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# Simulation of Solar Photovoltaic and Fuel Cell Energy System for Smart Community Simulator

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**Abstract** Today, increasing relevance of the energy demand for energy generation and the need of energy management systems with the integration of energy storage are the key motivations for developing a smart community simulator, which is used to model, design, analyze, and investigate the deployment of smart grid. In this paper, a solar photovoltaic and a fuel cell energy system for the smart community simulator are discussed. Their energy system performances under human activities have been revealed by carrying out the simulation verification using the real experiment data that is obtained from iHouse.

**Keywords** Smart Community Simulator, Energy Management System, Photovoltaic (PV), Fuel Cell (FC), iHouse

## 1. INTRODUCTION

Today, the energy demand continues to grow and more prominence is being placed on the energy providers and renewable/generated energy sources. As the technology advances, sensors are being installed all over the smart grid. This leads to the integration of smart grid and information and communication technology (ICT) to monitor and regulate power generation and the demand. The impact of the communication networks on the performance of power system dynamics can only be understood through numerical simulations. Thus, this paper provides an overview of available simulation techniques for smart gird communication.

First, a co-simulation frameworks called VPNET [1] has be used to analyze the impact of the communication networks using the multi-agent systems (MAS) based models. Second, Mosaik [2] that is an open, reusable and extendable smart grid co-simulation framework to simulate large-scale smart grid scenarios with various types of control strategies, for example centralized control or MAS based control. Open source Mosaik is written in Python and can be linked with JAVA-written simulator. Third, another open source simulator named OpenDSS [3] that stands for open distribution system simulator is an all-inclusive electric power system simulation tool primarily for electric utility power distribution systems with supported nearly all frequency domain analyses. Besides that, OpenDSS supports new analysis type, which is designed for future smart grid with modernization and renewable energy researches. Last, smart grid simulator [4] is a computer software based on advance algorithms that has the main purpose to lower the energy bill in the most optimized price for private household, companies or energy providers.

In this paper, the objective is to examine the models of solar photovoltaic and fuel cell work properly and to demonstrate the required battery capacity depending on the power sources of solar photovoltaic and fuel cell when the residents' activities are taken into account in the smart home environment. Two main contributions are achieved. First, this paper presents novel HEMS module of smart community simulator with simulated and verified electricity consumption based on the residents' activities and power sources. Upon realizing the HEMS module, this paper secondly investigates how to design the optimum battery capacity by minimizing the electricity consumption of power grid with the generation of power sources.

The rest of this paper is organized as follows. Section 2 introduces the background on generic module of smart community simulator its system model of HEMS. In Section 3, we describe the models of the solar photovoltaic and fuel cell energy system. Simulation scenario, setup, results and discussion are presented in Section 4. Some relevant conclusions and future works are drawn in Section 5.

## 2. BACKGROUND

### 2.1. Smart Community Simulator

A smart community simulator is a large-scale simulation software with a goal of building a quality of life (QoL) of smart community by using informatics and technologies in the aspects of energy, water, solid waste, transportation, health, and so on. In this paper, the smart community simulator is used for the energy demand and supply of community. The smart community simulator as shown in **Fig. 1** is designed as generic software modules, which include manager, high voltage receiving (HVR), distributed power source/battery storage (DPS/BS), community energy management system (CEMS), and other energy management systems, like HEMS, BEMS, FEMS, SEMS, and *x*-EMS that represent home, building, facility, school, *x*-component facilities, respectively. The functions of the manager module is to load a set of community profiles and parameters for other modules, to synchronize with other modules using *simulation control* messages, to trigger the start and end of the simulation and to collect all the stored results at the end of simulation. The function of the CEMS module is to manage the entire energy over a geographical area or a city to control the total energy consumption of the simulated community by issuing a demand response (DR) command according to the Open Automated Demand Response (OpenADR) standard. The function of the DPS/BS module is to incorporate with various power sources, such as solar photovoltaic, fuel cell, battery storage into the simulated community by monitoring and controlling the other EMS modules. In HEMS module, electric and heat consumptions are simulated in conjunction with the residents' activities and the physical conditions of a house environment.

The core module of smart community simulator is built using C++. For simple modification, Python is used for some part of the simulation submodules. The simulation environment is running on Linux on networked computer nodes. For example, one computer node is used for manager, DPS/BS, and CEMS modules. Five different computer nodes are all the EMS modules with a large quantity (e.g., 1000 units of household for HEMS module). At the initial phase, community profiles that is written in XML format is configured and defined. At the end of simulation, the generated data is stored in CSV format.

## 2.2. System Model of HEMS

We assume that a HEMS as depicted in **Fig. 2** including modules like solar photovoltaic, fuel cell, battery storage, load, and power grid. The battery storage is designed to allow bidirectional power flow. The power balance equation is given by

$$P_{grid} = P_{load} - P_{PV} - P_{FC} - P_{batt} \qquad (1)$$

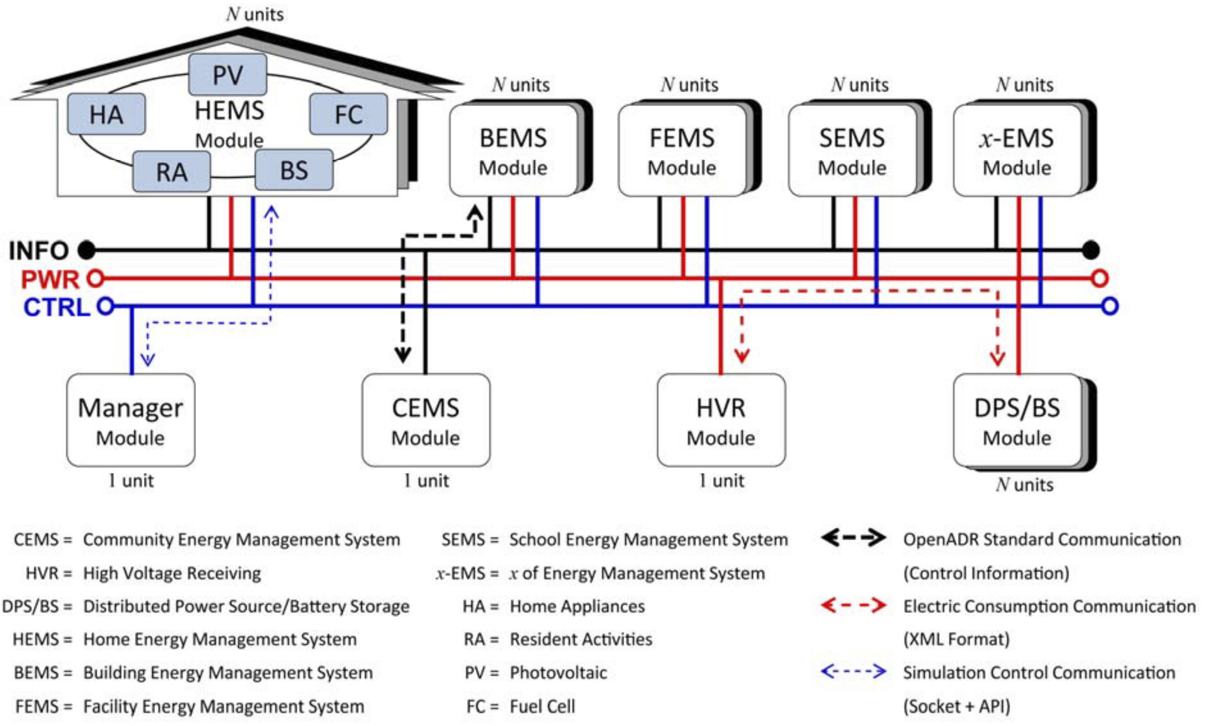


Fig. 1: Generic module of smart community simulator.

The objective of HEMS module is designed to minimize the consumption of power grid regardless of the residents' activities inside the house by using the generation of power sources from both solar photovoltaic and fuel cell.

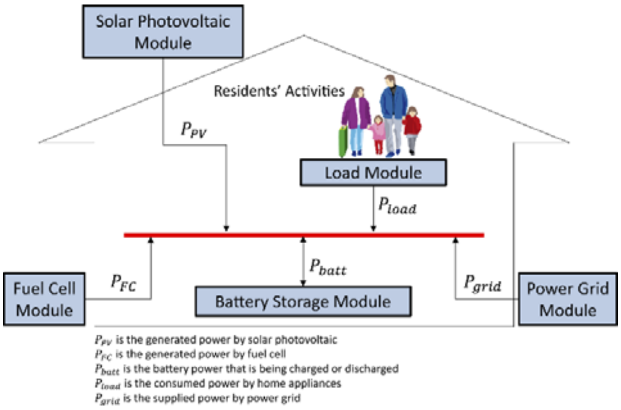


Fig. 2: System model of HEMS.

### 2.3. iHouse

iHouse stands for ishikawa, internetted, inspiring, intelligent house as shown in **Fig. 3**. iHouse that is based on Standard House Design by Architectural Institute of Japan is an advanced experimental environment for future smart homes. iHouse is located at Nomi city, Ishikawa prefecture that consists of sensors, home appliances, and electronic devices are connected using ECHONET Lite version 1.1 and ECHONET version 3.6. This configuration network results more than 300 objects.

Fig. 3: iHouse – example of smart homes.

## 3. MODEL OF POWER SOURCE MODULE

### 3.1. Solar Photovoltaic (PV)

Solar photovoltaic (PV) converts the sunlight in terms of solar radiation into the electricity. The solar photovoltaic panel receives three different kinds of radiation namely direct, reflected, and diffuse (see **Fig. 4**). Direct radiation is an unobstructed sunlight to the panel directly. Reflected radiation is a reflected sunlight by the ground. And diffuse radiation is a scattered sunlight by the cloud in the atmosphere. Sandia National Laboratories [5] proposes that the power generated from PV in the unit of Watt is given by

$$P_{PV} = \varepsilon R A_{PV} \mu_{soil} \left( 1 - \varepsilon_{thermal} \left( \frac{T_{panel} - 25}{100} \right) \right) \tag{2}$$

where $\varepsilon$ is the efficiency of PV panel (no unit), $R$ is the solar irradiance (unit is $\mathrm{Wm}^{-2}$), $A_{PV}$ is the area of PV panel (unit is $\mathrm{m}^2$), $\mu_{soil}$ is the soiling coefficient (no unit), $\varepsilon_{thermal}$ is the thermal efficiency of PV panel ($°\mathrm{C}^{-1}$) and $T_{panel}$ is the temperature of PV panel. The temperature of PV panel that is affected by surrounding objects and the reflected radiation can lead to high fluctuation on the generated power from PV. Therefore, fourth order Butterworth low pass filter with a cutoff frequency of 50 Hz is used to filter the frequency of the generated power, which is greater than 50 Hz.

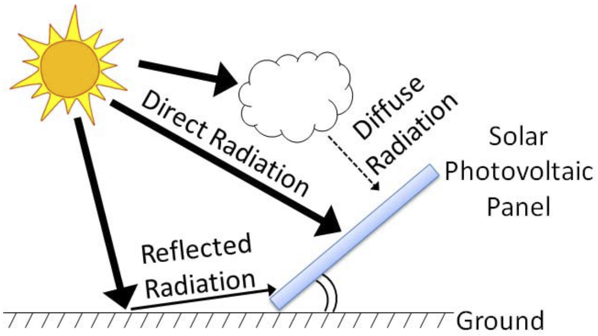


Fig. 4: Solar radiation towards solar photovoltaic panel.

### 3.2. Fuel Cell (FC)

Fuel cell (FC) converts the chemical energy into the electricity and heat. Proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are two common types of fuel cell. PEMFC is the most suitable choice for the generated power up to 100 kW nowadays. In PEMFC, the basic structure is two electrodes (anode and cathode) that are separated by a solid membrane. A hydrogen gas is fed continuously to the anode and air is fed to the cathode. A chemical reaction will happen and the electricity and heat are produced. The energy generated from FC is given by

$$E_{FC} = M_{gas} LHV \tag{3}$$

where $M_{gas}$ is the mass of hydrogen gas (unit is kg) and LHV is the low heat value of hydrogen gas (i.e., -33 kWh/kg). The heat loss to the surrounding of FC is given by

$$P_{loss} = UA_{FC}T_{diff} \tag{4}$$

where $U$ is the heat transfer coefficient of hot water tank (unit is $\mathrm{Wm^{-2}{}^{\circ}C^{-1}}$), $A_{FC}$ is surface area of the hot water tank (unit is $\mathrm{m^2}$), and $T_{diff}$ is the temperature different (unit is °C). The change of hot water temperature due to the heat loss is given by

$$\Delta T_{FC} = \frac{60P_{loss}}{M_{water}c} \tag{5}$$

where $M_{water}$ is the mass of water (unit is kg) and $c$ is the specific heat capacity of water (unit is $\mathrm{Wkg^{-1}{}^{\circ}C^{-1}}$).

The basic model of fuel cell as illustrated in **Fig. 5** consists of five components: i.e., fuel cell, heat recovery machine, power inverter (DC power to AC power), hot water heating machine, and hot water tank. The operation process of the fuel cell is based on JIS C 8851 standard [6] (see **Fig. 6**), which describes the energy efficiency on stationary fuel cell power systems for residents' activities calculating based on an 11-mode operation pattern in which the power consumption of typical Japanese house including starting and stopping is simulated. The test method for measuring the annual energy consumption when the stationary fuel cell systems are installed in a typical Japanese residence is also included. The JIS C 8851 standard is used in our FC module to specify and calculate the energy and heat consuming hours/day and the energy generating hours/day that based on residents' activities.

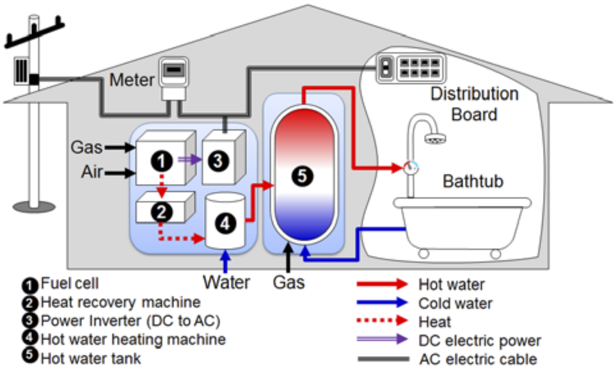


Fig. 5: Basic model of fuel cell (e.g., PEMFC).

## 3.3. Battery Storage (BS)

The function of battery storage (BS) is a way to store electrical energy with high efficiency. The model of battery storage that is used in BS module is based on generic rechargeable non-linear battery model as shown in **Fig. 7**. The rechargeable non-linear battery is a type of electrical battery that can be charged and discharged in unlimited times into a load. In particular, an equivalent circuit diagram of one time constant (OTC) model [7] is used to determine the state of charge and discharge of a battery. The battery capacity when the battery is charging is given by

$$C_c = C_{in} + C_{loss} \tag{6}$$

where $C_{in}$ is the actual input of battery capacity (unit is mAh) and $C_{loss}$ is the loss of battery capacity when the battery is charging or discharging (unit is mAh). Similarly, the battery capacity when the battery is discharging is given by

$$C_d = C_{out} + C_{loss} \tag{7}$$

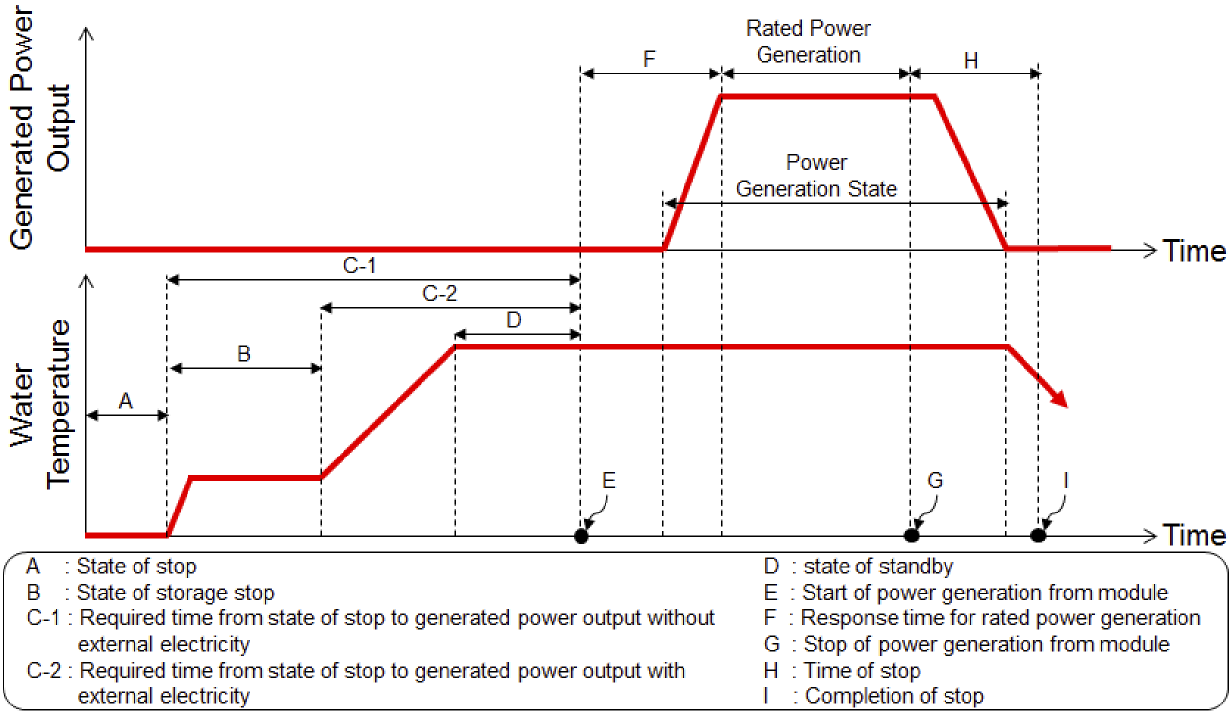
Since $C_{in} = I_{in} \times T_c$ and $C_{out} = I_{out} \times T_d$, in which $T_c$ and $T_d$ represent the elapsed time for charging and discharging, respectively. The actual input current of a battery is given by

$$I_{in} = \begin{cases} I_o & \text{if } C_{in} \le C_{opt} \\ \alpha(1-\rho_c)\dfrac{V_o}{R_{\text{int}}} & \text{if } C_{in} > C_{opt} \end{cases} \tag{8}$$

where $I_o$ is the operating current of a battery (unit is mA), $\alpha$ is the constant arbitrary that represents to the materials and chemicals of battery type (no unit), $\rho_c$ is the charging ratio (no unit), $V_o$ is the operating voltage of a battery (unit is V), and $R_{int}$ is the internal impedance of a battery (unit is Ohm). Also the actual output current of a battery is given by

$$I_{in} = \begin{cases} I_o & \text{if } C_{out} > C_{opt} \\ \alpha(1-\rho_d)\dfrac{V_o}{R_{\text{int}}} & \text{if } C_{out} \le C_{opt} \end{cases} \tag{9}$$

where $\rho_d$ is the discharging ratio (no unit). The battery capacity is designed to supply the ultimate load at the peak hours during the cloudy or rainy weather.



A : State of stop
B : State of storage stop
C-1 : Required time from state of stop to generated power output without external electricity
C-2 : Required time from state of stop to generated power output with external electricity
D : state of standby
E : Start of power generation from module
F : Response time for rated power generation
G : Stop of power generation from module
H : Time of stop
I : Completion of stop

**Source**: Japan Industrial Standard (JIS) C 8851, "Measurement methods for 11 mode energy efficiency of small fuel cell power systems and for annual energy consumption of standard residence," Japanese Standards Association, 2013

Fig. 6: JIS C 8851 standard on operation process diagram of fuel cell power generation unit.

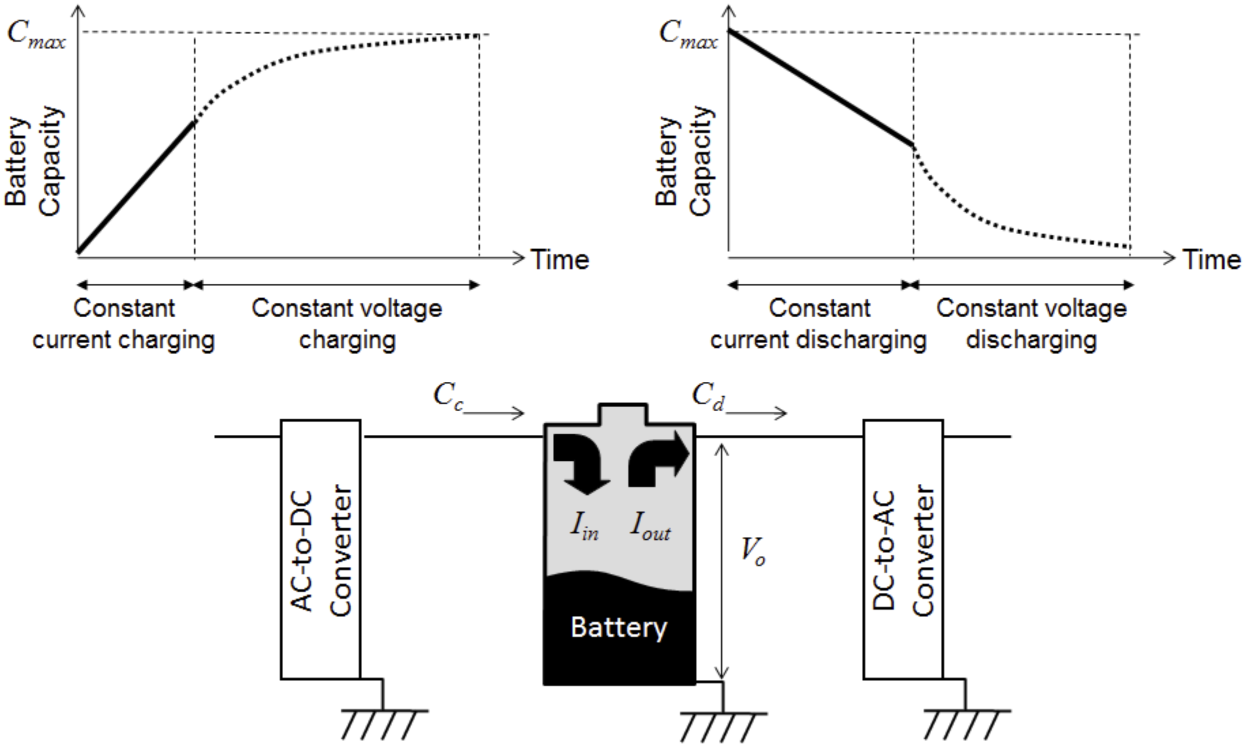


Fig. 7: Generic rechargeable battery storage model.

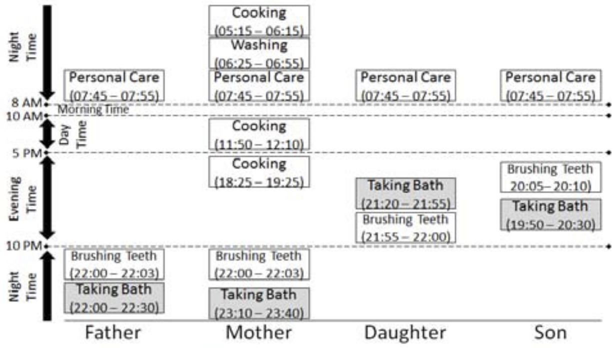
## 4. NUMERICAL SIMULATION

In this section, we investigate the performance of the simulated power of PV module and RA module. Then, we examine and discuss how to design the optimum battery capacity by minimizing the electricity consumption of power grid based on the generation of power sources. Since we can obtain directly the actual solar radiation of iHouse, the simulation of the generated power from PV module is compared and analyzed by using R-squared, which is a statistical result of how close the simulated data are to the actual data. Considering an actual data set has $n$ values indicated as $\{x_1,\ldots,x_n\}$, each of data is associated with the simulated $n$ values marked as $\{s_1,\ldots,s_n\}$. Thus, R-squared is given by

$$R^2 = 1 - \frac{\sum_i (x_i - s_i)^2}{\sum_i (x_i - \bar{x})^2} \tag{10}$$

where the mean of the actual data is as below:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{11}$$



Source: NHK Broadcasting Culture Research Institute, "Time habits of Japanese in 2005: A NHK survey regarding the use of time in the daily life of Japanese citizens," Japan Broadcasting Publishers Association, 2006

Fig. 8: Residents' daily activities.

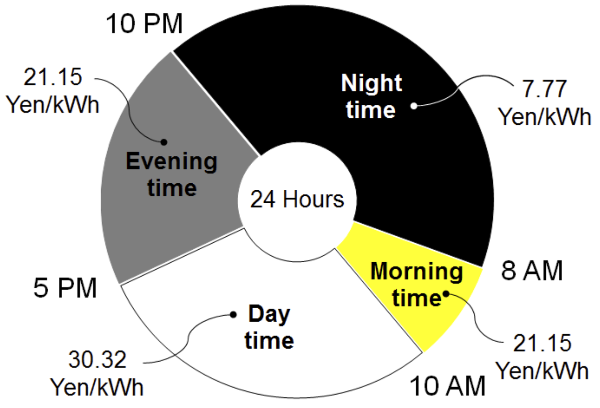


Fig. 9: Daily electric billing system.

In the simulation, the RA module considers four persons (i.e., father, mother, daughter, and son) with five activities based on NHK survey with a daily schedule of 24 hours (see **Fig. 8**). In conjunction with those activities, the daily electric billing system (see **Fig. 9**) is used to compute the total electricity cost per day. The rest of parameters that is used in the simulation is listed in **Table 1**.

Table 1: Simulation parameters and settings.

| **Parameter** | **Value [unit]** |
|---|---|
| Average room temperature of a house | 25 °C |
| Simulation time | 24 hours |
| Date of simulation | 14 May 2016 |
| ***PV Module*** | |
| Model | HIT-N225A01 |
| PV panel size | 1.58 m × 0.79 m |
| Panel type | Monocrystalline |
| Efficiency of PV panel | 0.202 |
| Maximum voltage | 43.4 Volts |
| Open circuit voltage | 53.0 Volts |
| ***FC Module*** | |
| Electrical efficiency | 0.39 |
| Exhaust heat recovery efficiency | 0.56 |
| Rated power | 7 kW |
| Average fuel pressure | 2.5 kPa |
| Average atmospheric pressure | 101.3 kPa |
| Average fuel temperature | 25 °C |
| LHV | 33.32 kWh/m$^3$ |
| Size of hot water tank | 200 liters |
| Water density | 1000 kg/m$^3$ |
| Heat transfer coefficient | 0.1 kW/m$^2$K |
| Surface area of hot water tank | 4.8488 m$^2$ |
| Storage mode temperature | 35 °C |
| Desired temperature of hot water tank | 20 °C |
| A | 2 min |
| B | 21 min |
| C-2 | 42 min |
| D | 21 min |
| E | 63 min |
| F | 20 min |
| H | 17 min |
| Entire operation process time | > 110 min |
| ***RA Module*** | |
| Taking bath | 10 J/min |
| Personal care/Brushing Teeth | 8 J/min |
| Washing | 12 J/min |
| Cooking | 12 J/min |

## 4.1. Results and Discussion

### *A) PV Module*

Using the R-squared, we can observe that the simulated power is very close to the actual generated power as shown in **Fig. 10**. The achieved R-squared value is 96.69% when the actual generated power on 14th May 2016 is compared. Throughout the year 2016, the R-squared value has more than 80% above is about 57.31% (see **Fig. 11**). These results reveal that the performance of the PV module model is moderately well-fitted.

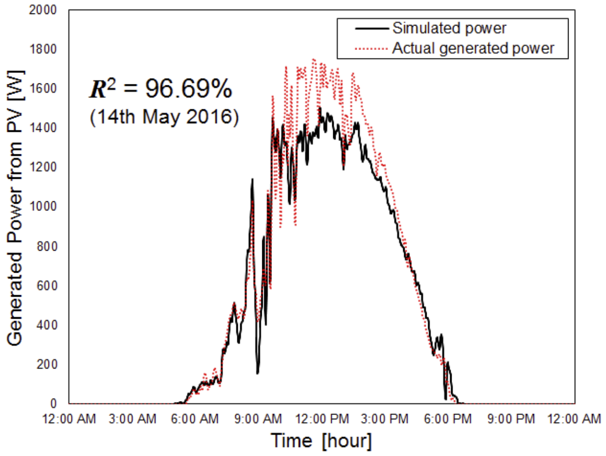


Fig. 10: Comparison of simulated power and actual power generated from PV.

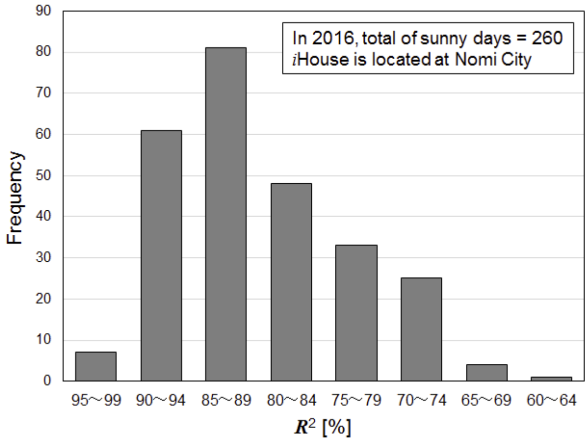


Fig. 11: Fitness test throughout the year 2016.

### *B) RA Module*

The energy and heat consumptions of RA module are well-simulated as demonstrated in **Fig. 12** and **Fig. 13**, respectively. We also can see that the cooking activity is the most energy and heat consuming in whole day.

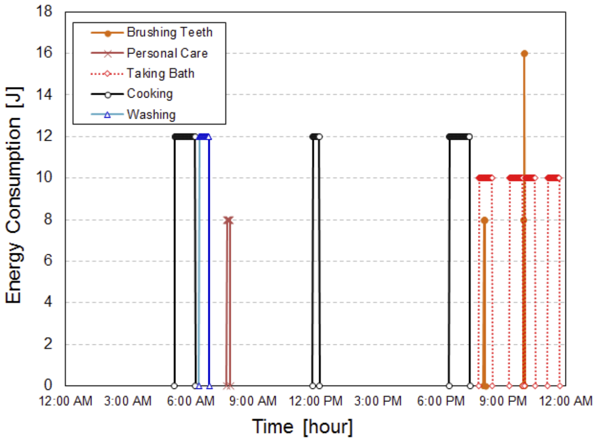


Fig. 12: Energy consumption of the simulated human activities.

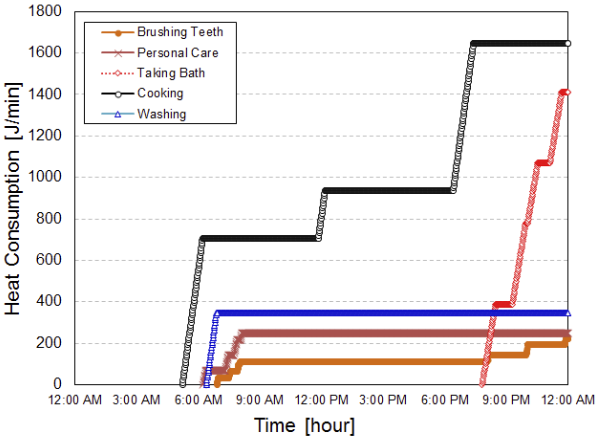


Fig. 13: Heat consumption of the simulated human activities.

### *C) Required Maximum Battery Capacity*

As shown in **Fig. 14**, the simulated power consumption by human activities is obtained and compared with the generated power from both PV and FC. At mid night, the power consumption by human activities is mainly consumed by initializing the operation of FC module. The power consumption value is about 3771 W. The charging amount of battery capacity is depending on the generated power sources. With both PV and FC, the total charging battery capacity is about 1082.14 mAh as observed in **Fig. 15(c)**. This lead to the required maximum battery capacity when both PV and FC as power generator. **Table 2** summarizes the total electricity cost and the required maximum battery capacity for different power generator. Through a large amount of HEMS module, we can able to obtain the optimum required battery capacity of a house. This work will be further investigated in near future.

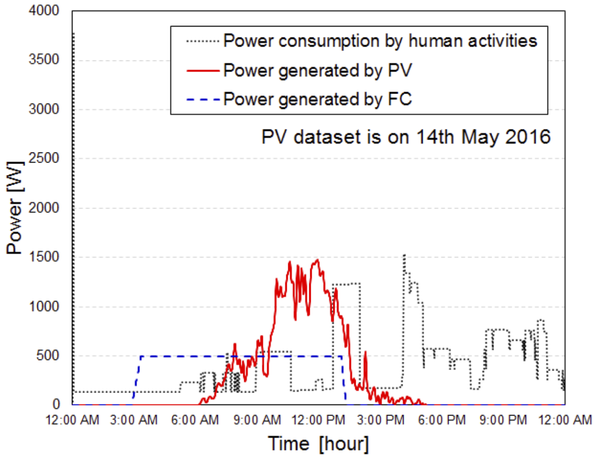


Fig. 14: Simulated power of human activities, PV and FC.

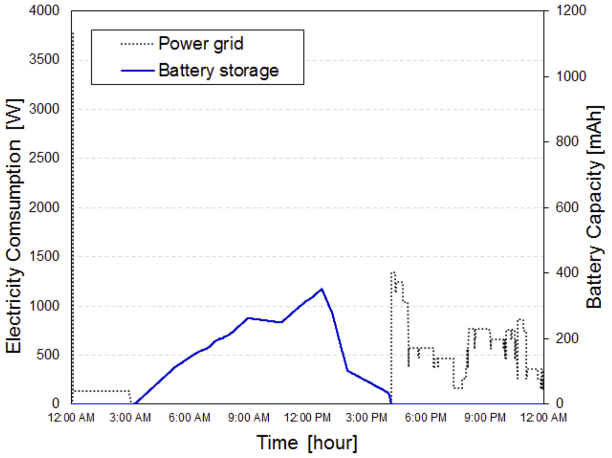


Fig. 15(a): Only FC as power generator.

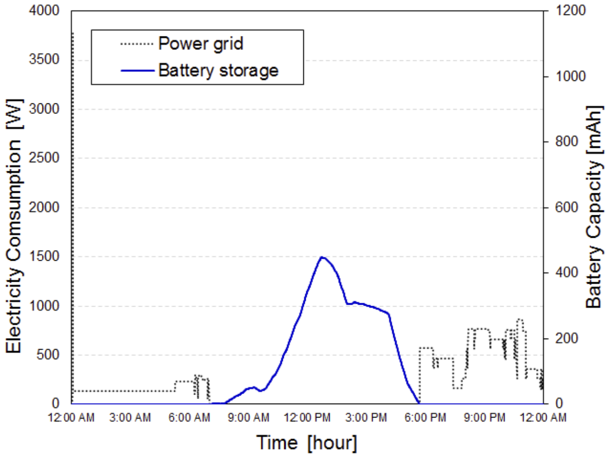


Fig. 15(b): Only PV as power generator.

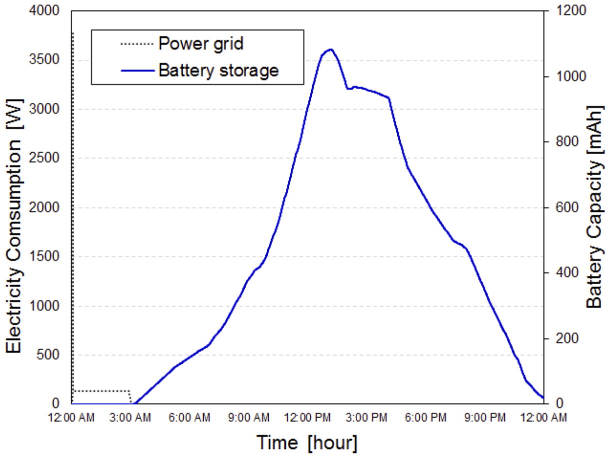


Fig. 15(c): Both PV and FC as power generator.

Table 2: Summary of total electricity cost and required maximum battery capacity.

| **Source of Power Generation** | **Total Electricity Cost [Yen]** | **Required Maximum Battery Capacity [mAh]** |
|---|---|---|
| Only FC | 99.19 | 351.72 |
| Only PV | 67.58 | 450.07 |
| Both PV and FC | **3.52** | 1082.14 |

## 5. CONCLUDING REMARKS

In this paper, the models of solar photovoltaic and fuel cell are examined and the required maximum battery capacity is also analyzed with power sources of solar photovoltaic and fuel cell when the residents' activities are taken into account in the HEMS module of smart community simulator. Further research works is required to verify the accuracy of the simulated results of all the modules of HEMS module. Besides that, a future work also will focus on examining the effect of generated power from both PV and FC modules when a city community with 10,000 household is considered.

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