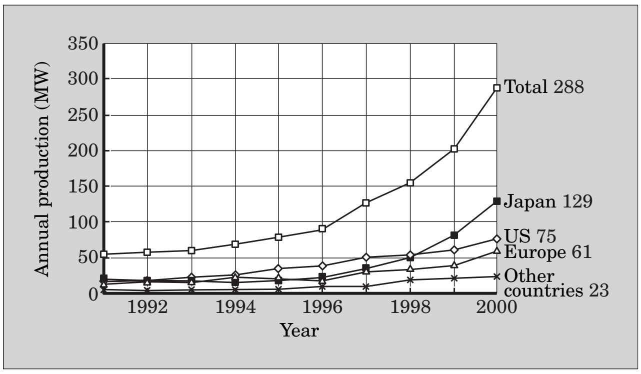
Fuji Electric is working to develop amorphous silicon solar cells, which are fabricated on a plastic film substrate and are formed from 1 µm or thinner semiconductor material. Amorphous silicon solar cells have the advantages of a relatively trouble-free supply of raw material because each cell only uses a small quantity of material; they are well suited for mass production, and cost reductions are expected. The large-scale, widespread use of amorphous silicon solar cells is anticipated, and it is believed that in the future the majority of solar cells will be amorphous silicon solar cells.

2. Market Trends

2.1 Production history

Solar cell production has continued to expand rapidly since 1997, and solar cell production in the year 2000 was approximately 300 MW. (See Fig. 1). As solar cells began to achieve widespread use, their annual production reached 100 MW in 1997. The rapid growth of today's market can be understood by considering the fact that it took 20 years to surpass the 100 MW level of annual production. With annual solar cell production of 128 MW in year 2000, Japan remained the global leader in solar cell production. (Japan was also the global leader in 1999.) Supporting this rapid expansion are lower costs enabled by

Fig.1 Global market for solar cell production



advances in manufacturing technology and the implementation of Japanese, U.S. and European governmental policies for the promotion of solar cell use. Leading the way is Japan's policy for the promotion of solar cells, and this is followed by other programs including the million solar roofs initiative (MSRI) in the US, the federal 100,000 roof program in Germany, and the 10,000 home solar power generation system initiative in Italy. Acting as a catalyst, this worldwide trend for solar cell use has boosted demand for solar cell modules by a large amount in 2001, and solar cell manufacturers worldwide have begun to increase their large-scale production equipment.

With the guarantee of economic efficiency due to policies that promote widespread use, solar cells have become familiar to users throughout the world.

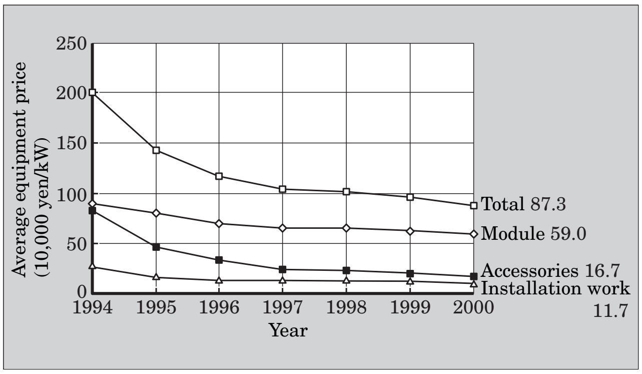
2.2 Policy to accelerate introduction in Japan

In Japan, the aggressive measures over the past 5 years to promote widespread usage of solar cells have been effective and, as a result, the market is growing. Against the backdrop of austere budgeting mandated by fiscal belt tightening, the budget for development and promotion of solar power generation systems grew by 10 % to 35.9 billion yen in 2002. This demonstrates the vigor of Japan's efforts to promote solar cell technology. A breakdown of this budget reveals 23.2 billion yen budgeted to promote usage by homeowners through subsidizing the foundation and maintenance work for installation of residential PV (photovoltaic) systems, and 4.5 billion yen budgeted to promote usage by companies through subsidizing industrial field test work. Together, these two items account for 77 % of the budget for promoting solar cells technology. The size of the subsidy per residential PV system was initially 1/2 the cost of the entire system. The subsidy was subsequently reduced to 1/3 of the system cost and then cut further in 2001 to 120,000 yen per 1 kW system so that more applicants could be recruited. A new phase was entered in 2002 with the inception of an experimental study of a centralized linked-type PV system that targets large-scale adoption in a specific region. Hereafter, the implementation may differ, but national and regional governments are expected to continue their policies of aggressive promotion of solar cell technology.

2.3 Technical trends

Historical average market prices per kW for a 3 kW PV system are shown in Fig. 2. In 2000, the average market price of PV system was 870,000 yen/kW, the market price of a PV module was 590,000 yen/kW or approximately 77 % of the total cost, and the remaining 23 % was attributable to the cost of the power conditioner, equipment installation, and other costs. Even though the price of residential electrical power may be considered expensive, without the subsidy, more than 20 years would be required to write off the initial cost of a PV system. The primary requirement for promoting widespread usage of solar cells is that the cost of a PV system be reduced to 1/2 or less of its present amount.

Fig.2 Historical market price for residential PV systems



The adoption of solar cell technology is most prevalent in residential applications, where the price of electrical power is relatively high. As the cost of power generation decreases, applications to large-scale buildings and the utilization of idle land are expected to increase. In the present Japanese market, the majority of PV system installations are for residential applications, and this trend is forecast to continue for the time being.

Residential solar cells can be classified as either existing type solar cells that are installed on the roof of an existing house, or as integrated building material that combines roof functionality with building material. In solar cell installations in new buildings or replacement roofs, because the equipment cost is low, applications of solar cell integrated building material are gradually increasing, and these applications are expected to become a key driver of future market growth.

3. Fuji Electric's Development of Amorphous Silicon Solar Cells on Plastic Film Substrate

3.1 Development history

Fuji Electric's efforts to develop amorphous solar cell technology began in 1978, only 2 years after the discovery in 1976 that p-n control can be applied to amorphous silicon (a-Si). In 1980, Fuji Electric was the first in the world to successfully develop and commercialize an amorphous silicon solar cell for use in calculators. During that same time, Fuji Electric also joined the Sunshine Project, and since then has advanced the research and development of amorphous silicon solar cells for the generation of electrical power. Over the years, Fuji Electric has developed a two-stacked tandem solar cell (30 cm × 40 cm), has demonstrated a stabilized efficiency of greater than 8 %, and was the first in the world to prove that amorphous silicon solar cells could be used to generate electrical power. Problems that surfaced during development included the long heating time due to the high thermal capacity of glass and the long time required for vacuum pumping due to the large size of the conveyer jig for the glass substrate. Without a solution to these problems, it would be difficult to manufacture large quantities of solar cells in a cycle time of several minutes.

To solve these problems, in 1994, Fuji Electric developed an amorphous silicon solar cell that has a substrate of 50 µm thick plastic film (See Fig. 3).

3.2 Advances in production technology and electricity generation performance

In contrast to a glass substrate, the film substrate has low thermal capacity and therefore only requires several seconds for heating. With a film substrate, it is possible to construct a roll-to-roll system that allows a 1,000 m long roll of film to be placed all at once into vacuum equipment and then automatically conveys the film from one roll to another. Additionally, the factor having the greatest effect on production capacity, the deposition rate of amorphous silicon film, has been greatly improved. Figure 4 shows the progress of the past several years in increasing the deposition rate of amorphous silicon. At present, the amorphous silicon film deposition rate for fabricating a good quality device is greater than 20 nm/min, and this is approximately 10 times the deposition rate in 1997 of several nm/min. In addition to this increase in deposition rate, the active area has been increased due to Fuji Electric's proprietary series-connection through apertures formed on film (SCAF) technology and the speed of laser patterning technology has been boosted. We are coming closer to the goal of constructing a 5-minute mass production system, in which each process is completed in a cycle time of several minutes.

In addition to these improvements in production technology, device structures have also made progress. Figure 5 shows the two-stacked tandem solar cell device configuration developed by Fuji Electric, using a silicon-germanium alloy in the bottom cell. Because longer light wavelengths can be used with silicon-germanium than with amorphous silicon, the electrical current generated per unit area is approximately 20 %

Fig.3 a-Si solar cell on plastic film substrate

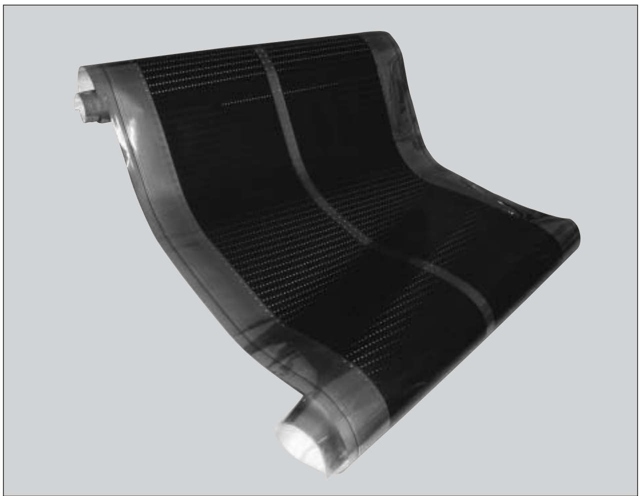


Fig.4 Progress toward faster deposition rates of a-Si

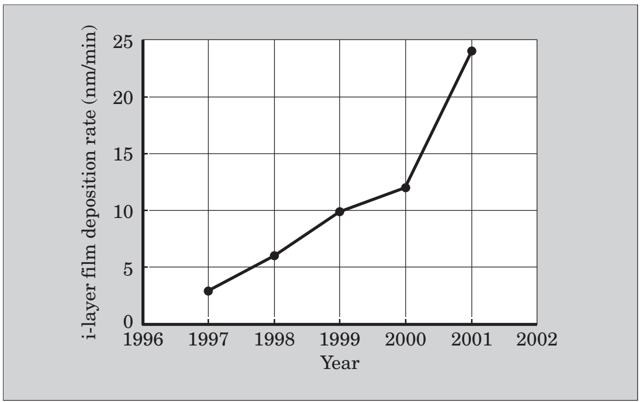


Fig.5 Device structure of two-stacked tandem solar cell

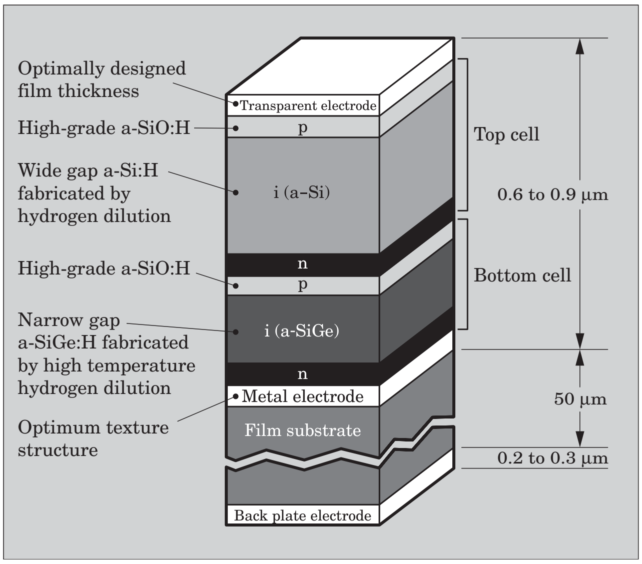
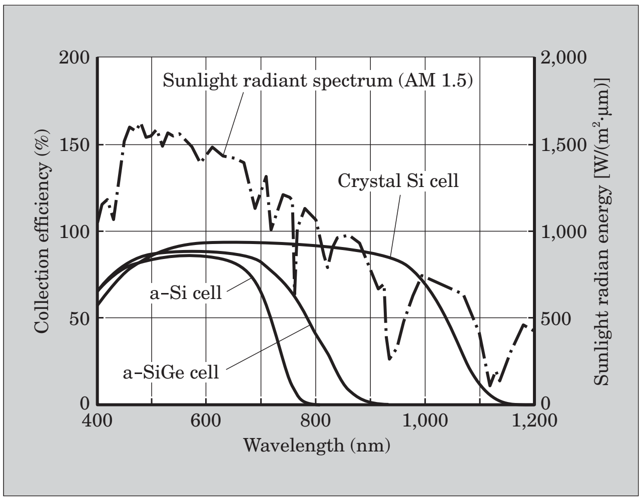


Fig.6 Solar spectrum and quantum efficiency of various solar cells



higher than that of amorphous silicon, and the power generation efficiency is improved proportionately.

Figure 6 shows the solar spectrum and light wavelengths that can be used effectively with solar cells. It can be seen that amorphous silicon solar cells use wavelengths approximately in the visible light range and that crystal silicon solar cells use longer light wavelengths. The reason for this difference in wavelength ranges of the utilized light is due to the different semiconductor energy gaps. Crystal silicon solar cells have a small energy gap and their performance is strongly temperature dependent. This is disadvantageous because when a module operates at high temperatures above 50 °C, its conversion efficiency will be less than when at room temperature. The results of a field test, standardized to the measurement of module power generation at room temperature, demonstrated that the annual quantity of power generated per unit capacity is at least 10 % higher for amorphous silicon solar cells than for crystal silicon solar cells.

3.3 Outdoors applications and verification of reliability

At Fuji Electric's Corporate Research and Development facility in Yokosuka City, Kanagawa Prefecture, 3 kW solar cells of both the glassless PV module-type that is encapsulated with plastic and was developed jointly with a building material manufacturer, and the conventional PV module-type with cover glass, have been installed on the rooftop of the facility's health promotion center. Field verification tests are ongoing to investigate the characteristics of outdoor power generation. Three years have passed since the solar cells were installed and both types of cells have continued to generate electricity stably. No difference in power generation characteristics has been found for different encapsulation structures of the modules.

In addition to the field test results, various reliability testing was performed and the goal of using glassless PV modules with more than 8 % of conversion efficiency outdoors has been clarified. By leveraging Fuji Electric's proprietary SCAF construction that makes it easier to implement high-voltage wiring and easy-to-fabricate integrated type solar cells formed from lightweight cells that are attached to building material for the roof or walls of a building, applications are expected to advance into various fields.

4. Conclusion

The history of solar cell development has been retraced from several perspectives and an overview the current status has been presented. For the ultimate objective of power generation, cost is the most important factor. The film substrate developed by Fuji Electric is well suited for the automation of production processes. By advancing well-timed applications and development, a new mode of solar cells that rejuvenate the old stately image will be transmit into the world as the standard-bearer for the next generation of mass-produced solar cells.

The very act of putting solar cells into practical use is in itself a contribution to the global environment. Fuji Electric, which has adopted the concept of "harmony with nature" as a basic philosophy, is on a mission to develop this technology.

Some of the results introduced herein were from research subsidized by the New Sunshine Program of the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry) or were obtained from research contracted to the New Energy and Industrial Technology Development Organization. The authors are grateful to all individuals involved.

Studies on the Outdoor Performance of Amorphous Silicon Solar Cells

Takuro Ihara
Hironori Nishihara

1. Introduction

The advantages of SCAF (series-connection through apertures formed on film) cells with plastic film substrate are as follows[1]:

(1) The output voltage can be adjusted based on the system requirements, and the wirings between the modules are simple due to the monolithic series-connected structure
(2) The cells can be applied on the slightly curved surface due to the flexible plastic film substrate
(3) Light weight cells can be realized due to the thin film structure

However, for practical uses, durability and the outdoor performance of the modules should be verified. Therefore, several accelerated tests were performed to evaluate the reliability of the modules. In addition, we are conducting the outdoor power generation tests to evaluate the effects of the azimuth and tilt angle, and material difference between crystalline silicon and amorphous silicon. The field tests verify the performance of the modules under the actual operating conditions on the roof. In this paper, we report the results of the outdoor field performance tests, which were conducted in the premises of Fuji Electric Corporate Research and Development Ltd.

2. Comparison of the Outdoor Performance of Several Solar Cell Modules

It is common practice to evaluate the performance of solar cells using a solar simulator and express the performance under standard conditions [i.e. irradiance: 1 kW/m^2, module temperature: 25°C and solar spectrum air mass (AM) 1.5]. However, it must be noted that it is seldom that the solar cells operate under the standard conditions during the field test. The performance of the solar cells varies depending on the operating environment. This is especially true for the amorphous silicon (a-Si) solar cells, as these cells exhibit a decrease of conversion efficiency at the initial irradiation and a recovery of the conversion efficiency by the thermal anneal. As a result, the amorphous solar cells exhibit different seasonal behavior from that of the crystal silicon (Si) solar modules. To maximize annual energy, it is common to install cells in the azimuth angle of 0° (toward the south) and position the tilt angle slightly lower than that of the latitude at the location of installation. But, due to limitations inherent at the installation location (e.g. the roof of a house), the actual installation conditions may differ from optimum conditions. We, therefore, installed several solar modules on the premises of Fuji Electric Corporate Research and Development Ltd. in Yokosuka City and measured the power generating status of these modules in order to evaluate the following aspects:

(1) Compare the amorphous solar cells to the crystal Si solar cells
(2) Compare the power generating performance of amorphous solar cells with different device structures
(3) Evaluate the effects of the module installation conditions (azimuth and tilt angle)

Below, we report the measuring system for the generated energy and the results of the tests to date.

2.1 Outline of the measuring system for the generated energy

Outline of the measuring system is summarized in Table 1 and some explanations are provided.

2.1.1 Type of modules and arrangement

Modules used for the tests consist of two types: the a-Si/a-Si module and the a-Si/a-SiGe module. Both types of modules are double-junction amorphous cells, which were developed by Fuji Electric. In addition, crystal Si solar cells and single-junction a-Si solar cells (a-Si single) were tested, in order to provide a comparison. The focus of the present experiment is the tandem (a-Si/a-SiGe) structure, which has a spectral response as shown on Fig.1. The rated power (nominal maximum output power) of several modules is summarized on Table 2. The listed values are the rated power of a-Si modules after stabilization.

To evaluate the power generating performance, each type of module was placed at the standard tilt angle of 6/10 (31°) and the performance was recorded. The effects of the installation conditions were evaluated using Ge tandem modules. The modules were installed on the roof of research facilities, and the arrangement was chosen to minimize unwanted shading from surrounding buildings and support structures.

2.1.2 Measuring system

In the regular solar power generating system, generated DC power is converted into AC power and the operating condition of the solar cells is controlled by the maximum power point tracking (maximum power: P_{max}). When the generated power of each module is measured, the power has to be consumed continuously by the load under the changing operating environment to keep the output power at P_{max}. In our tests, the generated power was consumed by the electronic load, while controlling the operating point by the P_{max} tracking circuit. The operating voltage and current were measured under these condition. Because the measured values are in DC, the generated power can be calculated by multiplying the voltage by the current. Generated power was measured at 10 second intervals and the mean power values over one minute were calculated and stored in the measuring computer. These data were automatically transferred to the database every day at 1:00 am. To date, there has been no deficit of measured data from this system.

Table 1 Outline of the measuring system for the generated energy

Item	Description
Location of the measurement	Yokosuka City North latitude 35°13′ East longitude 139°37′
Measured items	Irradiation, generated power and energy, ambient temperature, module temperature, wind velocity
Measured modules	Four types (2 modules for each type) a-Si/a-Si, a-Si/a-SiGe, crystal Si, a-Si single
Azimuth angle	East, west, south and north
Tilt angle	Standard tilt angle : 6/10 (31°) and vertical (partly)
Measurement of the generated energy	Operating point was controlled by P_{max} control circuit. Operating voltage and current were measured while the generated energy was being consumed by the electronic load.
Measuring interval	Measuring interval : 10 seconds, mean values were calculated at 1 minute interval.
Data processing	Data was transferred daily from the measuring computer to the Oracle data base automatically. Integrated and mean values were calculated at minimum 10 minutes interval.

Fig.1 Structure of the tandem film-substrate solar cell and spectral response

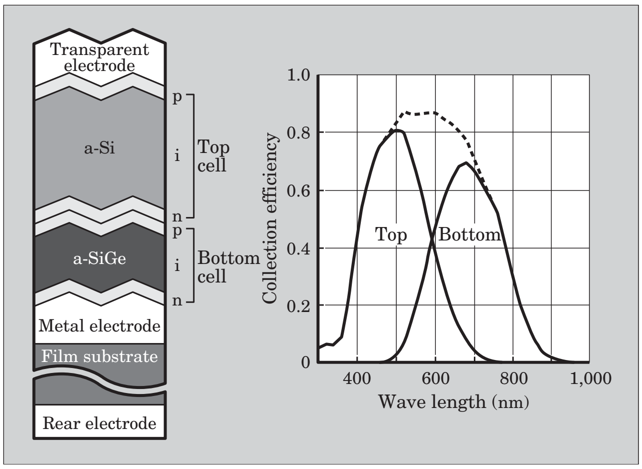


Table 2 Rated power of several modules (at the standard test conditions)

Type (abbreviation)	Device	Rated power (W)
Ge tandem	a-Si/a-SiGe	23
Si tandem	a-Si/a-Si	20
Crystal Si	Crystal Si	52
a-Si single	a-Si	28 (value on the nameplate)

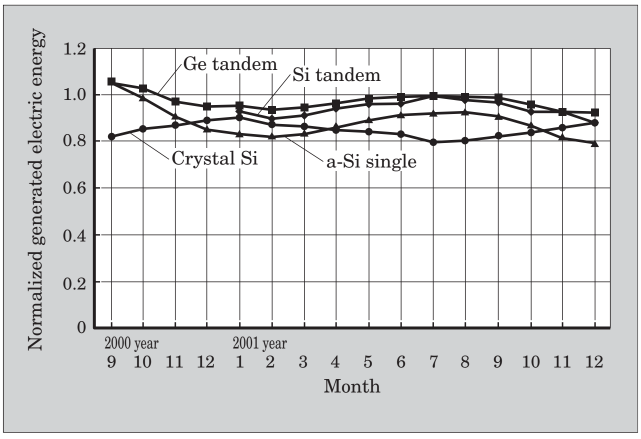
2.2 Comparison of the generated energy of several solar modules

On September 14, 2000, we started the measuring three solar module types: the Ge tandem, the crystal Si, and the a-Si single. Later in the study (December, 2000), the Si tandem was added.

Figure 2 shows the monthly change of the normalized generated energy of several solar modules. The normalized generated energy is the total generated energy divided by the product of rated power × irradiation period converted into 1 kW/m^2. This represents the ratio of total generated energy at the actual outdoor environment to the calculated energy, assuming that the energy conversion efficiency is operating under the standard conditions. Figure 2 shows that the monthly normalized generated energy of crystal Si modules is high in winter and low in summer. On the contrary, the monthly normalized generated energy of amorphous modules is low in winter and high in summer. This result is due to the following two reasons:

(1) Generally, semiconductor type solar cells have

Fig.2 Monthly normalized generated energy



negative output temperature characteristics. Amorphous solar cells show the same characteristics when the temperature rapidly changes but irradiation conditions remain constant. But, photo-induced defects are annealed and the conversion efficiency is improved during the summer in amorphous silicon cells. The output deviation of crystal Si, having a negative dependence on temperature, is roughly twice that of the amorphous type and these temperature coefficients range from −0.004 to −0.005, and −0.002 to −0.0025 for the crystal Si and the amorphous type, respectively.

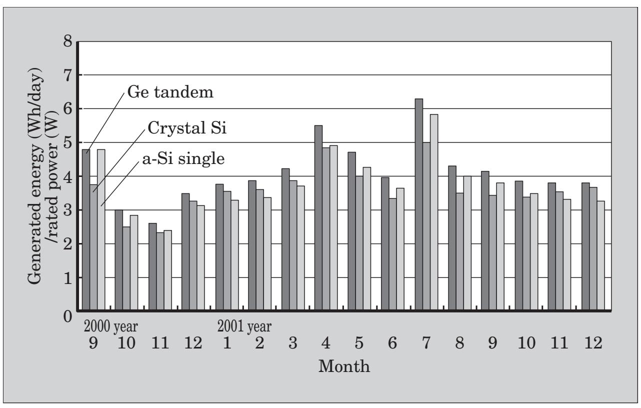
(2) Relatively, summer irradiation has higher energy in short wave length region and winter irradiation has higher energy in long wave length region. The amorphous type, which has a larger optical gap and higher short wave length sensitivity compared with those of crystal type, has an advantage in summer and disadvantage in winter.

Figure 3 shows the monthly change of the generated energy (Wh) per rated output (W) for Ge tandem, crystal Si and a-Si single solar cells. The solar power generating system user will usually select the solar modules based on the rated (nominal) power, which is the performance at standard conditions (i.e. irradiation: 1 kW/m^2, module temperature: 25°C, air mass 1.5). Despite the fact that different cell types may have similar power ratings, it is important to note that the actual generating energy varies depending on the type of solar cells. Table 3 shows the actual annual energy generated (from January, 2001 to December, 2001) from the three type solar cells under investigation. The following sections will serve to further elucidate these measured data.

2.2.1 Comparison of crystal Si and amorphous type (Ge tandem)

Generated energy on 2001 per rated power of 1 W was 1,540 Wh and 1,350 Wh for the Ge tandem and crystal Si, respectively. Generated energy of Ge tandem is about 14 % higher than that of crystal Si. Values are the measured energy on the DC side.

Fig.3 Monthly change of generated energy (Wh) per rated power of 1 W



Available energy on AC side can be obtained by multiplying by the inverter efficiency (0.9).

This result suggests that the user can gain more energy by applying the Ge tandem. Considerable differences during summer can be observed from Fig. 3. According to Fig. 2, the normalized generated energy of both types is almost identical in winter, but the difference in summer is as much as 20 %. The measured module temperature in summer was about 60°C, which is much higher than the standard module temperature of 25°C. The reason for such a discrepancy in power generated during summer is due to the large negative temperature coefficient of crystal Si.

2.2.2 Difference of the normalized generated energy by the device structure among amorphous types

As can be seen from the monthly change of the generated energy on Fig. 2, the declination of the performance of Ge tandem due to the initial irradiation is smaller than that of a-Si single. In addition, the fluctuation of the power generating performance by season is also small. Annual generated energy per rated power 1 W was 1,540 Wh and 1,384 Wh for the Ge tandem and the a-Si single, respectively (Table 3). Ge tandem has 11 % higher performance. The purpose of adopting the tandem structure, as shown on Fig. 1, was to realize a thinner electrical conversion layer than that of single junction structure, to increase the electrical field, and to increase the absorbed energy while suppressing the initial deterioration due to irradiation. From the test results of the generated energy, we were able to verify that the tandem structure is effective.

It is reported that a disadvantage of the tandem structure is spectrum fluctuation from solar irradiation. Because the irradiation must be absorbed equally among all cells (top cell and bottom cell), spectrum fluctuation destroys the balance of irradiation among cells. However, when considering the power generation results of the present study, this effect is negligible.

The measuring period for Si tandem was relatively short. The initial deterioration stage was included in the test period for annual generated power. As a result, it is not easy the compare the performance quantitatively. However, when considering only the monthly normalized generated energy (Fig. 2), it can be

Table 3 Generated energy on January to December, 2001

Type (abbreviation)	Total generated energy (Wh)	Generated energy (Wh) per rated power of 1W (Wh/W)	Generated AC energy (Wh) per rated power of 1W (Wh/W)*
Ge tandem	35,582	1,540	1,386
Si tandem	30,281	1,495	1,346
Crystal Si	70,523	1,350	1,215
a-Si single	38,739	1,384	1,246

* : AC energy is the measured generated energy of the solar cells multiplied by 0.9 (inverter efficiency)

seen that the behavior of Si tandem is similar to that of Ge tandem.

2.3 Effect of the installation conditions

2.3.1 Dependence of the generated power on azimuth angle

On Ge tandem modules, generated energy at several azimuth angles was measured at the fixed tilt angle of 6/10 (31°). As shown on Fig. 4, monthly change of the relative generated energy (assuming 1 for south) at each azimuth angle reached a minimum in December and a maximum in June. This result was expected due to the reported solar elevation. In December, the relative generated power ranged from 0.54 to 0.58 for east and west, and 0.14 to 0.19 for north. In July, the difference of the generated energy by the azimuth angle was small. Total generated energy in 2001 was 0.79 for east, 0.81 for west and 0.59 for north, assuming 1 for south (Table 4). The measured generated energy corresponds to the measured value of the pyranometer, which was placed on each azimuth angle with the same tilt angle as the solar modules.

2.3.2 Generated energy of the vertically arranged modules

Assuming the modules are installed on walls, the generated energy at the vertical surface was measured and compared to that of the standard tilt angle (31°). Azimuth angle was south. As expected from the solar elevation, the relative generated energy at the vertical wall (1 at south) was maximum (0.96 to 0.99) in December and minimum (0.29) in July, as shown on Fig. 5. The average value in 2001 was 0.60 as shown on Table 5.

2.4 Summary

We were able to verify that the Ge tandem structure solar cells with plastics film substrate, which are currently being aggressively developed by Fuji Electric, generate 10 % higher annual energy (Wh) than crystal Si solar cells. This is important for the photovoltaic power generation system users, and will allow users to save money spent on electrical energy. The main factor causing the difference in the amount of energy produced is that the actual outdoor operating temperature is much higher than the standard temperature (25°C), which is used as the basis of the rated power. This is due to the fact that the conversion efficiency will be improved in summer, as opposed to crystal Si, which has a higher negative temperature coefficient and is negatively affected by conversion efficiency in the summer. In summer, the generated energy of amorphous Ge tandem solar cells per rated 1 W of power is 20 % higher than that of crystal Si. This means that Ge tandem solar cells are suitable for peak-cut during the greatest power demanding period.

Among the various structures of the devices, we verified that the annual performance of the Ge tandem is higher than that of a-Si single.

In addition, we found that the annual generated energy of the north-facing modules, is about 60 % of that of south-facing modules. Moreover, we found that

Fig.4 Dependence of the generated energy on azimuth angle (January to December, 2001)

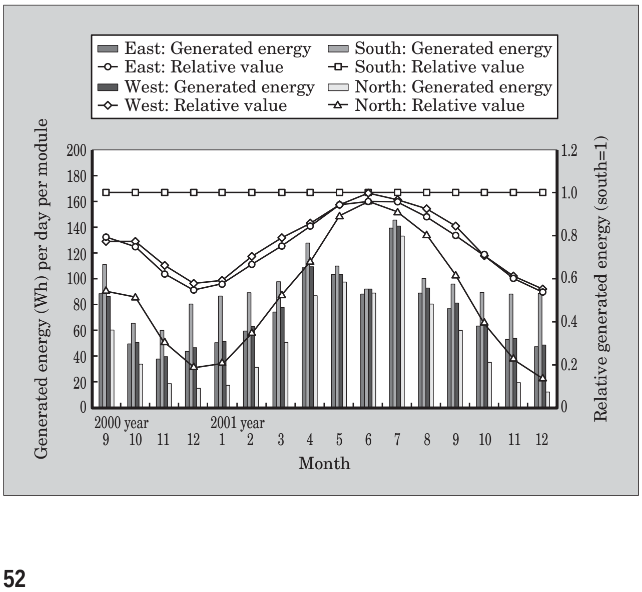


Table 4 Dependence of the annual generated energy on azimuth angle

Azimuth angle	Annual generated energy (Wh)	Relative values (south=1)
East	27,922	0.79
South	35,582	1
West	28,634	0.81
North	20,830	0.59

Fig.5 Dependence of the generated power on tilt angle

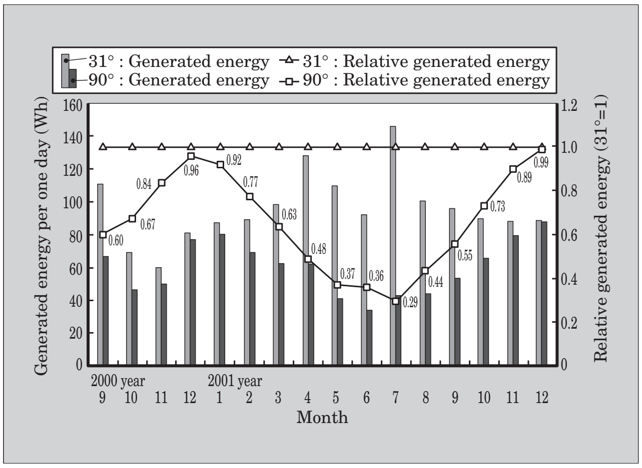


Table 5 Dependence of the generated power on the tilt angle (January to December, 2001)

Tilt angle	Annual generated energy (Wh)	Relative values (31°=1)
31° (normal)	35,582	1
Vertical	21,254	0.60

the annual generated energy of modules, which are installed vertically and face south, is about 60 % that of the tilted modules (31°).

In the near future, we would like to further analyze the effects of temperature and irradiation spectrum and continue the investigation on the large scale solar power system installed at Fuji Electric Human Resources Development Center Co. Ltd. As generated energy may be affected dramatically by environmental variables, a new standardized method, one which simulates actual operating environmental conditions, should be established for the verification of the performance of solar modules.

3. PV System for the Health Promotion Center

The solar modules composed of SCAF cells are being developed by Fuji Electric. In order to evaluate the performance of new modules in the outdoor environment, we installed two different type modules on the roof of the Health Promotion Center of Fuji Electric Corporate Research and Development Ltd. The continuous power generation tests were began in January, 1999. Below, we report the power generation test results.

3.1 Power generating system

Table 6 depicts an outline of the photovoltaic power generation system (PV system), which was installed at the Health Promotion Center. In the actual operating condition tests, we tested two different modules with a-Si tandem cells (a-Si/a-Si). Output from each module was converted into AC by an inverter. This output was then supplied to the load, and was used to power measuring and control equipment.

3.2 Specifications of the modules

In the actual operating condition tests, two distinct modules were used: Type A and Type B.

Type A : The surface is covered by a glass plate and the circumference is framed with aluminum.

Type B : The surface is covered by fluoric film, and integrated with roof tile.

The construction of type A is fundamentally the same as that of the conventional crystal Si solar module but instead of using crystal Si cells this type uses SCAF cells. In the SCAF cells, a flexible plastic film substrate is used. On SCAF cells, connections between the unit cells can be done automatically without the need for any production line wiring work. As a consequence, the wiring work is dramatically simplified and the cost for mass production may be reduced.

Type B is being developed in conjunction with building construction material manufacturers for the purpose of easy installation. Fuji Electric will manufacture the SCAF cells and encapsulate them with resin and protective film. The construction material manufacturers provided roof tiles and installed the solar cell modules. Glass covers and frames, which were used for the conventional modules, were eliminated in our developing modules and this significantly lightened the weight of the solar modules.

The type B model is relatively easy to wire and can be applied in a flexible manner. Because glass plates and frames are not required, direct material costs can be reduced and light weight construction can be realized. Due to these advantages, it is anticipated that there will be a large market for these models in the future.

Table 6 Outline of PV system for the Health Promotion Center

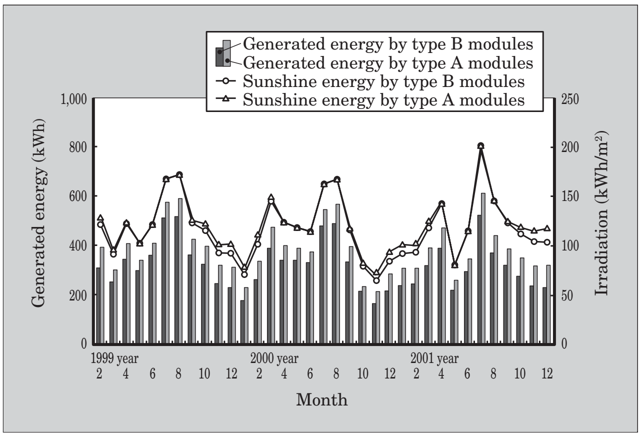
Item	Type A	Type B
Device structure	Si tandem	Si tandem
Installation area (aperture)	48.0 m^2	44.1 m^2
Installation tilt angle	19.3°	12.6°
Number of modules	80 modules	294 modules
Rated output of the installation	3.2 kW	3.0 kW

3.3 Power generating performance

Figure 6 shows the appearance of the Health Promotion Center. Type A is installed on the left side and type B is installed on the right side. We began testing in the middle of January 1999, approximately three years ago. Figure 7 shows the monthly generated energy for the three year study period. The difference of the generated energy between the modules is mainly due to the difference of the power generating surface area and the tilt angle of the installation. Both modules generated energy proportional to the irradiation and operated stably. Average annual generated energy per rated kW during the three year study period was approximately 1,360 kWh in DC (AC output was 1,209 kWh). This generated energy could reach a value of 1,495 kWh, which corresponds with the results at the test site detailed in Chapter 2. Generated

Fig.6 Appearance of the Health Promotion Center

Fig.7 Monthly change of the generated energy



energy was 10 % higher than that of the crystal type solar cells.

Based on the three years of power generation test results, sufficient data has accumulated in order to show that both A type and B type modules are suitable for practical uses.

We will continue these tests under actual operating conditions. These data will be collected and analyzed.

4. Conclusion

We introduced the outdoor performance of amorphous solar cell modules with a plastic film substrate.

We were able to verify that the Si/Ge tandem structure amorphous solar cell, currently being developed by Fuji Electric, provides 10 % higher annual generated power than that of crystal Si solar cells. This is due to the excellent power generating characteristics of amorphous solar cells at high temperatures. This quality will be regarded as advantageous and desirable to users.

In addition, the reliability of the flexible modules (the models without glass cover on the module surface) is being refined. At present, the flexible modules have almost the same reliability as that of the conventional modules (the models with glass cover). In the near future, the flexible modules will be widely used in marketplace due to their flexibility and light weight design.

An increase in the a-Si film deposition rate and a reduction in the amount of man-hours necessary to produce a module are being realized. Fuji Electric will continue to make an effort to enhance all aspects of the business of solar cells and continue to research and develop cells, which possess remarkable features.

This work was partially supported by the New Energy and Industrial Technology Development Organization under New Sunshine Program of METI.

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Application of Solar Cell Integrated Roofing Material at Railway Stations

Kaname Senda
Yoshirou Makino

1. Introduction

At present, countermeasures against global environment problems such as, global warming, are well publicized. In an effort to address these environmental concerns, electric railway companies are implementing state of the art strategies, which utilize clean energy sources.

Various slate materials are used on the platform roofs of railway stations and these materials typically maintain their structural integrity for approximately 10 to 20 years. Currently, stations planning to undergo slate roof renovation are integrating solar cell modules into traditional roof materials in order to generate clean energy. This system is expected to become into widely adopted in the near future because it promotes the effective use of platform roof space, which occupies a substantial part of a station.

This paper will describe a power generation system, which uses amorphous silicon solar cell modules that are integrated with roof materials. The performance of the Meidaimae Station and the Wakabadai Station of Keio Electric Railway Co. Ltd. will be described as an example of this clean energy system.

Figure 1 depicts platform roofs with integrated solar cell modules.

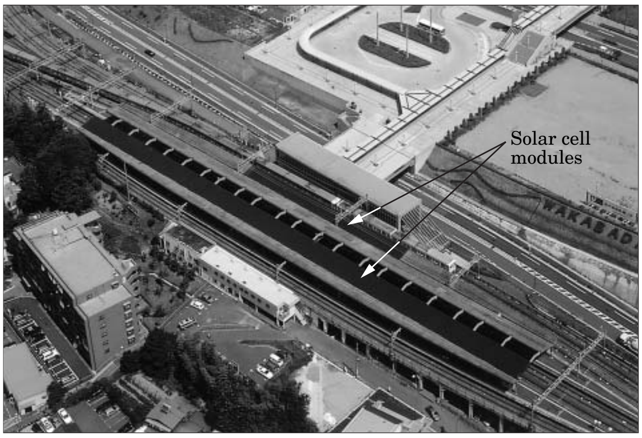
2. Features of Roof Materials Integrated with Solar Cell Modules

Solar cell modules, many of which are now used for power generation, are classified roughly into two categories based on the cell material: one comprised of crystal silicon and another comprised of amorphous silicon.

The crystal silicon solar cell module generally has a panel-like structure. The front surface of the cell is covered with tempered glass. The rear surface is enclosed with a weatherproof tetra resin film, and covered with a fireproof board as the roof material.

In contrast, amorphous silicon solar cell modules have a quite different structure. These cells consist of a piece of stainless steel foil filmed with amorphous silicon, which is fastened to a plate material (e.g. steel)

Fig.1 Appearance of solar cell modules integrated into platform roofs at a railway station



and enclosed with a durable film material. Despite these noticeable differences, the amorphous silicon solar cell modules have the same panel-like structure as the crystal silicon solar cell module (i.e. the front surface of the cell is covered with tempered glass and the rear surface is enclosed with a tetra resin film).

The solar cell modules utilized at this time in the two stations are comprised of amorphous silicon solar cells, which are secured to a steel plate. This system has the following features:

(1) When integrated into the roof material, the solar cell module is lighter than those cells with the tempered glass panel-like structure The mass per unit area of the solar cell module with framework members is 7.2 kg/m^2, which is roughly half the density of a comparable tempered glass type panel structure. Therefore, integrating modules into the roof material allows for roofs to be renovated without the need to reinforce the existing roof support structure.

(2) Roof surface temperatures may reach 60 to 80°C during the summer. Generally, the output power of the crystal silicon solar cell shows a dramatic, negative relationship to temperature. This negative relationship is less pronounced when the amorphous silicon solar cells are utilized by aniel effect. Therefore, the photo-voltaic capacity of the

cell is greater during summer and less during winter.

(3) Less energy is required for manufacturing the amorphous silicon cells than required for producing the crystal silicon solar cells. Resource and energy saving manufacturing of the cells is possible because the required temperature for the manufacturing process is low. In this process, amorphous silicon thin film is accumulated on a substrate by decomposing a silane based source gas in a vacuum. The process has a short energy payback time (EPT: a value of the energy required for manufacturing a solar cell divided by the power generated by the cell) and a significant energy creating effect.

In contrast to the features of the secured-on-steel-plate type amorphous silicon solar cell, which are described above, the crystal silicon solar cell is characterized by having a better conversion efficiency. In currently available solar cells, the crystal silicon solar cell has a conversion efficiency ranging from 12 to 15 %, while the amorphous silicon solar cell has a conversion efficiency ranging from 8 to 10 %.

In the two railway station examples presented in this paper, the secured-on-steel-plate type amorphous silicon solar cell module was adopted. The decision to utilize these modules was based upon the amount available area of renovated roofs pace, the desire to renovate without having to reinforce the existing roof support material, and the desire to complete the renovation in a timely manner.

3. Specifications and Characteristics of Solar Cell Modules

In the two examples under investigation, amorphous silicon solar cells were applied to the modules and integrated with roof materials. Depending on the shapes of the existing platform roofs, two types of the modules were used. The specifications and characteristics of each type solar cell module are shown in Table 1.

Table 1 Specifications and characteristics of solar cell modules combined with roof materials

Item \ Classification		Long size solar cell module	Short size solar cell module
Dimension	Length	5,440 mm	4,000 mm
	Width	525 mm	525 mm
Mass		23.3 kg	17.1 kg
Rated maximum output power		153.0 W	109.0 W
Rated maximum output voltage		31.5 V	22.5 V
Rated maximum output current		4.84 A	4.84 A
Rated open circuit voltage		42.8 V	30.6 V
Rated short circuit current		5.68 A	5.68 A
Number of solar cells		21 in series	15 in series

4. Structure of Solar Cell Module

The structure of the solar cell module is illustrated in Fig. 2. The module consists of a steel, 0.8 mm thick roof plate, a stainless steel plate with a filmed, amorphous silicon solar cell, which is secured on the roof plate, and a fluorocarbon resin film to adhere both plates together in order to provide protection. The shape of this system is similar to that of the typical roof steel plate and the contained solar cells are virtually imperceptible. Figure 3 depicts the solar cell modules installed on a platform roof.

Figure 4 illustrates the architecture of the roof with

Fig.2 Structure of solar cell module

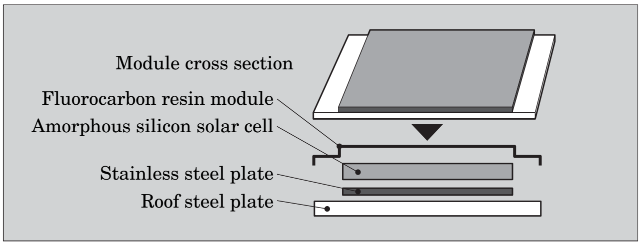


Fig.3 Appearance of solar cell modules installed on platform roof

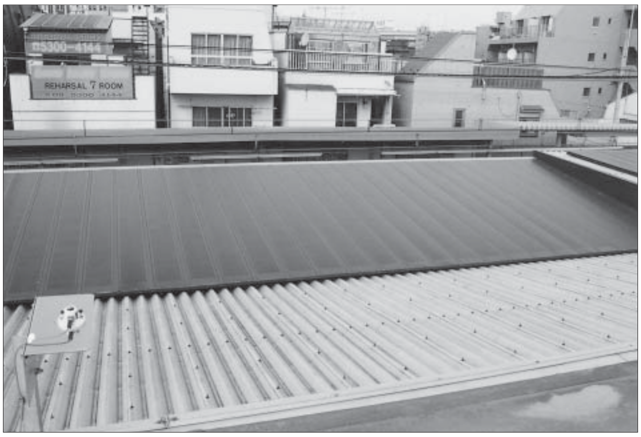
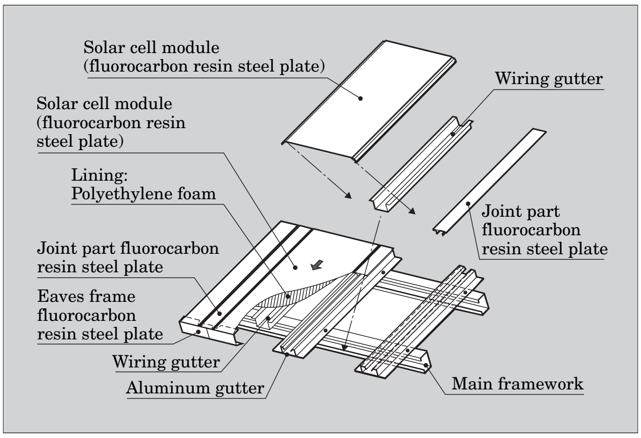


Fig.4 Architecture of platform roof with solar cell modules installed



the solar cell modules installed. The solar cell part is caught between the gutters fastened to the main framework and further secured by the joint parts.

Output wiring from a necessary number of solar cell modules is connected in series through the wiring gutters. In addition, each of the plus and minus cables from the serially connected group is wired through a cable duct to a connection box under the platform roof.

5. Application Example of Two Railway Stations

This photovoltaic power generation system was planned and installed based on the “photo-voltaic power generation field test operation” of New Energy and Industrial Technology Development Organization.

The Meidaimae station system has a rated capacity of 30 kW, and consists of the above-mentioned eighteen groups of ten serial 153 kW solar cell modules and two groups of fourteen serial 109 kW modules. Figure 5 shows the arrangement of the solar cell modules installed on the platform roofs of the Meidaimae station. For each 10 kW of output from a serial group of solar cell modules, a connection box is installed under the platform roof. Each of these is

Fig.5 Arrangement of solar cell modules on platform roof

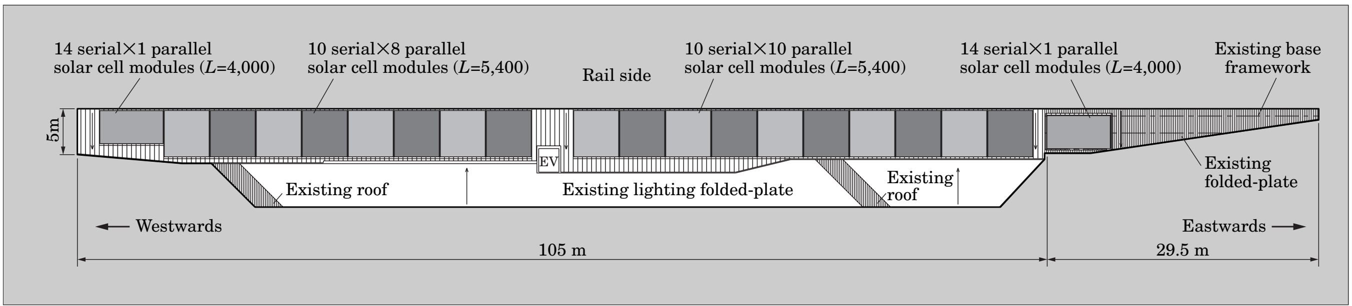
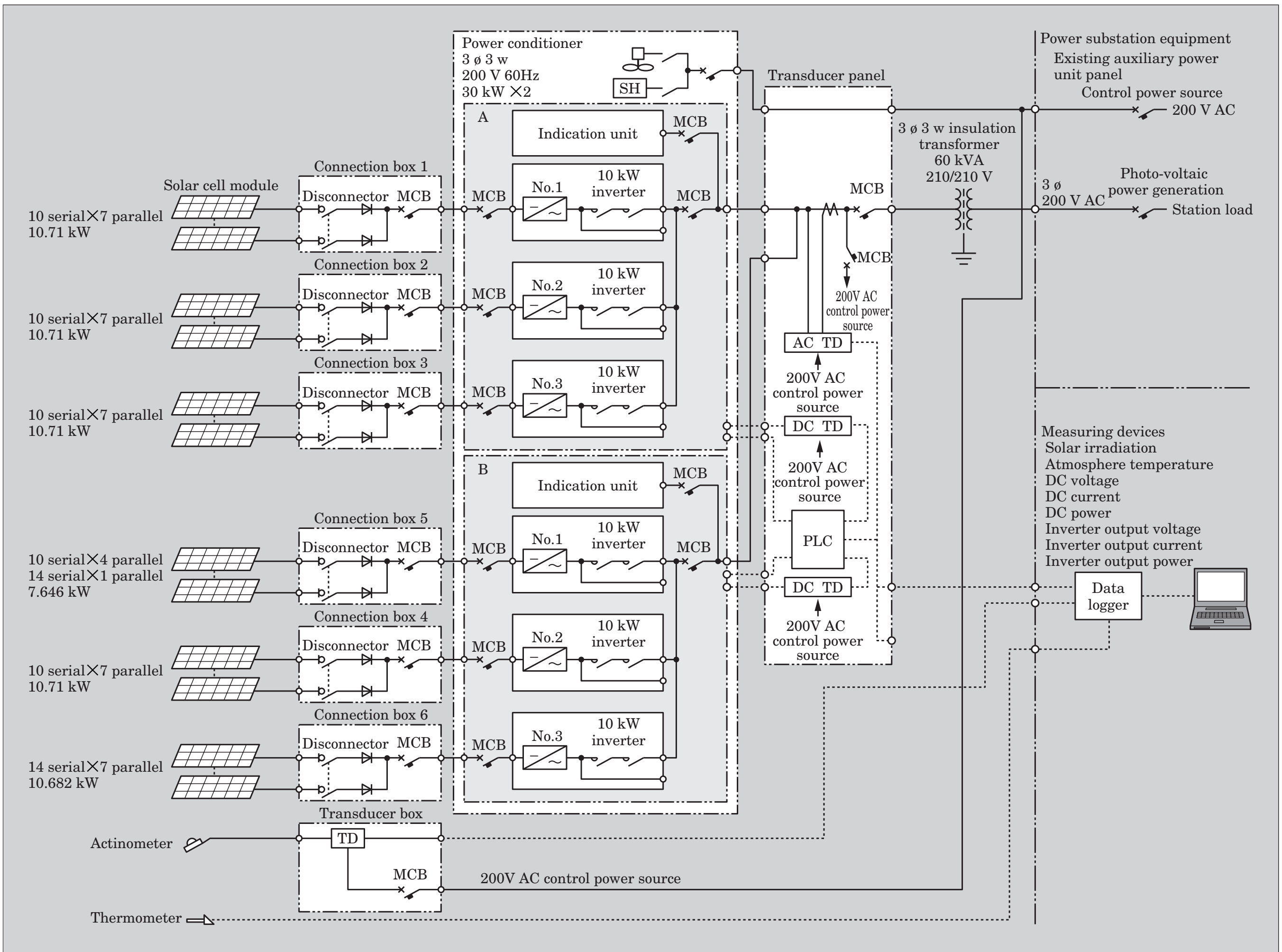


Fig.6 Photovoltaic power generation system in railway station



connected to a corresponding 10 kW unit inverter. It is important to note that when wiring cables, one should utilize existing cable racks and troughs in order to reduce construction costs.

The Wakabadai station system has a rated capacity of 60 kW, which represents a configuration that is approximately two times the capacity of the Meidaimae station system. Figure 6 details the structure of the photovoltaic power generation system at the Wakabadai station.

In order to most efficiently conduct platform roof renovation and concurrent solar cell module installation, the following work restrictions are recommended during the operating hours of railway stations:

(1) In high-use stations, roof construction work should not be conducted during business hours.
(2) If work is to be conducted at night, consideration of noise to neighboring businesses and residences is necessary
(3) When there are electric feeders or high voltage distribution lines over the platform roofs, the electric power supply should be turned off in order to prevent electric shock
(4) During periods of inactivity, platform roofs should be protected against rain

In order to complete the work in a timely manner and in accordance with the above mentioned work restrictions, the construction plan should be carefully studied

Because the Meidaimae station has no electric room and the Wakabadai station's electric room has little space, the inverters in the both stations are placed in outdoor spec switchboards.

6. Investigation into Effects of Train Electromagnetic Noise to Solar Cells

Before applying the solar cell modules to the platform roofs, the effects of electromagnetic noise from trains passing nearby or trolley wires were investigated at the Wakabadai station. The Wakabadai station is a logical location for such an investigation as express trains pass through this station at an accelerated pace.

In order to conduct this investigation, a board mounted with the solar cell modules combined with roof materials and electric and magnetic field sensors was fixed on the platform roof and monitoring devices were installed at the end of the platform. Data were collected during business operation. The results indicate that electromagnetic wave levels on the platform roof reached an electric field of several V/m and a magnetic field of several mA/m, and these levels are less than one tenth of the accepted safety standard level to the human body. The noise voltage between the solar cell output leads was about 200 mV and the noise current was below the measuring limit of 2 mA. These levels of electromagnetic noise did not impede the functioning of the solar cells.

7. Field Data

The chart in Fig. 7 shows each monthly utilization factor (a value of the system output energy divided by the product of the rated output power of solar cell array and the operation time) of the photo-voltaic power generation systems in the Meidaimae and the Wakabadai stations from April 2001 to January 2002.

The average annual utilization factor is typically about 12 % when solar cells are installed at the most suitable tilt angle. Values obtained from the present study were 6.1 to 14.4 % at the Meidaimae station system and 8.4 to 17.4 % at the Wakabadai station system.

Both stations have solar cell modules installed on their platform roofs, and the tilt angles ranged from 7 to 10 degrees at the Meidaimae station and were 15 degrees at the Wakabadai station. Therefore, these data suggest that the system utilization factors are lower than would be expected if the most suitable tilt angle (approximately 30 degrees) was utilized. Utilizing this tilt angle enables the solar cell modules to receive a maximum annual amount of solar irradiation. The reason why the system utilization factors are greatest in July is due to the fact that the amount of solar irradiation in July is approximately 1.5 times the normal value.

The following factors are thought to have caused the difference between the system utilization factors of the Meidaimae and the Wakabadai stations:

(1) The tilt angle of the platform roof of the Meidaimae station is less than that of the Wakabadai station. Also, the roof of the Meidaimae station faces to southeast, while the roof of the Wakabadai station faces almost due south.
(2) The Meidaimae station is located in a commercial area and buildings around the station, though low-rise, give an effect on the solar irradiation. In contrast, the Wakabadai station is situated in a good, open location. There are no other buildings around it, which would interfere with solar irradiation.

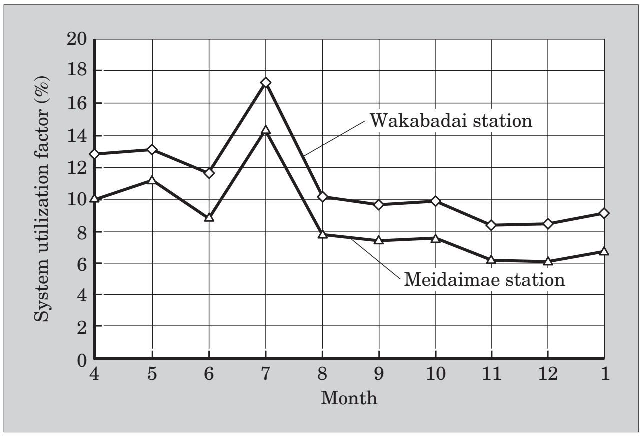
The calculated difference caused by the tilt angle is minor when compared to the overriding effect of impeded solar irradiation.

System utilization factors observed from field test data indicate that the photovoltaic power generation systems in the both stations are operating smoothly. With the accumulation of long-term data, the photovoltaic power generation systems installed on the station platform roofs are expected to be favorably evaluated in the future.

8. Conclusion

The station platform roof in railway represents a

Fig.7 Transition of system utilization factor



space that is seldom utilized but has great potential to be put to an effective use. If the price of the solar cell modules combined with roof materials is further reduced in future, the photovoltaic power generation systems on the platform roofs are believed to become widely used.

When considering the future of the global environment, reliance on fossil fuels for power generation should be reduced as much as possible. Fuji Electric promotes the establishment of energy-conservation and effective use of new, clean energy systems including, but not limited to, photovoltaic power generation.

Fuel Cell Development Trends and Future Prospects

Noboru Furusho
Hirao Kudo
Hiroshi Yoshioka

1. Introduction

As we enter the 21st century, it is more urgent than ever to respond to energy and environmental issues, not only within Japan, but on a global scale. The major challenge facing the 21st century is the problem of global warming, and energy problems are themselves environmental problems. When considering the problem of energy, it is important to not be distracted by nearsighted economic factors; we must also consider medium and long-term environmental concerns.

Fuel cells are actively being researched for use as distributed power units and vehicular power sources. Because of their high efficiency and friendliness to the environment, the early adoption of fuel cells as new energy resource in practical applications is anticipated.

Table 1 Types and characteristics of fuel cells

Item \ Type	Phosphoric acid fuel cell (PAFC)	Molten carbonate fuel cell (MCFC)	Solid oxide fuel cell (SOFC)	Polymer electrolyte fuel cell (PEFC)
Electrolyte	Phosphoric acid (H_3PO_4)	Carbonate (Li_2CO_3, K_2CO_3)	Zirconium oxide (ZrO_2)	Proton-exchange membrane
Ion conductor	H^+	CO_3^{2-}	O^{2-}	H^+
Fuel (reactant gas)	H_2	H_2, CO	H_2, CO	H_2
Fuel	Natural gas, LPG, methanol, naphtha, biogas	Natural gas, LPG, methanol, naphtha, coal gas	Natural gas, LPG, methanol, naphtha, coal gas	Natural gas, LPG, methanol, hydrogen
Operating temperature (°C)	170 to 210	600 to 700	900 to 1,000	Room temp. to 100
Power generation efficiency (%)	40 to 45	45 to 60	50 to 60	35 to 60
Development status	Commercialization phase	Demonstration plant, development for practical application	Demonstration plant	Verification testing, development for practical application

Fuel cells are classified into several types according to the type of electrolyte they use. Characteristics of the major types of fuel cells are listed in Table 1. Among the various types, only the phosphoric acid fuel cell for onsite use has reached the commercialization phase.

Fuji Electric began to research and develop alkaline fuel cells (AFCs) in the 1960s. Thereafter, Fuji has researched phosphoric acid fuel cells (PAFCs) since 1973 and polymer electrolyte fuel cells (PEFCs) since 1989. This paper describes the trends and future prospects for PAFCs and PEFCs.

2. Trends and Prospects of Phosphoric Acid Fuel Cell Development

2.1 Development trends

PAFCs utilize an electrolyte and phosphoric acid solution. They operate at a high temperature of approximately 180°C and are well suited for cogeneration systems.

Using hydrocarbon fuel instead of the pure hydrogen-oxygen fuel mixture that was used in the spacecraft power source AFCs, PAFCs began to be developed by the United States in the 1960s for applications on earth. Japan began developing PAFCs in the 1970s. During the development stage, 5 MW and 11 MW PAFCs were operationally verified as an alternative to thermal power generation; however, due to concerns regarding the reliability and economic feasibility of pressurized fuel cells, this did not lead to practical applications. On the other hand, despite their low capacity, 50 kW, 100 kW and 200 kW onsite PAFC systems have a high power generating efficiency of 40 % (low heat value (LHV) standard). These onsite PAFC systems have achieved the initial development goal of a cell life of 40,000 hours (approximately 5 years). The cost, for a single PAFC system, ranges from 450,000 to 600,000 yen per kW, and is economically advantageous when the Japanese national subsidy is applied.

As of the present date of March 2002, Fuji Electric has successfully manufactured 113 power generation systems (101 of which are onsite fuel cell systems), having a capacity of approximately 14,000 kW. In

October 2001, Fuji Electric began selling a second-commercial-type (FP-100F) 100 kW PAFC having a cost of only two-third that of prior models. Basic specifications and the external appearance of the second-commercial-type PAFC are shown in Table 2 and Fig. 1, respectively. In 1998, Fuji began selling a first-commercial-type (FP-100E) 100 kW PAFC that operated with high reliability and a high degree of capacity utilization, and the second-commercial type maintained this high reliability while achieving reduced cost. Future goals include lengthening the time between overhaul maintenance and furthering the cost reduction. Most of the cost of an overhaul is due to the fuel cell stack, and by extending the phosphoric acid lifetime of a cell, the interval between overhaul maintenance will become longer and costs incurred during the life cycle will be reduced. Present development efforts continue to enhance cell materials and improve cooling techniques in order to achieve a phosphoric acid lifetime of 60,000 hours.

Table 2 Standard specifications of a 100 kW phosphoric acid fuel cell power unit

Item	Description
Rated output (power transmitting side)	100 kW
Rated voltage	200 V (210 V, 220 V)
Power generation thermal efficiency	40 % (for rated output, power transmitting side, LHV)
Overall thermal efficiency	87 % (for rated output, power transmitting side, LHV)
Exhaust emission	NOx : 5 ppm or less SOx , dust concentration : below detectable limit
Higher harmonics	Total current distortion : 5 % or less Distortion of each current harmonic : 3 % or less
Fuel consumption	22 Nm^3/h (Town gas 13A)
Thermal output	High temperature water : 90°C/85°C (Return) 180 MJ/h Lower temperature water : 50°C/45°C (Return) 243 MJ/h
Fuel type	Town gas 13 A, low pressure
Operation system/mode	Fully automated, linked to the utility system
Main dimensions	2.2 m (W) × 3.8 m (L) × 2.5 m (H)
Mass	10 t

Fig.1 External appearance of a 100 kW PAFC

In this era of heightened environmental awareness, sewer digester gas and biogas, formed from methane fermented raw refuse or industrial wastewater, have been used as fuel in actual PAFC applications. In this case, unlike cogeneration that uses town gas as fuel, the fuel for PAFCs is nearly free of cost. Also, differing from the case of a fuel cell power generation system that uses town gas as fuel, technology is being developed to improve techniques for processing impurities in biogas or to improve methods to control fluctuations in the quantity of biogas generated. Because a fuel cell power generation system contains a built-in inverter, it is therefore able to continue supplying electrical power to critical loads even when utility power is interrupted. Power utilization is being leveraged to expand the range of applications for PAFCs.

2.2 Future prospects

As stated above, of the various types of fuel cells, only the onsite-use PAFC has achieved a level of technical and economic feasibility suitable for commercialization. Future advances such as cost reductions enabled by further technical development, expanded use of biogas or sewer digester gas as fuel, and a wider field of applications such as supplying power to critical loads, are expected to steadily pave the way for bringing PAFCs to market. Japanese national policies to promote the introduction of fuel cell power generation systems include subsidies (subsidy percentage of 50 % for a municipality and 33 % for the private sector) as specified by the Special Law for Promoting New Energy Utilization and the Taxation System for Promoting Investment to Improve Energy Demand and Supply.

PEFCs are being actively researched and developed, and because they are suited for power generation systems having smaller capacity than a PAFC, and have a low waste heat temperature level, PEFCs are expected to coexist with PAFCs in the future, with each being used in fields where they are best suited.

3. Trends and Prospects of PEFC Development

3.1 Development trends

PEFCs employing polymer ion-exchange membranes as electrolytes were used to power the Gemini spacecraft, but they were subsequently replaced as the main spacecraft power source by AFCs, which had superior performance. During the 1980s, the performance of ion-exchange membranes was improved and the application of fuel cell power generation systems as vehicular power sources was studied. Since the late 1990s, there has been a dramatic increase in activity regarding the research and development of fuel cells.

PEFCs have a low reaction temperature of approximately 80°C above room temperature and can potentially use inexpensive materials. If mass-produced as vehicular power sources, a large drop in price is expected. Because fossil fuels are predicted to be depleted by the year 2030, and also because of the problem of global warming, fuel cells that use hydrogen fuel are thought to be ideal for use as vehicular power sources. Eyeing the California state law requiring zero emission vehicles (ZEVs) by 2003, automakers are accelerating their development efforts.

Meanwhile, unrelated to the above vehicular use, a great many manufacturers have developed power units as transportable and distributed power sources, ranging in capacity from several hundred watts to several kilowatts, and are aiming to introduce home-use cogeneration systems by 2005.

The Ministry of Economy, Trade and Industry (METI) has positioned fuel cells as a key technology for next generation energy and environmental preservation. In December 1999, as a step toward the practical application and popularization of PEFCs, the Research Committee for Household Application of Fuel Cells was established as a private research panel of the Director-General of the Agency of Natural Resources and Energy, and the Committee issued a report in January 2001. In August 2001, the Committee prepared a strategy for the development of utilization technology for PEFCs and hydrogen energy. The scenario for promoting practical applications and widespread use consists of three phases: ① a base arrangement and technology verification phase (from year 2000 to 2005), ② a market entry phase (from year 2005 to 2010), and ③ a diffusion phase (beginning in 2010). The targeted adoption quantities are 50,000 Fuel Cell Vehicles (FCVs) and approximately 2,100 MW of stationary fuel cell system capacity by 2010, and approximately 5 million FCVs and approximately 10,000 MW of stationary fuel cell system capacity by 2020.

Fuji Electric began researching and developing PEFCs in 1989, at the time when the potential for enhancing the performance of polymer electrolytes became feasible. With the goal of building a high-efficiency power generation system that runs on hydrogen fuel, Fuji Electric developed a stack module having an output capacity of several kilowatts. Thereafter, Fuji Electric worked to improve cell reliability and to miniaturize the size of the cell stack, and performed run-time evaluation testing for more than 15,000 hours with a 1 kW-class stack (Fig. 2) running on hydrogen fuel. Since 2000, Fuji Electric has built a prototype of a 1 kW-class power generation system that runs on town gas fuel, has performed continuous operation testing for approximately 3,000 hours as well as other tests including start/stop testing, and has performed an evaluation of the system as a PEFC power system. Figure 3 shows the external appearance of the 1 kW-class PEFC power generation systems and a hot water tank. Power generation systems including reformers and inverters are well suited to the technology acquired during PAFC development. Through the process of prototyping and evaluating 1 kW-class power generation systems, Fuji Electric has been able to identify potential problems, estimate cost reductions, and investigate suitable applications for PEFC power generation systems.

Fig.2 1 kW class PEFC stack

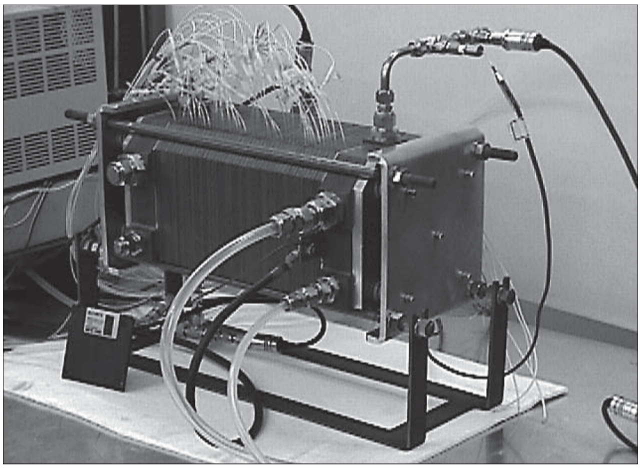


Fig.3 1 kW class PEFC power generation system and hot water tank

3.2 Future prospects

The development of PEFC power systems has been accelerated for vehicular and home-use applications. Due to the differences in the fields for application, it is believed that performance and cost specifications will also differ. The selection of an appropriate fuel is an issue for vehicular applications, and at the moment, pure hydrogen fuel appears likely to be the main choice. On the other hand, home-use and stationary fuel cell systems use fuels such as town gas or liquefied petroleum gas (LPG), which have been used as the fuel in conventional cogeneration applications. There is a need to develop reformers compatible with this fuel and fuel cells compatible with reformed gas. Although it is possible for vehicular and stationary fuel cell systems to use the same material for the separator in the main fuel cell unit, the cell unit design (especially the electrode) differs according to whether hydrogen or reformed gas will be used, and therefore these power generation systems require different types development. Furthermore, in addition to home-use applications, it will be necessary to examine other suitable applications such as industrial applications that leverage the special features of stationary PEFC power systems.

Under present conditions there is not much to say about the cost of PEFC power systems, but it will be necessary to decrease the cost to less than that of existing PAFC power systems before the demonstration device introduction phase that is slated for year 2005.

4. Conclusion

Among the fuel cells for which early applications are promising, the development trends and future prospects have been described for PAFC and PEFC technology, which is being developed by Fuji Electric as key technology for the 21st century.

By positioning fuel cells as a key component in the fields of energy and the environment, Fuji Electric will continue to promote the commercialization of PAFCs and to accelerate the development of PEFCs.

The authors wish to thank the Japanese government and all other affiliated parties for their guidance and cooperation through these many years of development. We are also deeply indebted to each user who actively adopted this fuel cell technology. In the future, we request your continued understanding and support for the introduction and technical development of this fuel cell technology.

Development of Polymer Electrolyte Fuel Cells

Akitoshi Seya
Shunsuke Ohga

1. Introduction

Polymer electrolyte fuel cells (PEFC) use an ion exchange membrane as the electrolyte.

Fuji Electric initiated research on PEFC cells and fuel cell stacks in 1989. We have conducted fundamental research and development of PEFC cells and the fuel cell stack and have accumulated data, which allows us to evaluate the reliability of the power generating system[(1)].

To promote the practical use of PEFC system, we worked on the demonstration and verification of the 1 kW class stationary PEFC system from 2000 through 2001. We produced the prototype stationary PEFC system, which consists of a power generation unit, a hot water unit and an inverter unit. In addition, we evaluated the performance of the system. The problems, which needed to be solved, were defined and the fundamental data necessary for the system upgrade were collected.

In this paper, we will discuss the prototype system and the results of the evaluation. In addition, recent developments of reformed gas fuel cells will be presented.

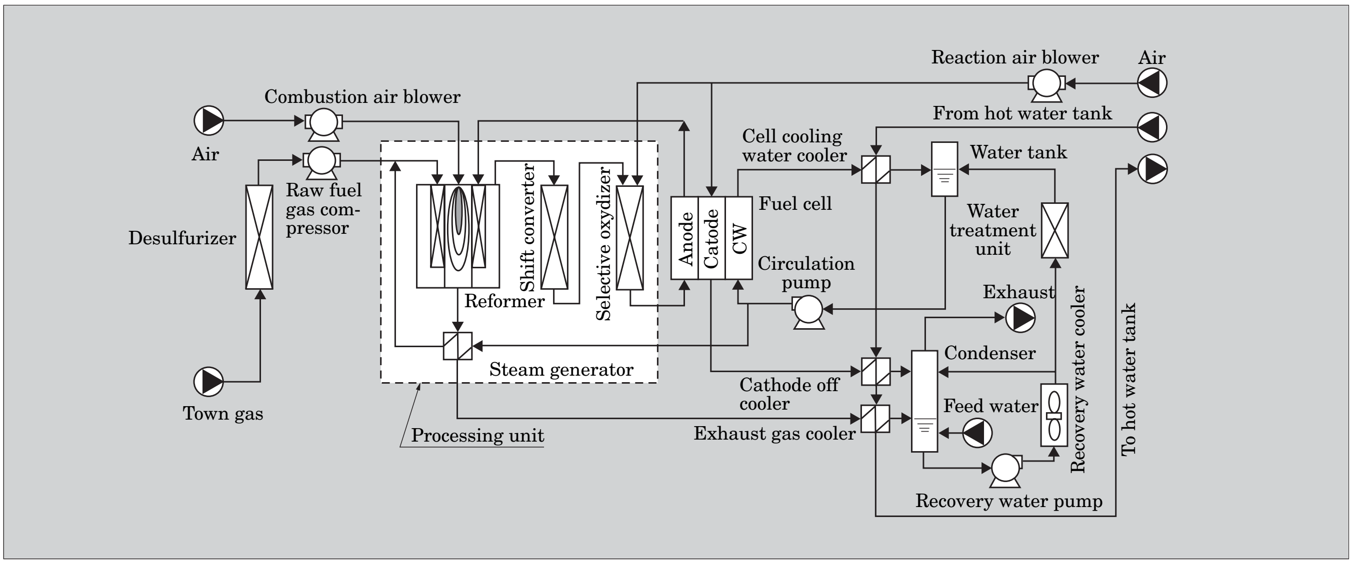
2. Development of the 1 kW System

2.1 Description of the system

The power generating system consists of a fuel processing unit, a fuel cell stack, and auxiliaries, such as a heat exchanger and a rotating machine. All of these components are self-contained in a package. Figure 1 shows the system flow diagram. Appearance of the package is shown in Fig. 3, “Fuel Cell Development Trends and Future Prospects” in this special issue.

Supplied town gas will be reformed to a hydrogen rich gas, which has a CO content less than 10ppm. This process is mediated by reforming devices, which consist of a desulfurizer, a reformer, a CO shift converter, and a CO remover. Following this process, the gas is introduced to the fuel cell stack. In the fuel cell stack, 60 to 70 % of the hydrogen in the reformed gas will be consumed during power generation. The balance of the hydrogen will be burnt in the burner and will be utilized as the heat source of the reformer. Throughout this process, the heat balance will be maintained. Electrical output will be converted into 200 V AC via an inverter unit and this electricity will

Fig.1 Process flow diagram of 1 kW class PEFC system



be supplied to the grid of the electric system. Waste heat will be recovered from the reformer exhaust gas, cell stack cooling water and cathode off gas, which pass through a heat exchanger. Heated water (60°C) will be stored in the hot water tank. Table 1 shows the specifications of the system.

The system is fully automated and can reach the power generating condition just by pressing a start button. The electrical output can be adjusted at any value between 30 and 100 % via a touch panel.

The control system is based on technology established by phosphoric acid fuel cells. Thus, the reliability and stable operation of the system is ensured.

2.2 Fuel processing unit

The fuel processing unit consists of the following four reaction devices, a desulfurizer to remove the sulfur in the town gas, a reformer for the steam reforming reaction, a CO shift converter to reduce CO content down to less than 1 %, and a CO remover to reduce CO content down to below 10 ppm. Table 2 shows the specifications of the fuel processing unit.

An ambient temperature desulfurizer was adopted in order to simplify the system. The cartridge was filled with the quantity of desufurizing agent required for approximately one year of full operation.

A steam reforming system, which was used for onsite fuel cells, was adopted. This allowed for the size to be reduced, due to the fact that in this system the reformer and CO shift converter are combined. Steam for the reformer is superheated in the CO shift converter. Figure 2 shows the appearance of the reformer/CO shift converter.

A selective oxidation CO removal method was adopted. This procedure oxidizes CO by mixing air in the pre-stage in proportion to the CO concentration in the reformed gas. Previously, the reaction tank consisted of two layers. However, we used a single reaction layer type to achieve a more compact size.

Because the operating temperature of the fuel cell stack is relatively low on PEFC power generating system, it is not possible to obtain the necessary steam required for the reformer from the fuel cell stack. Consequently, the steam had to be provided by a steam generator. This generator produced the steam from the combustion of the reformer's exhaust gas. The steam generator is an important component of the fuel processing unit.

The steam was generated by a steam generator without pulsation and the temperature of combustion exhaust gas from the reformer was lowered to 110° at the outlet of the steam generator. Thus, efficient heat utilization was achieved.

With the exception of the desulfurizer, the fuel processing unit (inside of the dotted line in Fig. 1) was integrated and its size is only ϕ300 × 650 mm (including thermal insulation material).

Table 1 System specifications

Output power	1 kW class (AC)
Electric connection	1 phese 3 wires 200 V AC
Heat recovery	60°C
Fuel	Town gas
Operation	Full automatic
Dimension Width,Height,Depth	1,100 × 1,100 × 400 mm

Table 2 Specifications of the fuel processing unit

Desulfurizer	Fuel	Town gas 13 A
	Catalyst	Zeolite
	Operating temp.	Ambient temp.
	Outlet sulfur concentration	Less than 10 ppb
	Exchange cycle	8,000 h
Reformer	Fuel	Town gas 13 A
	S/C	2.5 to 3.0
	Catalyst	Precious metals
	Operating temp.	650 to 680°C (Outlet)
	Outlet CH_4 concentration	Less than 2.0 dry %
CO shift converter	Catalyst	Cu-Zn
	Operating temp.	320°C/180°C (Inlet/outlet)
	Outlet CH_4 concentration	Less than 1.0 dry %
CO remover	Processing gas	Reformed gas (CO concentration 1.0 dry %)
	O_2 to CO mol ratio	1.0 to 1.5
	Catalyst	Precious metals
	Operating temp.	220°C/80°C (Peak/outlet)
	Outlet CH_4 concentration	Less than 10 ppm

2.3 Test results

2.3.1 Start-up/shut-down, load changing and rated load performance tests

Start-up time required to achieve the rated output was about 110 minutes for the cold start and about 60

Fig.2 Appearance of the reformer/CO shift converter

minutes for the hot start.

Figure 3 shows the catalytic layer temperature of the fuel processing unit during the start-up from the cold condition and the corresponding load change. The load changed from a rated load of 100 % to 30 %, and then back to 100 %.

Temperature of each part was controlled properly and the load change was able to be done in a stable manner.

Electrical efficiency was 38 % (LHV: lower heating value) at the DC generating output end on the rated load.

2.3.2 Continuous operation tests

To verify the temperature of each component, gas composition and water quality after a long period of operation, we performed the continuous operation tests from June to July of 2001. Figure 4 shows the test results on temperature, and pressure for the fuel processing unit.

Temperature and pressure of each part were controlled properly. We utilized a small direct contact heat exchanger in the water recovery section and achieved a closed-loop, self watering operation (water required for the steam reforming is obtained from the water contained in the combustion exhaust gas and the operation can be done without an external water supply). This process was previously believed to be difficult to conduct during the summer. Because the closed-loop, self watering system does not rely on an external water supply, the quality of recovered water can be improved. Therefore, the life of the water treatment equipment may be extended. This represents an economic advantage of this system.

Fig.3 Start-up and load changing test results

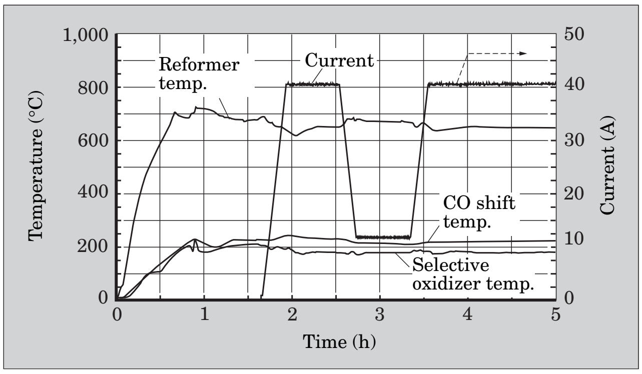
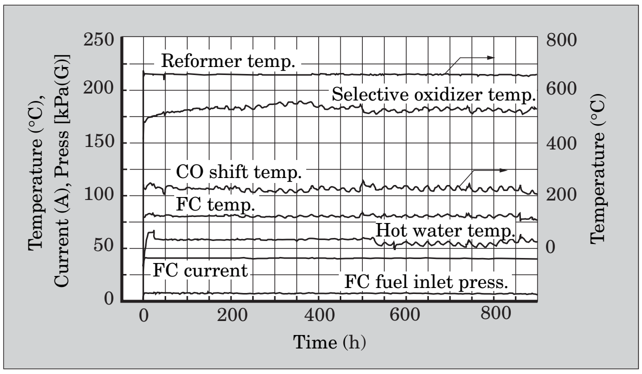


Fig.4 Continuous operation test results



2.3.3 Repeated start-up/shut-down tests

To verify the effect of repeated start-up and shut-down of the system, we conducted a 50 cycle start-up and shut-down (one or two cycles a day) operation. Any abnormalities were detected by inspecting the fuel cell voltage and the reformed gas composition. After 50 cycles of operation, the gas tightness was maintained and the temperature distribution of each catalytic layer of the fuel processing unit remained unchanged. From these test results, we were able to verify that the fuel processing unit was not damaged or deformed after 50 cycle start-up and shut-down operation.

3. Development of the Fuel Cell Stack for the Reformed Gas

3.1 PEPC fuel cell stack

The PEFC fuel cell stack is constructed from fuel cells connected in series, which comprise the power generating unit. These cells are bolted together. Each cell consists of a fuel electrode, an air electrode, and an ion exchange membrane. The reaction gas will supplied to each electrode. Each electrode consists of a catalyst layer and a gas diffusion layer. Catalyst layers consists of a catalyst (platinum or its alloy particles supported on carbon black particles) and a persulfonate ionomer solution. In the cell, water must be controlled in order to ensure that the reformed gas passage is not impeded. In contrast, the ion exchange membrane must be maintained in a continuously wet condition in order to ensure proper functioning.

When the reformed gas is used as fuel, a small amount of CO is contained. The catalyst of the fuel cell electrode can be poisoned by CO. Such poisoning can be relieved by conducting this procedure at a high temperature or by using an alloy catalyst.

Fuji Electric has performed a detailed study[2] on water management technology and has unique knowledge on non-humidifying operation. As an example, the 1 kW class fuel cell stack, which generates pure hydrogen fuel, is currently being operated successfully after 10,000 total hours with this technology[3]. Based upon the experience of this operation, we reexamined the operating temperature of the reformed gas fuel stack and improved the water management conditions. In addition, we evaluated the ability of the electrode catalyst to resist CO poisoning and we selected the most appropriate catalysts.

3.2 Long life tests of the single cell for reformed gas

We are evaluating the durability of a single cell based on the test results obtained to date. Figure 5 shows the change in cell voltage after a long period of operation under typical operating conditions (cell tem-

Fig.5 Long life test results for the single cell

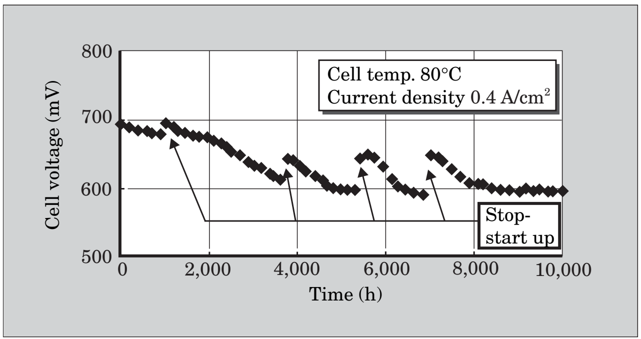


Table 3 Specifications of 1 kW class fuel cell stack for reformed gas

Fuel	Reformed gas
Oxidant	Air
Humidification	Internal humidification for air
Operating temp.	80°C
Operating pressure	Atmospheric pressure
Electrode area	100 cm²
Number of cells	60
Current at 100 % load	40 A
Output power at 100 % load	1.6 kW DC

perature: 80°C, current density: 0.4 A/cm²). From Fig. 5, it can be seen that cell voltage increases after restarting, and cell voltage gradually recedes before shut-down. This phenomenon is assumed to be caused by changing water conditions in the cell when restarting. When the system is continuously operating, the voltage will stabilize after 5,000 total hours.

We are studying the possibility of improving the electrode in order to enhance its initial performance and endurance. The results of this study are currently being evaluated.

3.3 1 kW class fuel cell stack for reformed gas

Table 3 shows the major specifications of the 1 kW class fuel cell stacks. The appearance of the fuel cell stack is shown on Fig. 6. Air will be humidified inside the fuel cell stack. As a consequence, the reformed fuel gas without humidification will be supplied to the fuel cell stack.

The fuel cell stack was subjected to component power generation tests and then assembled into the power generating system. Figure 7 depicts I-V performance of the component and performance of the power generating system at rated power. The I-V characteristic was satisfactory and the performance at rated power satisfied design requirements.

4. Conclusion

We evaluated the 1 kW class PEFC system and stack for reformed gas and verified that these can be operated in a stable manner for a relatively long time.

Fig.6 Appearance of 1 kW class fuel cell stack for reformed gas

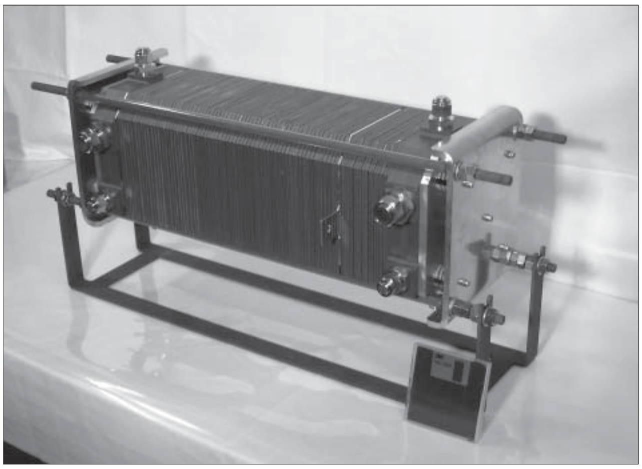
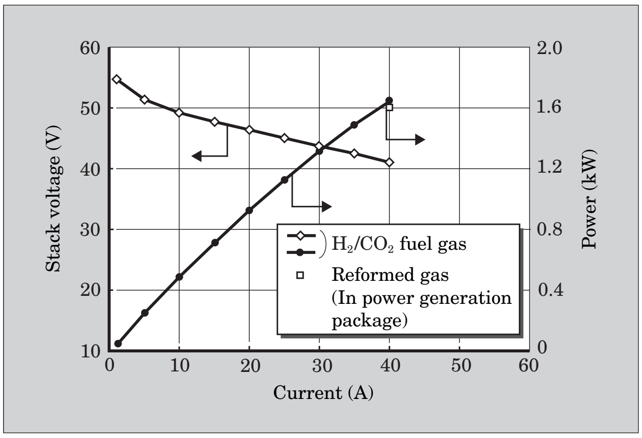


Fig.7 Performance of 1kW class fuel cell stack for reformed gas



We will continue to study practical applications of the PEFC power generating system. The following aspects will be the focus of future research:

(1) Creating long life reformed gas fuel cells and at lower costs
(2) Cost reduction by the simplification of the system
(3) Improve efficiency by reducing auxiliary power loss and heat loss
(4) Optimizing the generating capacity and developing reformed gas fuel cells with larger electrode area

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Present Status and Future Prospects of Biogas Powered Fuel Cell Power Units

Kokan Kubota
Kenichi Kuroda
Koji Akiyama

1. Introduction

Recently adjustment of laws, development of technologies and business movement have encouraged the transition to a recycling-based society. Biogas energy is being watched with keenest interest as environmentally-friendly, alternative energy source instead of petroleum. It is proposed that biomass energy will be introduced worldwide in large quantities. Particularly for Japan, which lags behind other industrialized nations in the widespread adoption of environmentally-friendly energy sources, the utilization of "biomass from wastes," such as waste wood, wood chips, sludge, garbage, edible oil waste and animal refuse, represents a promising alternative energy source, which would serve to protect the environment from the symptoms of industrialization, such as global warming.

In 1999, Fuji Electric began developing phosphoric-acid fuel cell power units using methane fermentation gas from garbage, and to this day, the produced units have been operating successfully. From 2001 to 2002, Fuji Electric produced 100 kW phosphoric-acid fuel cell power units, which use biogas from garbage and digested gas from sewage.

This paper presents examples of a methane fermentation facility and a sewage water treatment plant. In addition, an overview of these systems is presented.

2. Differences Between Town Gas and Biogas

The gas produced through anaerobic fermentation of organic wastes is referred to as biogas. Biogas consists of approximately 60 % methane, 40 % carbon dioxide, and some impurities, such as hydrogen sulfide, ammonia and hydrogen chloride (refer to Table 1). The low heating value of biogas is approximately 23 MJ/m^3, approximately half the value of town gas. Since impurities such as hydrogen sulfide harm the catalysts used in fuel cell power units, they need to be removed in advance. Although town gas contains sulfur compounds as an odorant, biogas contains sulfur compounds several hundred times greater than that of town gas. As a result, biogas pretreatment equipment is normally provided upstream of a fuel cell power generating system. As shown in Table 2, there are various desulfurization methods. With regard to biogas, dry sulfurization is normally used because it is easy to handle and inexpensive. In addition, depending on their amount, impurities other than hydrogen sulfide are removed with an active carbon tower. Therefore, with some modification to the fuel cell power generating system for town gas or LPG (liquefied petroleum gas), the biogas can be used to generate electricity.

Table 1 General characteristics of biogas (digested gas)

Element	Biogas (digested gas)	Inlet requirements to FC power units (after treatment)	Town gas (13A)
Methane	ca. 60 %	60±2.5 %	88 %
Ethane	–	–	6 %
Propane	–	–	4 %
Butane	–	–	2 %
Carbon dioxide	ca. 40 %	40±2.5 %	–
Nitrogen	Less than 0.8 %	Less than 0.1 %	–
Oxygen	Less than 0.2 %	Less than 50 ppm	–
Hydrogen sulfide	500 to 1,000 ppm	Less than 2 ppm	–
Sulfur compound (other than H_2S)	Less than 500 ppb	Less than 50 ppb	6 ppm
Ammonia	Less than 1 ppm	Less than 1 ppm	–
Heating value (kJ/m^3)*1	21,500	21,500	41,600

*1: Low heating value, 0°C, 1 atm standard

3. Fuel Cell Power Units Using Biogas from Garbage and Digested Gas from Sewage

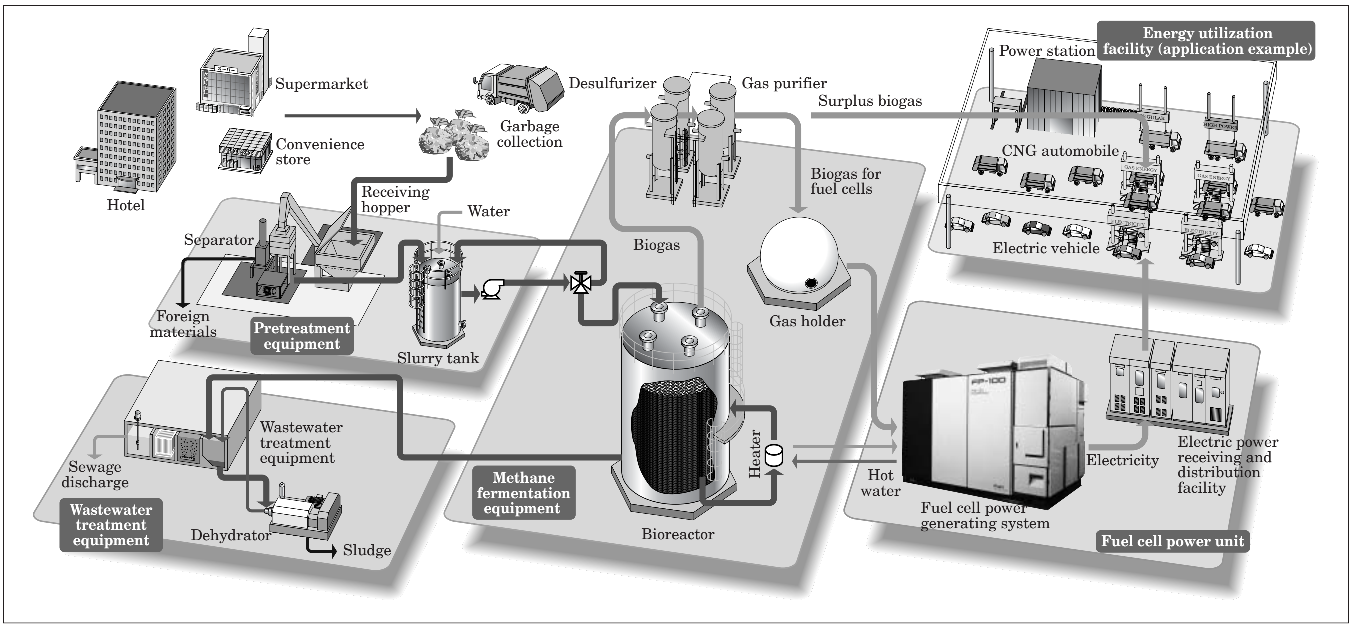
In July 2001, Fuji Electric developed a methane fermentation facility for garbage and a fuel cell power generating facility (Port Island District, Kobe City, Ministry of the Environment). In addition, a power generating system, which uses digested gas from a sewage treatment plant (Yamagata City Purification Center), was developed in March 2002.

Table 2 Comparison among various desulfurization methods

Item \ Desulfurization method	Ordinary temp. desulfurization	Hydro-desulfurization	Dry-desulfurization	Dry-desulfurization
Desulfurization agent	Zeolite family	Ni-Mo family +ZnO Co-Mo family +ZnO	Iron oxide family	Iron-Zn oxide family
Kind of sulfur	TBM (tertiary butyl mercaptan) DMS (dimethyl sulfide)		H_2S (hydrogen sulfide)	H_2S (hydrogen sulfide)
Adsorption	Physical adsorption	Chemical adsorption	Chemical adsorption	Chemical adsorption
Main reaction	—	$R\text{-}CH_2SH+H_2$ $\rightarrow R\text{-}CH_3+H_2S$ $H_2S+ZnO \rightarrow ZnS+H_2O$	$Fe_2O_3+3H_2S$ $\rightarrow Fe_2S_3+3H_2O$	$ZnFe_2O_4+3H_2S+H_2$ $\rightarrow ZnS+2FeS+4H_2O$
Reaction temp.	Ordinary temp.	250 to 300°C	Ordinary temp.	440 to 450°C
Application	Town gas, LPG	Town gas, LPG	Digested gas, biogas	Coal gasification
Fuel cell	Polymer electrode fuel cell	Phosphoric-acid fuel cell	Phosphoric-acid fuel cell	Molten carbonate fuel cell

TBM: $CH_3CH_2CH_2CHSH$, DMS: CH_3SCH_3 (methyl sulfide)

Fig.1 Schematic diagram of a power generating system using biogas from garbage



3.1 Power generating facility using biogas from garbage

3.1.1 Overview of the facility

As shown in Fig. 1, the facility consists of pretreatment equipment, a methane fermentation system, wastewater treatment equipment, a fuel cell generating system and energy-utilization facilities, which will be installed in the future. The methane fermentation system is a “high-temperature methane-fermentation organic- wastes-treatment system” (trade name: METAKURESU) and is commercialized by Kajima corporation. The fuel cell generation system is a “100 kW phosphoric-acid fuel cell power unit” (trade name: FP-100), which is manufactured and commercialized by Fuji Electric. A laboratory-level performance evaluation of both systems was reported in the, “FY 1999 New Industrial Creative Proposal Publication Work”, which was sponsored by NEDO (New Energy and Industrial technology Development Organization). But, this is the first time the practical type system has been installed. Figure 2 shows an exterior

Fig.2 Exterior view of power generating facility using biogas from garbage

view of the power generating facility, which generates biogas from garbage.

Outline of the facility is described below.

(1) Pretreatment equipment

Garbage (6 t/day) discharged from hotels in Kobe City is carried by garbage collection trucks into the facility and is transferred into receiving hoppers. After bags are broken and garbage is crushed, foreign materials such as plastic wrap, metal chips and disposable chopsticks are separated by an oil hydraulic press separator. Once separated, the biodegradable organic matter is processed into paste. Since paste-form organic matter is high in viscosity and is rather coarse, water must be added to the paste-form organic matter in a slurry tank before it is micro-crushed by a crushing pump (cutter pump). Once adequately crushed, the garbage slurry is discharged into a downstream bioreactor.

In order to collect garbage, the Ministry of the Environment supplies hotels (garbage discharger) with biodegradable plastic bags, which are biodegraded in downstream wastewater treatment equipment, even if they are not removed by the oil hydraulic press separator.

(2) Methane fermentation equipment

The body of the bioreactor is a stainless-steel fixed-bed cylinder, which is 5,200 mm in diameter and 8,500 mm high. The inside of the bioreactor consists of a cylindrical carbon-fiber biological carrier, which is 100 mm in diameter and 6,500 mm long. Micro-crushed garbage slurry is charged through the top in the methane fermentation tank. This slurry is anaerobically fermented by high-temperature anaerobic (principally methane) microbes as it flows down through the tank. Average retention time is approximately eight days. Fermented liquid drawn out from the bottom of the reactor is heated to 55°C via a heat exchanger and is then returned to the top of the reactor. Hot water from a fuel cell power unit is utilized as a heat source for the exchanger.

Biogas produced through high-temperature anaerobic fermentation consists principally of methane, carbon dioxide, and some impurity gases, such as hydrogen sulfide and ammonia. Since these impurity gases adversely affect the downstream fuel cell power generating system, they are removed while passing through a desulfurization (iron oxide) and refinery tower (active carbon). Following this process, the biogas is fed into the fuel cell power generating system.

Part of desulfurized and refined biogas is stored in a double-balloon structure gas holder, which is 30 m^3 in capacity. This feature allows the system to adequately store the fluctuating volumes of produced biogas.

(3) Wastewater treatment equipment

Fermented wastewater which overflows from the bioreactor and discharged wastewater from various processes are collected into wastewater treatment equipment in the facility. After subjected to an anaerobic and aerobic treatment, they are discharged to a sewage line, which passes through a penetration membrane. Sludge produced through the wastewater treatment is dehydrated and discharged outside the facility.

(4) Fuel cell power unit

A phosphoric-acid fuel cell power unit produces a direct current (DC) via a chemical reaction between hydrogen (H_2), which is reformed from the methane (CH_4) in biogas, and atmospheric oxygen (O_2). The reformer is situated inside the fuel cell package. The direct current produced is converted into a 200 V, 60 Hz alternating current (AC), and is supplied to the facility. All of the service-power in the facility is covered by the fuel cell power unit, and a surplus totaling 40 % of the generated power can be effectively used.

(5) Energy utilization facilities (future plan)

In this project sponsored by Ministry of the Environment, surplus electricity and gas are planned to be utilized for recycling projects appropriate for the region with the goal of creating a recycling-based society.

Installation of “a gas filling station for gas vehicles” and “an electricity-charging station for electric vehicles” is under review.

3.1.2 Introduction benefits of biogas power generation

With the introduction of the system mentioned above, the following benefits are expected:

(1) Reduction of fossil fuels and suppression of carbon dioxide emissions due to a reduction in the volume of garbage without incineration
(2) Reduction of fossil fuels and suppression of carbon dioxide emissions due to utilization of surplus electric power
(3) Reduction of fossil fuels and suppression of carbon dioxide emissions due to utilization of surplus gas
(4) Reduction in whole waste volume due to separate garbage collection
(5) Repercussions due to the practical environmental training on the theme of this project

Implementation and verification of the project is scheduled to run three years in duration.

3.2 Power generating system using digested gas from a sewage treatment plant

Anaerobic treatment of sewage sludge is currently conducted at approximately 300 facilities in domestic sewage treatment plants. Overall, digested gas generated in these facilities totals approximately 260 million m^3/year. This gas is currently utilized for heating digested gas holders, for digested-gas power generation, and as an auxiliary fuel for sludge combustion. Approximately 15 % of the digested gas utilized for power generation is utilized for gas engines. Recently, fuel cells have been introduced because they are superior to gas engines in terms of their power

Fig.3 Schematic flow diagram of the fuel cell power generating facility for Yamagata Purification Center

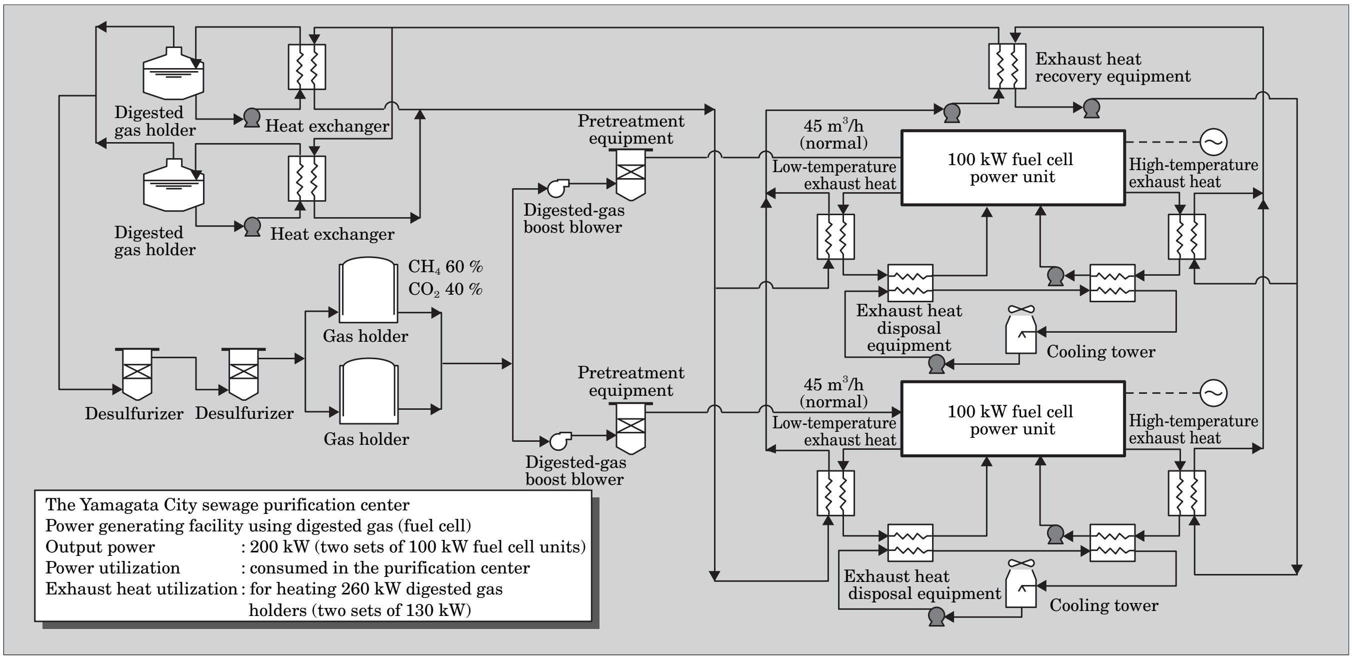


Table 3 Specifications of the fuel cell power unit for Yamagata City Purification Center

Item	Specifications
Rated output	100 kW (at output terminals)
Rated voltage, frequency	210 V, 50 Hz
Power generation efficiency	38 % LHV (at rated operation, at output terminals)
Overall efficiency	87 % LHV (at rated operation, at output terminals)
Fuel	Digested gas(methane: 60 %, carbon dioxide: 40 %)
Fuel consumption	45 m^3/h (normal)
Operation mode	Fully automatic operation, parallel operation with mains
Thermal output	20 % (90°C hot water) 29 % (50°C hot water)
Exhaust gas	NOx : less than 5 ppm, SOx: beyond detection
Operating noise	65 dB (A) (average value at a distance of 1 m from the unit)
Size	2.2 m (W), 4.1 m (L), 2.5 m (H)
Mass	12 t

generating efficiency and environmental impact. In March 2002, Fuji Electric delivered fuel cells to Yamagata City Purification Center. The center averagely treats 40,000 m^3 of sewage water per day and produces approximately 4,200 m^3 of digested gas per day through anaerobic fermentation. Part of the digested gas produced is utilized for a 178 kW gas engine in order to generate electricity. With the increase of digested gas, however, two sets of 100 kW phosphoric-acid fuel cells have been introduced to generate electricity and to utilize the generated heat to a digested gas holder. Figure 3 shows a schematic flow diagram of the system. Table 3 shows the specifications of the fuel cell power unit.

Energy-saving effects and environmental benefits through the introduction of fuel cells are as follows (with two sets of fuel cell units):

(1) Energy-saving effects (crude oil equivalent): 458 kL/year
(2) Reduction in CO_2: 1,140 t/year
(3) Reduction in NOx: 460 kg/year
(4) Reduction in SOx: 412 kg/year

4. Future Prospects

Unlike conventional gas powered generating machines, such as gas engines and gas turbines, fuel cells can generate electricity without fuel combustion and without first being transformed into rotational energy. As a result, exhaust gas is very clean (NOx: not more than 5 ppm, SOx: beyond detection), and power generation efficiency is very high. Hot water produced during electrochemical reaction required for power generation can be utilized through heat recovery.

Due to the implementation of the "Food Recycling Law" (Law for Promoting Reuse of Recycling Food Resources), it is envisioned by related industries that the practice of food recycling will be widely adopted without waiting (the typical) three years for verification testing. The results from these tests, which indicate that biomass from garbage can be harnessed to generate power, will be used as demonstration examples of the Food Recycling Law.

Of the sewage-digested gas facilities in Japan, approximately 100 facilities produce the required amount of digested gas for a 100 kW fuel cell power unit. However, the digested gas is currently utilized as fuel (heat energy), such as that which would be required for a boiler. It is expected that fuel cells will become widely utilized and will therefore, aid in the reduction of CO_2 emissions. In a report by New Energy Division of Advisory Committee for Natural Resources and Energy of Agency for Natural Resources and Energy, an introductory target for biomass power generation for 2010 is set at 330 MW/year, in terms of installed capacity (four times that for 1999, crude oil equivalent: 340 thousand kL/year).

In the future, Fuji Electric is determined to concentrate on the following developments to increase applications of fuel cell power units using biogas:

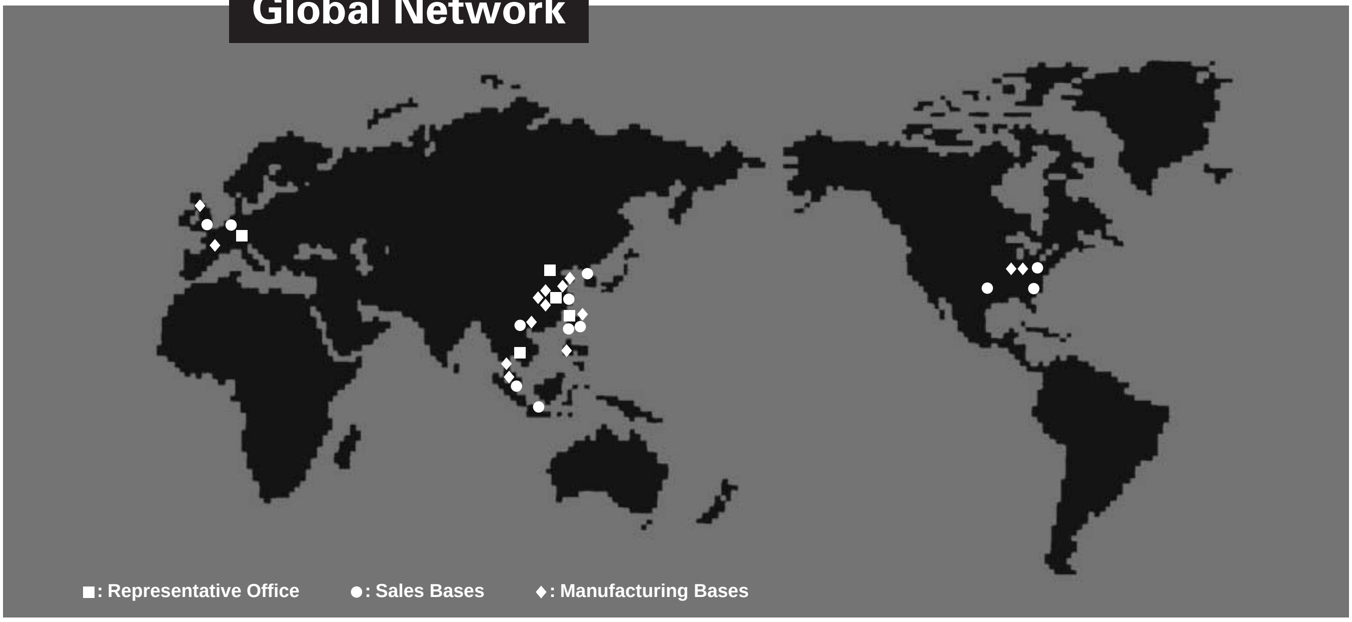
(1) Development of fuel cells capable of using as low as 50 % density methane gas
(2) Development of fuel cells responding to 0 to 100 % fluctuation of the amount of biogas produced
(3) Development of exhaust heat utilization suitable for methane fermentation facilities

5. Conclusion

This paper describes applied examples of phosphoric-acid fuel cell power units, which use biogas from garbage and digested gas from sewage sludge. Methane fermentation is the most suitable technology to reduce the volume of organic wastes because this process conserves energy, and the fuel cells are suitable for utilizing the produced methane gas.

It is strongly recommended that fuel cell power generation using biogas be encouraged under the assistance and guidance of all concerned parties.

Global Network



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