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Fuel cells and the city of the future — a Japanese view

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Abstract

The development and practical application of fuel cells have been promoted aggressively in Japan, and the on-site phosphoric acid fuel cell (PAFC) has been attained with the prospect for practical market entry in commercial buildings by the middle of the 1990s. Fuel cells have features of less environmental impact and high energy efficiency which meet the requirements of the utility system for the future city. In Japan, the recent concentration of social functions and population to the city have begun to cause many serious problems. To resolve these environmental and resource related problems and to move towards developing and constructing a new city, one answer offered is the concept of CAN (community amenity network). CAN is a sophisticated utility system which integrates fuel cells as well as a system for effective use of unused energy and recycling of waste disposal and water. For solving the housing shortage problem in the next century, the concept of skyscraper building cities is currently proposed. Fuel cell systems can also be applied to these cities as a major element of the integrated zone energy supply network facility.

Current status of fuel cell development in Japan

The development of the fuel cell as a power generation system began in the 1960s in the US. In the 1970s the excellent energy efficiency of the fuel cell and its compatibility with a clean environment attracted the attention of Japanese gas utility companies and electric utility companies. They started research and development on fuel cells by participating in US projects such as Target Project or FCG-1 Project, and they conducted demonstration tests of the 40 kW packaged on-site phosphoric acid fuel cells (PAFC) and the 4.5 MW PAFC power plant. Meanwhile, Japan's original national project became active in 1981, and demonstration tests of two 1 MW PAFC power plants were conducted successfully in 1987.

Japanese gas utility companies are now promoting the practical application plan of on-site PAFCs through the development by Japanese manufactures and the introduction of advanced IFC's technology.

Development plans of PAFCs in Japan are shown in Fig. 1. For 50–500 kW on-site PAFCs, placement on the market is expected to take place by the middle of the 1990s with the target costs and specifications as shown in Table 1. At the beginning, however, the price will not be reasonable because of an insufficient reduction of production costs due to small scale production, so that the fuel cell will be applied to commercial buildings which will be able to take advantage of the economical benefit of co-generation. The practical application of the 1 MW on-site PAFC and 11 MW

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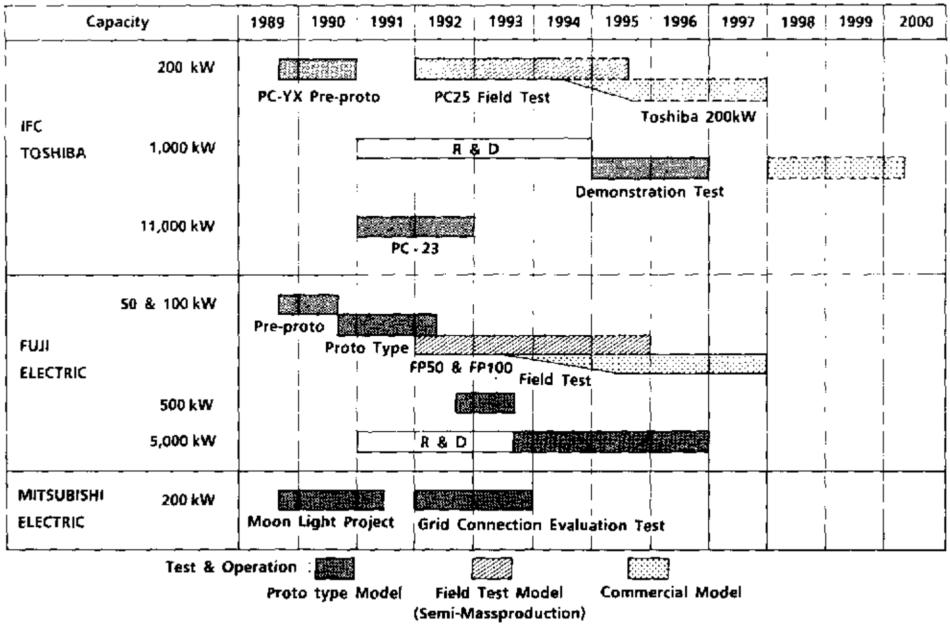

Fig. 1. Development and commercialization of PAFC in Japan.

TABLE 1

Target specifications of on-site PAFC by middle of 1990s

Electrical efficiency (%)	36 (HHV)
Overall efficiency (%)	76 (HHV)
Thermal output (%)	
Steam (170 °C)	25 (HHV)
Hot water (60 °C)	15 (HHV)
Size (footprint) (m^2/kW)	0.08
Operation mode	automatic, grid-connected and independent
Start-up time (h)	less than 2
Cost (yen × 10^3/kW)	200 ~ 300 ($1400 ~ 2000/kW)

PAFC dispersed power station will be achieved by the end of the 1990s. Further progress of technological improvement and commercialization is expected toward the 2000s, and the improved on-site PAFCs with the specifications shown in Table 2 should be realized at that time.

The cell technology of the molten carbonate fuel cell (MCFC) is now being developed in Europe, US and Japan. 10 kW cell stacks have already been developed and tested successfully in the US and Japan. They are now developing 100 kW cell stacks, which are due for testing within a couple of years. The MCFC development schedule of Japan's national project is shown in Table 3. The electric efficiency of the MCFC is expected to be 10–15% higher than that of the PAFC. The MCFC system may be more complicated than that of the PAFC, because of the high operating temperature and the addition of a CO_2 recycling system. Therefore, the MCFC is being developed as a dispersed power station, or power plant using coal gas as fuel.

TABLE 2

On-site PAFC specifications perspective for 2000s

Electrical efficiency (%)	40 (HHV)
Overall efficiency (%)	80 (HHV)
Thermal output (%)	
Steam (170 °C)	25 (HHV)
Hot water (60 °C)	15 (HHV)
Size (footprint) (m^2/kW)	0.06
Operation mode	automatic, grid-connected and independent
Start-up time (min)	30
Cost (yen $\times 10^3$/kW)	150 ~ 200 ($1100 ~ 1400/kW)

The capacity will be as high as 1 MW or higher. Practical application will begin early in the 2000s.

For the solid oxide fuel cell (SOFC), the progress of the tubular-type cell developed by Westinghouse is the most advanced. In Japan, gas utility companies conducted evaluation tests of the 3 kW cell stack produced by Westinghouse in 1987. An evaluation test of the 25 kW power generation system will be conducted this autumn, and the tests of the 25 kW co-generation system will be conducted in the spring of 1992.

Westinghouse is now planning to develop a 100 kW power generation system. Development of SOFC technology is also being carried out in the US, Europe and Japan besides at Westinghouse. However, the capacity of those cell stacks is limited to less than 1 kW at the moment.

The electric efficiency of the SOFC is expected to be as high as that of the MCFC. In addition, there is a possibility of reducing its size by internal reforming of fuel gas. It is, therefore, promising for use as a next generation on-site fuel cell. Mechanical strength and durability must also be improved in order to stand the thermal shock during the starting and the stopping operations. Commercial use will begin in the 2000s at the earliest.

Current status of city and energy in Japan

Energy demand in Japan greatly increased in the 1970s, matching the high rate of economic growth. However, the oil crises of the late 1970s and the early 1980s suppressed economic growth. Furthermore, the development and propagation of energy saving technology halted and stabilized the increase in energy demand in the 1980s.

During the late 1980s and the early 1990s, the energy demand again tended to increase due to a diversification of lifestyles and an increase in the demand for comfort, as shown in Fig. 2. About a 30% increase in energy demand is projected for the year 2000 as compared with 1990. The share of electric power of the total energy demand will definitely increase.

Serious problems arise concerning the global environmental pollution, since the increase in energy consumption will increase the greenhouse effect through increased release of carbon dioxide (CO_2) and the destruction of forests because of acid rain resulting from increased sulfur dioxide production. Although CO_2 emission per person in Japan is 2 ton/year, which is low compared with the rate in Europe, the US and

TABLE 3

MCFC development program by Moonlight Project

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Large-scale cell stack	R&D ←	—	—	—	—	—	→				
				10 kW Stack ↔		100 kW Stack ←	→				
Plant components and control	R&D ←	—	—	—	—	—	—	→			
				100 kW FPS test ←	—	→					
Application for coal gasification fuel					R&D and test ←	—	—	—	→		
Demonstration plant								Construction ←	→	Operation ←	→

△ Interim evaluation (1994)

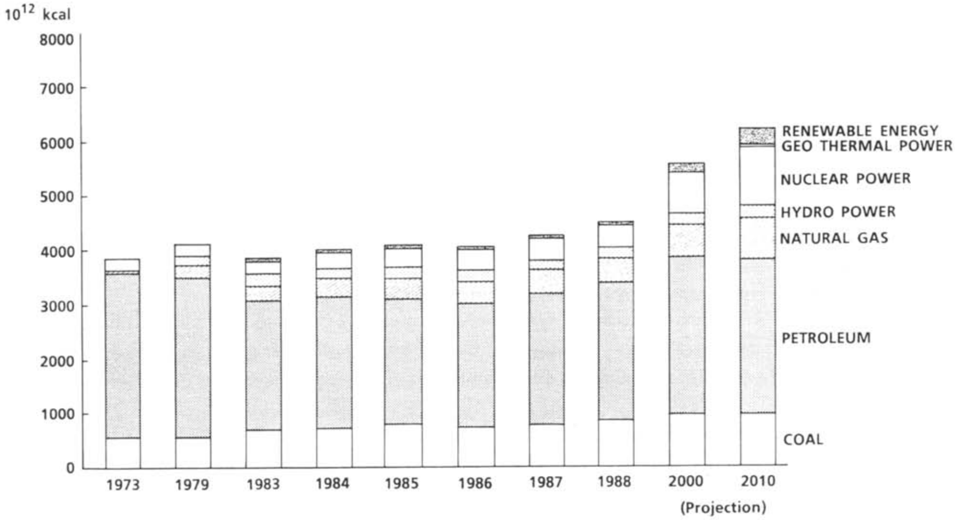

Fig. 2. Primary energy supply in Japan.

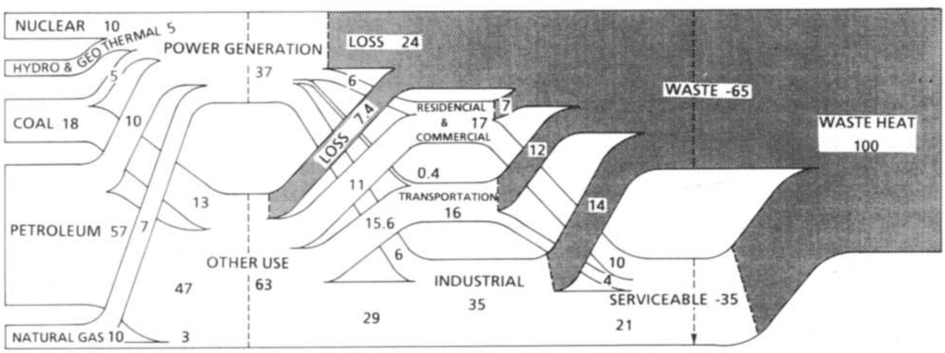

Fig. 3. Flow chart of energy supply and consumption in Japan.

the USSR, the net quantity of CO_2 emission in Japan is as high as about 5% of the total world emission. Another problem we have to take into consideration is that 65% of precious energy consumption is wasted, since it is not used effectively. Figure 3 shows the energy supply and consumption flow chart for Japan.

Recently, social functions and the population have tended to become centralized in the big cities in Japan. Consequently, the cities faces some serious problems including housing shortages, air pollution by NO_x emission, difficulties with increasing garbage and refuse treatment, difficulties of securing water resources etc. The energy demand has also become concentrated in the big cities, where a huge amount of thermal energy that could be used effectively is wasted. The waste heat distribution in the Tokyo metropolitan area is shown in Fig. 4. The amount of waste heat is as large as 40×10^{12} kcal/y, which is equivalent to about half of the total heat demand of Tokyo. About half of the waste heat is discarded from thermal power plants.

The amount of garbage and refuse in big cities is rapidly increasing, too. Over the past five years in Tokyo, it has increased by 20%, reaching a total of about

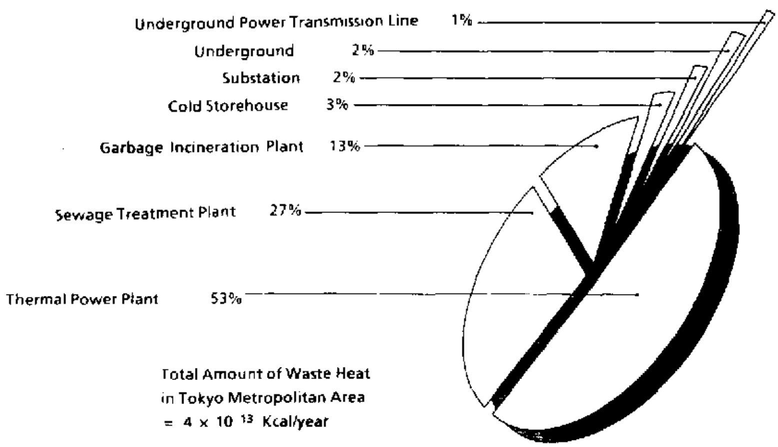

Fig. 4. Distribution of waste heat in Tokyo metropolitan area.

5 million tons. Although combustible garbage should be burnt, while non-combustible refuse should be reclaimed, some combustible garbage is also reclaimed because of the insufficient capacity of incinerators. The shortage of dumping areas for reclaimed garbage has also become a serious problem. The unit heat generated from the incineration of combustible garbage has also increased by 20% from 1720 kcal/kg in 1984 to 2060 kcal/kg in 1988. The heat generated by garbage incineration has also attracted public attention as a renewable energy resource.

Japan has been blessed with abundant water resources. At present the private use of water amounts to approximately 90 l/person/day. There has been no remarkable change in this figure over the past decade. However, the increase in the population of Japan, especially in the big cities, has resulted in an increase in the total demand for water. Ensuring the necessary amount of water is now becoming more and more difficult in big cities.

About 20% of the water used in private homes and more than 50% of the water used in office buildings is consumed as flush water in toilets, water to spray gardens and cooling water for machinery. Recently, water saving by recycling waste water after treatment or by using rainwater has been taken into consideration, and is being tried in limited ways.

A proposal for CAN (community amenity network)

A new arrangement of urban life functions is now being sought in order to develop a healthy and comfortable urban life by solving problems concerning energy, water resources and the environment. One answer to these problems is offered by Tokyo Gas as a concept of CAN (community amenity network).

CAN is a sophisticated utility system which has been designed to make effective use of waste energy and resources coming from each building in a community and to save energy by recycling or conserving these resources. The conception is shown in Fig. 5. CAN is designed as a community unit consisting of buildings over an area

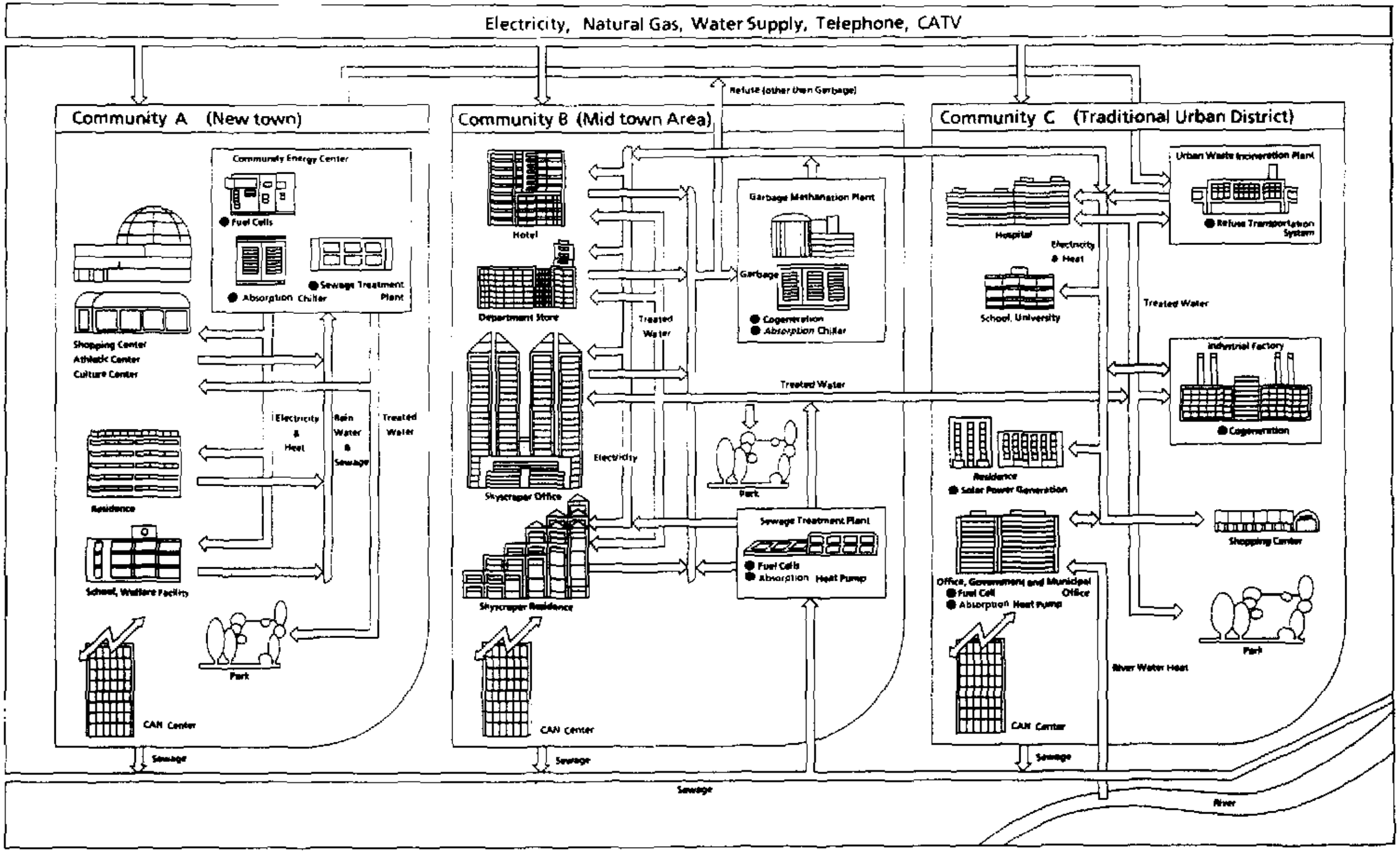

Fig. 5. Conception of CAN (community amenity network).

of about 100 hectares, with facilities suitable for the community built to supply energy and water, as well as to recover waste heat and to treat the garbage of the community, linking the buildings within the community into a network.

Through the comprehensive network, the waste energy and resources coming from each building are collected so that they can be utilized efficiently. Consequently, large-scale energy and resources saving can be achieved over the total city area. Environmental protection can also be assured.

The facilities included in CAN depend upon the features of the community. Fuel cells will play an important role in the energy supply system of CAN. Because of the excellent compatibility of the fuel cell with a clean environment, it can be installed on-site within the community itself. Further more, its high power generation efficiency and its ability to supply energy for air conditioning by using high quality waste heat makes it possible to supply heat and electricity efficiently to the community throughout the entire year. It is also possible to install it at a factory nearby, which consumes a large amount of heat. In this way, it will supply power and heat to the factory and also supply surplus electricity to other buildings within the community at the same time.

It is rather difficult to use solar energy as a total power supply system in Japan, especially in urban areas which consume a huge amount of energy, because of the low density of solar energy. However, it is possible to utilize this energy by installing solar cells on the roofs of private houses or public buildings with a large space, and partially provide the electricity required by that house or building.

Garbage and refuse are collected in distinct groups, e.g. combustible, non-combustible, recyclable, etc. Combustible garbage is collected at any time of the day through a pipeline. Raw garbage from residential areas is used for methane gas generation through fermentation, and the gas thus produced is fed into either the fuel cell or a conventional co-generation system. Combustible garbage from office buildings is incinerated, while combustion heat is used to generate power and heat supply.

Waste water from residential areas and rainwater is collected within the community to be treated and recycled as a flush water for toilets or cooling water for machinery. The municipal sewage treatment facility treats the final sewage that is discharged into rivers or the sea. At the same time, the low temperature waste heat that comes from the bio-treatment is recovered by a heat pump and is used for heating and the hot water supply. The river water can also be used for energy recovery with the heat pump because it is warmer in winter and colder in summer than the ambient air.

The function of one unit of CAN is not limited to one community, but rather contributes to the whole society through a network between each CAN to effectively utilize energy and resources within a total system, where the advantages and drawbacks of an individual CAN can be compensated.

The application effect of CAN on the community A in Fig. 4 was evaluated. Community A of a new town consists of 8000 private houses, commercial facilities, schools, and cultural and sport facilities. The total floor area is about one million square meters. The energy demand has been estimated to be about 10 thousand kW of electricity and 28 Gcal/h of heating, 20 Gcal/h of hot water supply, and 1390 Gcal/h for air conditioning. The features of community A are described in Table 4. As for CAN facilities, the following equipment has to be installed: 10 000 kW fuel cell for power supply, steam boilers, steam-driven double-effect absorption chillers, and absorption heat pump to supply heat. The basic conception of the energy supply system for the community is shown in Fig. 6. For the fuel cell, the PAFC will be employed

TABLE 4

Features of Community A

Type of building			Energy demand	
			Peak	Year
Residential	960000 m^2	Electricity	9913 kWh/h	35179 MW/h
Commercial	100000 m^2	Hot water supply	20286 Mcal/h	22690 Gcal
Educational	60000 m^2	Heating	28256 Mcal/h	26186 Gcal
Cultural	20000 m^2	Cooling	13294 Mcal/h (4400 RT)	14272 Gcal
Athletic	10000 m^2			
Total	1150000 m^2			

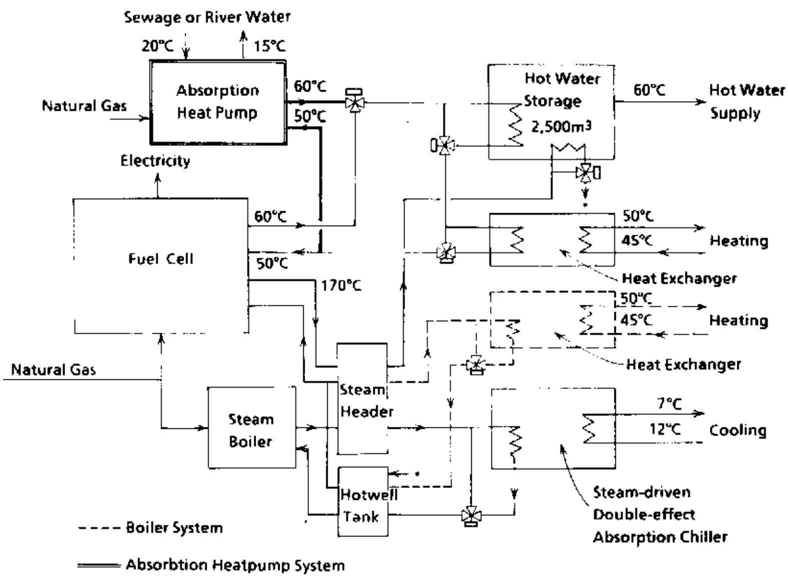

Fig. 6. Conception of energy supply system for the community.

because it is the most technologically advanced. The efficiency at the rated power will be 40% for electricity, 20% for steam and 20% for hot water supply.

The simulation of energy consumption is illustrated in Fig. 7 and Table 5. Although each building in the community shows an individual demand pattern of electricity and heat, the cumulative demand in the community is equalized. As a consequence, about 80% or more of waste heat can be effectively used at all times except during the night or in the summer when all the low-temperature heat from the fuel cell cannot be used effectively. The overall efficiency is as high as 70%.

Comparing this with the conventional energy supply system consisting of electricity distribution from a thermal power plant, the annual energy saving in community A is estimated to be 43×10^3 Gcal, or 28% of the total consumption. In addition, the utilization of energy from sewage treatment by absorption heat pumps increases this energy saving rate to 35% (Table 6).

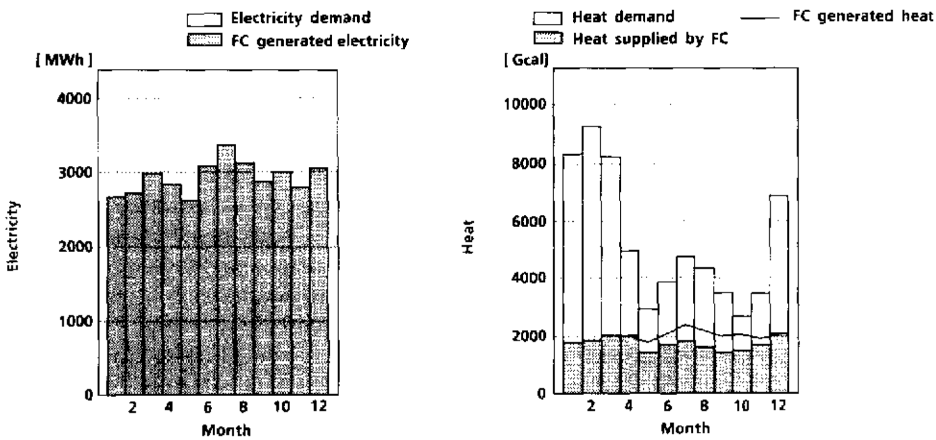

Fig. 7. Energy demand and supply in community A.

TABLE 5

Simulation results of energy supply

Supply from fuel cell system			Demand
Electricity (kW h)	35179	(100%)	35179
Hot water (Gcal)	12572	(55.4%)	22690
Hot water (with storage (Gcal)	15430	(68.0%)	
Heating (Gcal)	3843	(14.7%)	26186
Cooling (Gcal)	7251	(50.8%)	14272
Heat total (Gcal)	23666	(37.5%)	63148
(with hot water storage)	26524	(42.0%)	
Overall efficiency of fuel cell system	71.0% 74.8% (with storage)		

TABLE 6

Comparison of energy consumption

	Conventional system	CAN system			
		Boiler case		Absorption heat-pump case	
		Heat storage	Without storage	Heat storage	Without storage
Energy consumption (Gcal/y.)	154×10^3	105×10^3	110×10^3	98×10^3	101×10^3
Energy saving rate (%)		32	29	36	34

In the future, it will be possible to save 25% or more of water by collecting rainwater and recycling waste water. The amount of effluent in the sewage will be also reduced by 30%.

Skyscraper future cities and fuel cells

As a measure against land shortages and population concentration in the cities, unique ideas for a space city have been proposed by Japanese building contractors. The outline is shown in Table 7, and the exterior view is illustrated in Fig. 8. The height is 1000–2000 m and the floor area is 1.5–11 million square meters. The population is between 50 and 500 thousand. This type of gigantic building will make up the future city. Though each building differs in terms of height, floor area and lead time to construction, all of them are conglomerate buildings which include offices, hotels, shops and private homes. A module system is adopted for the construction of the building, and each module has an adequate open space.

The adoption of a conventional energy supply system is not economical and efficient because of the long distance over which materials and energy must be transported. A zone energy supply system in which energy is supplied to each module is adopted rather than a conventional system. Natural gas is supplied to each zone as the main energy source in order to minimize the transportation loss. Each zone is equipped with a power and heat supply plant in which the fuel cell plays the most important role. A second energy supply network is formed within the zone to meet the energy demand for illumination, communication, motive power, air conditioning, cooking and hot water supply. An interzone network is also composed to provide support by balancing and equalizing the energy demand.

Taking the dynamic intelligent building as an example, this building consists of 12 units and each unit is cylindrical, measuring 50 m in diameter, 200 m in height, and having an total floor area of 1.5 million square meters. As the peak electricity demand of the building is 50–100 MW, each unit is supposed to be equipped with a 5 MW fuel cell system.

Tap water supply, waste water treatment, and garbage collection and transportation will be big problems. The concept of CAN will solve these problems, however. Though the afore-mentioned CAN was for a two-dimensional planar community, the future city of skyscrapers will be a three-dimensional vertical one. Rainwater collection, waste

TABLE 7

Conception of the future city by skyscraper building

	Aeropolis 2001	Skycity 1000	Dynamic intelligent building
Height (m)	2001	1000	800
No. floors	500	196	200
Floor area (million m^2)	11	8	1.5
Daytime population	300000	100000	40000
Nighttime population	140000	35000	7000
Construction period (y)	25	14	7
Construction cost (yen)	47×10^9 ($3.4 billion)	4.7×10^9 ($340 million)	1×10^9 ($72 million)

(a)

(b)

(c)

Fig. 8. Exterior view of skyscraper cities: (a) Aeropolis 2001, (b) Skycity 1000, (c) dynamic intelligent building.

water recycling, and garbage collection and utilization will become easier by developing a three-dimensional CAN. Another advantage of the vertical structure is that it will facilitate power generation by utilizing the waste water head and recycling the water produced by the fuel cell.

Other applications

The role played by fuel cells in the future city is not limited to the role it plays as an important element of the utilities supply system. The development of energy supply technology and energy utilization has given us a new vision of energy utilization in the future city by making the best use of the various characteristics of fuel cells.

An example is the d.c. distribution system. A d.c. power source is currently used for computers, communication systems, stabilized illumination controlled by high frequency, and comfortable air conditioning controlled by a variable frequency motor drive. The conventional electricity distribution system mostly employs a.c. power, and this a.c. power is converted into d.c. power before being used in this equipment.

The development and spread of equipment for which d.c. can be used makes it possible to adopt the d.c. power supply system. Since the power primary generated by the fuel cell is d.c. power, the use of a fuel cell as a power plant is most advantageous to the economy of equipment and its efficiency.

D.c. power has already become the power source of computers and communication systems, i.e. a battery is used as an uninterrupted power supply (UPS) to the equipment in cases of emergency. The system combining the d.c. part of the UPS and the fuel cell output is considered one of the most advanced systems in the future city.

The adoption of a d.c. supply system makes it possible to create a hybrid system including solar cells which also generate d.c. power of renewable energy. The solar cell is an excellent system since it is the energy source with the least harmful environmental impact. However, as power generation by solar cell is limited to the daytime, and is weather dependent, it cannot be used as a fundamental energy supply system by itself. The low energy density of the solar cell makes it difficult to supply sufficient energy to crowded cities such as those in Japan. It can be used only as an auxiliary power source. However, combining solar cells and fuel cells together with a d.c. supply system of UPS can create an efficient and practical system.

The most advanced fuel cell in the future will be a power generation system which employs a hydrogen energy system. The present fuel cell system consumes natural gas or other fossil fuel and emits carbon dioxide. Hydrogen is an excellent fuel because it produces only water which does not adversely affect the natural environment. At present, however, no economical hydrogen production method which does not require a fossil fuel as source has been established. It is expected that a hydrogen energy supply and utilization system combined with solar cells will be produced in the 21st century. The solar cells will be installed in the desert or on the ocean surface, and the generated power will be consumed in the electrolysis of water to produce hydrogen. It will therefore be possible to store and transport the hydrogen thus produced to the place where it will be used in fuel cells to generate power and heat. Fuel cells employing hydrogen will be simplified in structure to give a higher power generation efficiency. Today's rapid technological progress will make it easy to realize this goal. The real problem that must be solved, however, is how to supply this hydrogen.

Conclusions

The fuel cell is one of the most promising energy systems for the city of the future, since it offers a high power generation efficiency and compatibility with environmental protection goals. The results of research and development and operational testing carried out over the last 30 years are now being harvested. However, this is not the goal of the development of the fuel cell. A longer service life and lower economic costs must yet be realized. A further improvement of the power generation efficiency is anticipated from an energy saving point of view. For advanced fuel cells such as the MCFC and the SOFC, fundamental research and development is still continuing concerning the cell itself and the cell stack.

The development and practical application of fuel cells in the world will contribute to the creation of future cities in which it will be possible to enjoy a comfortable and functional life as well as resolving the environmental problems.