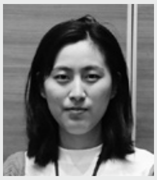
Performance Analysis of Residential Energy System in Low Carbon District: Case Study in Kyushu



Xiaoyi Zhang[1], Yanxue Li[2], Weijun Gao[1,2]*,
Yingjun Ruan[3], Yoshiaki Ushifusa[4], Hiroatsu Fukuda[1]
1 Faculty of Environmental Engineering, the University of Kitakyushu
2 iSMART, Qingdao University of Technology
3 Institute of Mechanical Engineering
4 Faculty of Economics and Business Administration, the University of Kitakyushu

低炭素社会の実現に向けて北九州市で進められている社会実験を例に、家庭レベルで可能なかぎり二酸化炭素の排出を減らし、実質ゼロに近づける取り組みの進捗状況を報告し、目標達成に必要な課題を検証した。

Abstract

Driven by the wide application of distributed energy system and liberalization of energy market in Japan, customers are expected to participate more in future sustainable energy system development. HEMS (Home Energy Management System) provides cost-saving potential for consumers through optimal automatic control strategies. This research mainly investigated the participation performances of residential consumers in meeting near zero carbon district project in Japan. Annual energy and economic performances of on-site generators under specific energy contract were exhibited according to their historical operational data. Results of survey analysis indicated that residential customers responded effectively to the electricity liberalization and chose the suitable pricing contract to meet maximum economic benefit. Smart schedule strategy of home appliances under HEMS environment provided promising energy cost reduction chance for the consumers. Meanwhile, the energy and economic performances of two residential zero energy house were examined. Demand response mechanism could help consumers to shift electricity usage and provide chance to participate in regulation within local energy system. A large percentage of consumers equipped with HEMS could be aware of the economic benefit under all electrification environment. However, large ratio of customers still payed less attention to the dynamic information of HEMS display. Survey results may provide valuable reference for the local policy maker.

Keywords Survey; HEMS; energy performance; participation performance

Introduction

After the 2011 Great East Japan Earthquake, the energy self-sufficiency ratio of Japan had sharply dropped, the amount of greenhouse gas emissions in Japan had been increasing, reaching a historical high fiscal in 2013 due to the accelerations of conventional thermal power plant. In order to improve energy efficiency and energy conservation, Japan government implement 1.4 billion Yen budget for energy subsidies for 2017-2018 fiscal year. Power consumption in residential sector experienced an increasing trend over decades, which has increased from 27.0% in 1990 to 33.5% in 2016, reached a large share ratio of national power supply [1]. Average annual energy consumption is about 33.4GJ per household in 2016, heating load and hot water account for a large portion of residential energy usage, 24.1% and 28.3% respectively. National greenhouse emission ambitious 26.0% reduction target by 2030 was launched by METI, 39.3% reduction was ratio set for residential sector from 2013 level, reduce to 122 million ton CO_2 per year. ZEH (Zero Energy House) is a house equipped with efficient energy technologies, annual net energy needs can be balanced by on-site generators, meanwhile maintaining comfort and convenience available to consumers. Ref [2] estimated the reduction potential of electricity demand and CO_2

emissions in the residential sector through energy saving efforts, around 25TWh maximum reduction estimated, which could greatly contribute to the greenhouse emission reduction target. To achieve energy saving in building sector, ZEH has been introduced as one key energy saving concept in national strategic plan, which utilizes a combination of distributed energy integration and energy efficient equipment. ZEHs are becoming a popular practice and attracted much attention in Japan considering advantages of reducing energy consumption and enhancing energy supply reliability during the disaster. The government offered fixed-amount subsidies for new ZEH builders. Japan Strategic Energy Plan specified the target for ZEH clearly, aiming at achieving zero emission in standard newly-constructed houses by 2020[3]. Meanwhile, wide development of integrated distributed energy resources and advanced energy technologies within the ZEHs enables the residential customer become not only a consumer but also a producer of heat and electricity, which could be called as active prosumer[4]. Real time communication network and appliance technologies used by these ZEHs are combined with HEMS (Home Energy Management System) to ensure an increase in energy efficiency, this combination constitutes what is known as smart houses feature with efficient energy utilization and active customer participation. Japanese government has introduced subsidies to encourage HEMS development, which has led to an increased installation of smart houses across Japan especially among ZEHs. There is also a target program to install HEMS devices in every household by 2030[5], providing efficient energy supply resolutions for customer including electricity, space heating, cooling and hot water supply[6, 7].

Wide uptake of smart meter and Internet of Things (IoT) enable the real time communication and trade-off between energy supplier and consumer[8], coordinate demand side management are expected to capture benefits of both, such as high efficiency, energy savings and smart services[9, 10]. Aggregated effects of coordinate demand side participations may provide significant value to supply side including reduce load frequency[10], cut peak load[11] and reduce negative effects from intermittent renewable generation[12]. Meanwhile, customers could gain potential cost saving with optimal load shift or energy saving under incentive dynamic pricing scheme[9, 13, 14]. Smart contracts of ZEHs have the potential to allow automatic control of energy transfer in decentralized form, and turned the passive consumers into collaborative prosumers in response to incentive signal. HEMS is seen as key solution that enables demand side response in microgrid and households, providing the chances for residential customers to acquire the real time load and coordinately participate in district energy system management.

This research will analyze the energy and economic performances of the residential consumer equipped with advanced energy supply system, detail scenarios of power consumptions and generations of selected residential ZEHs were presented. Meanwhile, a survey investigation is carried out to examine the role of HEMS and the attitude of customer are classified in the zero carbon district project. Finally, summarized the conclusions.

Objective

Jono Low Carbon District Project locates at Kitakyushu city, Japan the area covers around 19.0 ha [15]. This project is defined as an advanced ‘Zero Energy Residential District’ that deliberately aims to manage local energy resources and develop sustainable way to achieve a balance of social, environmental and economic objectives. Fig. 1 illustrated the annual scenario of district ambient temperature, it shows an obvious seasonal variations across the year, and indicated a longer heating period.

Various technologies and advanced energy technologies are employed in this demonstration project, such as uptake of residential rooftop PV, fuel cell, battery storage, Eco-cute and HEMS. All of the house in this demonstration project are equipped with HEMS, Fig. 2 depicted the detail architecture of HEMS comprises energy and information flows. HEMS could receive the variability and uncertainty information of customers provided by smart meters, planned to be installed in all household by 2024[16]. Real time energy consumption,

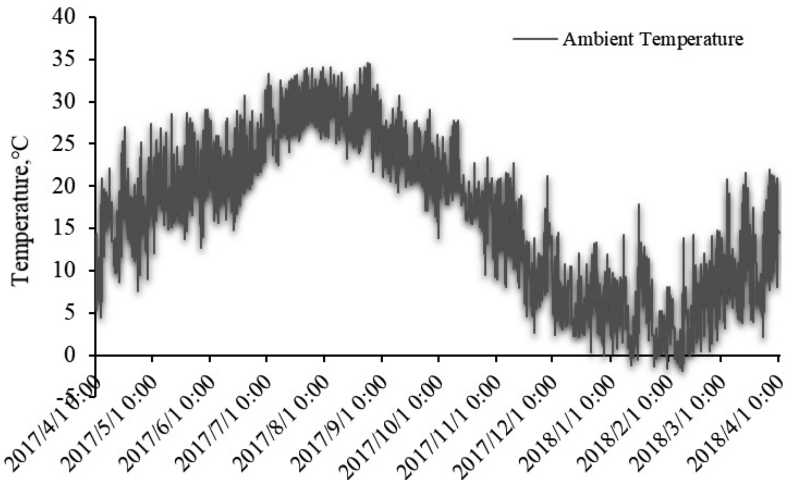


Fig. 1. Weather condition of this district

renewable generation and feedback signal from central supplier were visualized in home display, visualization function aims at inducing customers to reduce energy usage, cost and forming energy conservation life-style[13]. Japan METI (Ministry of Economy, Trade and Industry) has approved ECHONET Lite as standard communication protocol between devices and HEMS controllers, with open-source software could be connected with home existing internetwork. Customers could acquire the detail power consumption and operation information of building based on ECHONET-Lite compliant switchboard. A rule-based HEMS will help remote schedule and control the on/off status of home appliances, that include heat pump, fuel cell, AC (air conditioner) and washing machine. The power consumption and generation from grid feed-in PV obtained from smart meter will be transferred to central energy management system in real time.

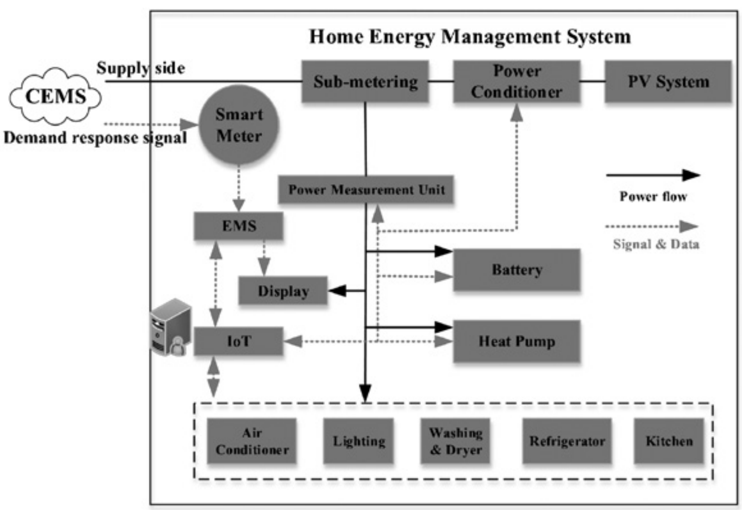


Fig. 2. Structure of the HEMS

Method

A public survey of energy users across the Jono Low Carbon District was conducted in March, 2018, in terms of building information, energy pricing choice, HEMS utilization, local on-site production and consumption. Questionnaire survey data was collected from 108 residential objectives, includes 59 detached houses and 59 apartments. According to the collected data, statistical analysis was applied to identify the participation performances of residential customers in this low carbon district, including their awareness of energy saving and preferences about energy liberalization market. Fig. 3 reveled the information about the surveyed objectives in Jono low carbon district.

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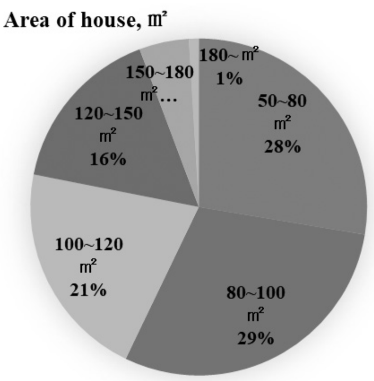

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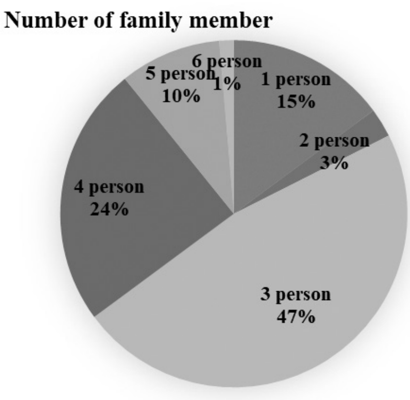


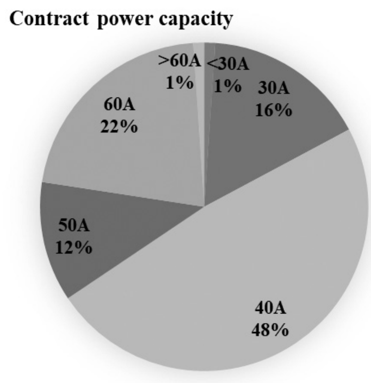
Fig. 3. Survey results of residential customers: size of residential building (a), number of family member

Result and Discussion

In order to reinforce industrial competitiveness, protect customer benefits and create new service, Japan government opened the retail electricity market to competition to allow business consumers more options to manage their energy consumption, consumers can choose their own preference about energy retailers that best meet their needs.

Contracted power capacity (A) and preferences of energy retailers among residential customers were illustrated in Fig. 4. There were various types of chosen electricity pricing schemes provided by the electricity utilities.

(a)



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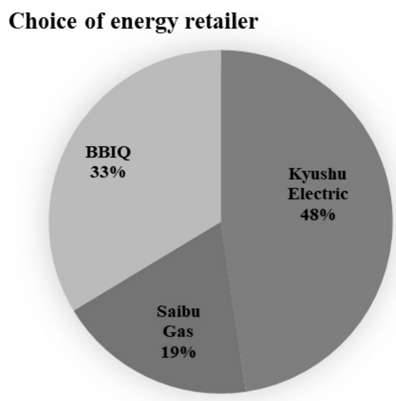


Fig. 4. Survey results of energy retailer choice: contracted power capacity, A (a), choice of energy retailer (b)

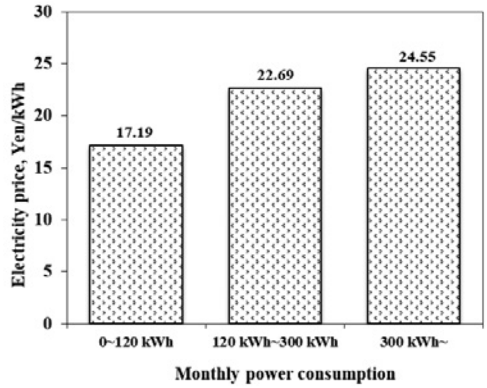
Heating load contributes to a large ratio of residential energy consumption, generally used for hot water and space heating. Therefore, the selection of heating supply system will significantly influence their preferences about choosing their electricity price scheme. Hot water system can be seen as a thermal storage system and utilized as flexible source. Heat pump water heater using CO_2 as a refrigerant had gained a popularity in Japan, which generally operated to produce hot water during off-peak price period, and stored energy in thermal storage system for daily later usage. HEMS features with characteristics of learnability and memorability, the volume of hot water production could be determined by average amount of history daily hot water consumption.

Currently, there are novel tariff schemes designed for residential sector in Japan that are suitable for the residential customers to choose for energy cost saving. Representative tariff schemes include monthly foundational charge (a) and TOU (b) were depicted in Fig. 5. Meanwhile, survey investigation found that there are 91 fuel cell, 14 eco-cute (heat pump), 3 gas boiler among the examined objectives, 47 residential houses feature with rooftop PV system that their nominal capacity generally ranges from 3kWp to 9kWp, which indicates a promising electricity bill saving potential by introducing local generations to reduce imported electricity from the public grid, especially for the customer contracted monthly foundational charge scheme with power company as shown in Fig. 5(a).

Combined heat pump and thermal storage (power to heat) provides chances for residential customers under TOU scheme Fig. 5(b) [17]. On-site generators, such as PV and fuel cell decrease the total imported electricity from supplier, reduce the power at higher pricing stage, and induce the customers to contract the monthly foundational charge scheme [18]. Management and economic benefits are critical for consumer switching, consumers tend to switch their provider if the transaction costs are lower, 13 residential customer equipped with eco-cute chosen the TOU pricing scheme according to the survey result.

There was an all electrification trend among residential sector, which indicate potential economic benefit under electricity liberalization scheme via choosing their own preferred pricing. Respondents' attitudes toward cost saving compared with previous price scheme before moving into Jono low carbon district was shown in Fig. 6, results present that large ratio of surveyed residential customers tend to response with a cost drop perception.

(a)



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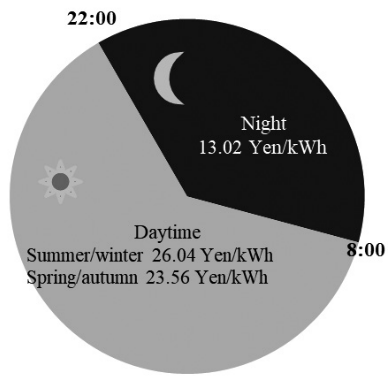


Fig. 5. Typical two electricity schemes: monthly foundational charge (a), daily time of use (b)

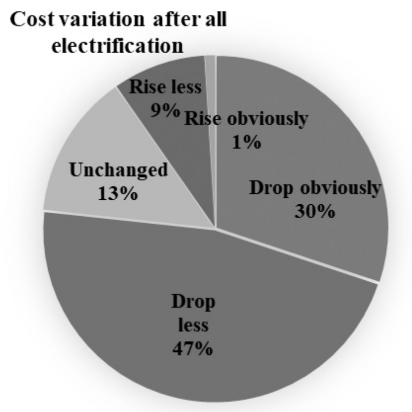
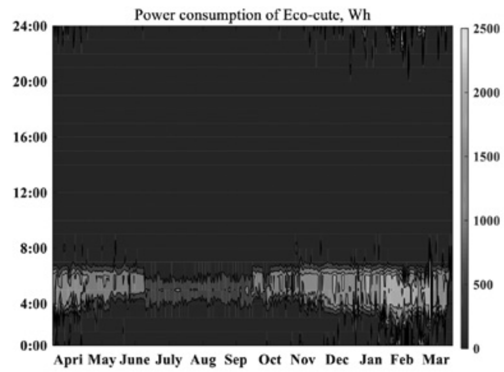


Fig. 6. Cost saving perception of residential customers toward all electrification transfer

Fig. 7 presented the variable power consumption of eco-cute system, which is collected from HEMS environment at 30 min interval from April,2017 to March,2018. The variability of Eco-cute power consumption of two ZEHs in color scale was presented in Fig. 7(a). It was obviously seen that the working period of Eco-cute concentrated during the early morning corresponding to the lower price period of TOU scheme. The amount of heat pump power consumption shown significant seasonal or daily variations, heat pumps produced a high level of heat over a longer period during winter time. Fig. 7(b) illustrated the relationship between power consumption of Eco-cute and ambient temperature at nominal output, power consumption rose in linear trend with decreasing of ambient temperature. Under HEMS control environment, working period of eco-cute (combined residential heat pump and thermal storage system) could be scheduled on valley pricing period of TOU, which indicated cost saving potential for the customer via automatic control under HEMS environment. Customer with efficient heat pump system might choose the TOU pricing scheme, generated and stored thermal energy during off-peak price period, obtained energy and cost saving benefits.

(a)



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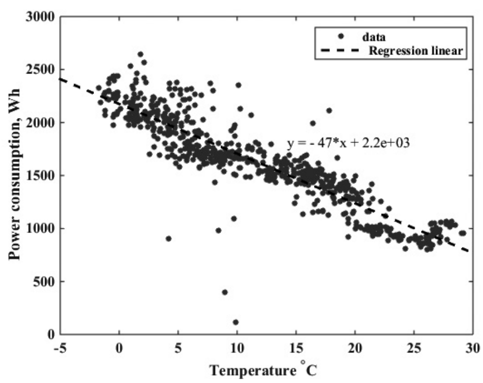

Fig. 7. Performance of residential heat pump system: color scale distribution of power consumption (a), the impact of temperature on power consumption (b)

Fig. 8 provided the performance of residential combined heating and power system, the fuel cell adjusts its output via tracking the time series heating demand, as a result the output of fuel cell presents a significant variation across the year. Fig. 8(b) presented the relationship between the power generating efficiency and load factor according to the monitored gas consumption and power generation (calculated LHV of nature gas is 45MJ/Nm3), it was worth noting that the electricity efficiency may drop sharply when its load factor was less than 0.40. Fuel cell cogeneration system of the examined ZEH operated in a daily start-and-stop mode, the output of fuel cell was determined by simultaneous heating and electricity load profiles. It could obviously see that output of fuel cell was as a function of time of day and seasonal periods, and presented considerable daily or seasonal variations across the year. Pattern of daily hot water consumption has a significant effect on electricity output of the fuel cell, leading the maximum production concentrated in early morning and night hours during winter period, decreasing hot water usage shorten the operation period of fuel cell in summer time. It indicated that the simultaneous heating and power demand had a great impact on the energy saving performance of the micro cogeneration system, longer period of considerable heating demand may enable higher overall energy efficiency of the fuel cell.

Rated power generation efficiency of fuel cell is 39%, and waste heat recovery efficiency is 47%. Assuming low heating value of nature gas is 45MJ/Nm3, fuel cell will supply variable output to meet time series residential loads, power efficiency of two monitored fuel cell under different part load ratios was calculated according to monitored gas consumption and power output, detail scenario was illustrated in Fig. 8(b).

(a)

(b)

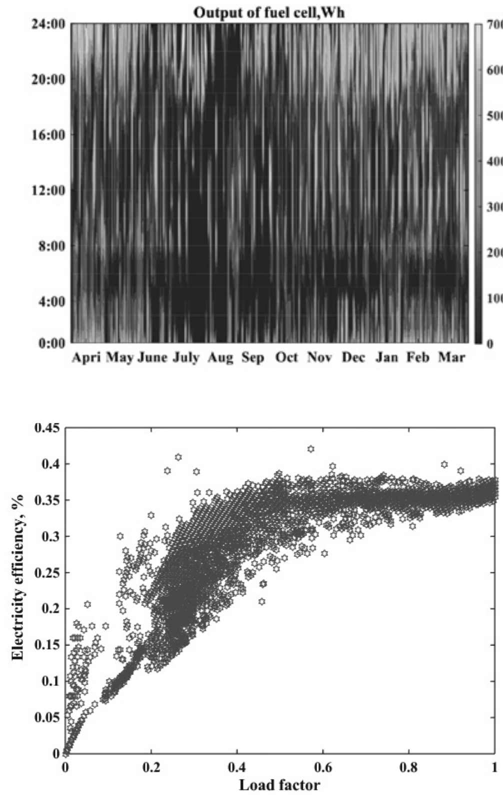

Fig. 8. **Performance of residential cogeneration system: color scale distribution of power generation (a), relationship between electricity efficiency and load factor (b)**

(a)

(b)

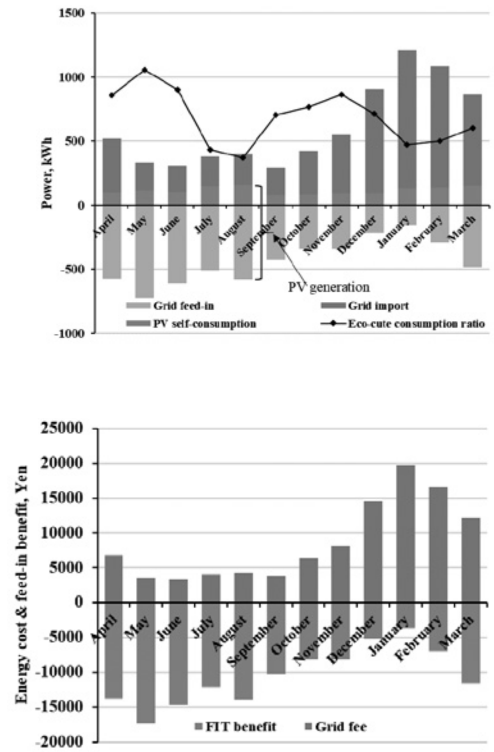

Fig. 9. **The residential consumer with PV and eco-cute system: power consumption and generation (a), energy cost and feed-in benefit (b) PV feed-in tariff is 24 Yen/kWh**

Fig. 9 presented the monthly power consumption and generation of the all electrified residential house with PV and eco-cute system. The annual maximum PV power generating reached 2.6kW, driving by the cooling load and great solar radiation, the amount of PV self-consumption is higher in summer compared other seasons. The annual net load power was feed-in power minus the imported power -657.2 kWh. However, a great ratio of PV generation had been fed into the grid due to low correlation between residential load and PV generation, especially during the mid-season period. Monthly power consumption of the all-electrified house will rise sharply during heating period, and electricity fee will be increased significantly.

Fig. 10(a) provided detail the scenarios of power generation and consumption in each month, limited to the heating load fuel cell contributes less to the residential load during summer period. PV and fuel cell contribution was generally over 50% of residential monthly load, electricity fee accounted for a less ratio of monthly total energy cost as shown in Fig. 10(b). Uptake of fuel cell or PV system could benefit the customers through reducing imported electricity with higher cost under foundational electricity charge scheme. It was worth note that annual net power was 4702 kWh, which indicated that a large ratio of PV generation had to be sold into the grid. Backup was triggered to produce hot water to meet the total heating demand, and monthly gas feet will rise sharply and gas cost becomes the main part of monthly energy cost.

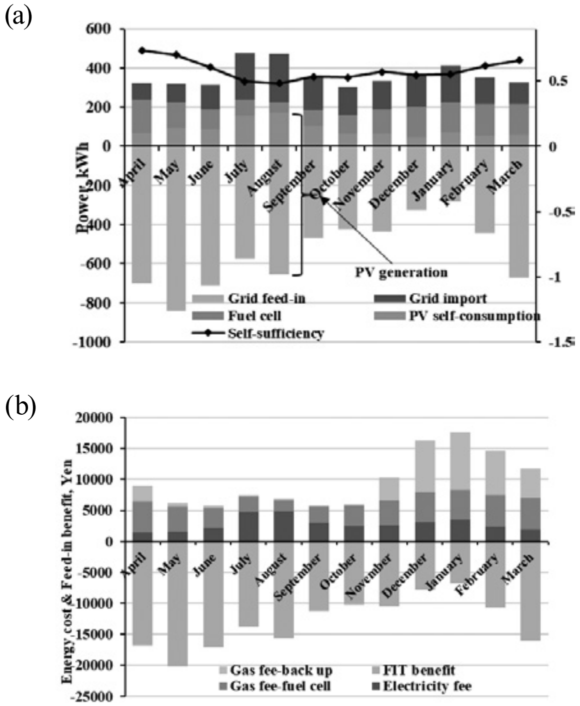

Fig. 10. The residential consumer with PV and fuel cell system: power consumption and generation (a), energy cost and feed-in benefit (b) PV feed-in tariff is 24 Yen/kWh

There was a wide uptake of energy efficiency appliance and grid connected distributed energy systems. Taking into account of the high energy intensity in the residential sector, active demand side management is expected to induce the energy user to participate more in low carbon energy system and make more energy-saving lifestyle. Therefore, policy makers must look beyond simply the technology and need to know what extent consumers can engage in demand side management, especially after the application of smart meter, home display and application of dynamic pricing scheme. Fig. 11 depicted the HEMS utilization frequency of HEMS dynamic information among surveyed customers, result indicate that around 70% of respondent seldom or never watch the HEMS home display. It shows a low utilization frequency of the HEMS display function, which can revel the real time power consumption, variable power output from on-site generators (PV, fuel cell) and dynamic price information.

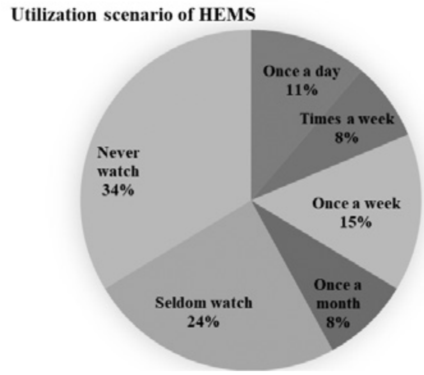

Fig. 11. Survey results of HEMS utilization frequency scenario

Conclusion

In this research, we used a survey investigation approach to analyse the participation performances of residential customers in the zero carbon district project in Japan. Meanwhile, we also examined energy and economic performance of the zero energy house based on monitored history data under HEMS rnvironment, including Eco-cute and fuel cell and other home devices. Results indicate that customers can response effectively to the electricity liberalization, customers will choose various energy price scheme that can better satisfy their needs. Customers equipped with heat pump system (power to heat) in all electrification environment tend to choose the time of use tariff to maximize their benefit. Energy saving performance of residential micro-cogeneration system still highly depends on the simultaneous heating and power load. Smart contract provided distributed operator responsibilities within local energy systems, however, the energy-saving or cost saving chances of HEMS still largely depends on the automatic control function, customers shown weak awareness of dynamic information of home display, which aims at inducing customer to form energy saving lifestyle. Results could also provide possible policy implication for policy maker during construction process of low carbon district, especially considering the participation of demand side.

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