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Assessment on Energy Self-Sufficiency Rate for Building Integrated Photovoltaics and Fuel Cell System in Japan

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Abstract

A building integrated photovoltaic (PV) and fuel cell (FC) system is proposed for assessment of the energy self-sufficiency rate in a city in Japan. The electricity consumed in the building is mainly supplied by solar panels, while the gap between the energy demand and supply is solved by the FC that is powered by the H_2 produced by water electrolysis with surplus power of PV. A desktop case study of using the proposed system in Tsu city which is located in central part of Japan, has been conducted. The results found that the self-sufficiency rates of PV system to electricity demand of households (R_{PV}) during the daytime in April and July are higher than those in January and October. The results also reveal that the self-sufficiency rate of FC system to the electricity demand (R_{FC}) is 15% - 38% for the day when the mean amount of horizontal solar radiation is obtained in January, April, July and October. In addition, it is found the optimum tilt angle of solar panel installed on the roof of the buildings should be 0 degree, *i.e.*, placed horizontally.

Keywords

Smart Building, Photovoltaics, H_2 Produced by Water Electrolysis, Fuel Cell, Self-Sufficiency Rate

1. Introduction

Fossil fuel reserves are limited and intensive burning of hydro-carbon based fuel sources are impacting on global climate. There is continuous encouragement to increase the penetration of environmental friendly energy sources for fulfilling growing energy demand and also to minimize the use of hydro-carbon based power plants. Renewable energy sources such as wind, solar photovoltaic (PV), solar thermal, geothermal, bio-energy are drawing attention as alternative environment friendly energy sources. However, the energy density of these renewable energy sources is low. Most of them are dependent on nature and have intermittent characteristics. Therefore, it is very important to develop proper strategies and technologies to integrate these renewable energy sources into the power system network in order to fulfill the energy demand.

Integrating renewable energy sources into the existing energy system network is an effective approach in the development of the so-called smart cities. Introducing renewable energy systems into the built environment (*i.e.* building) is a typical such approach. However, in the built environment, it is challenging to integrate intelligently renewable energy sources and distributed generators as the existing building infrastructures are not designed to accept them into the power system infrastructure. The development of a smart city or a smart building requires harmonizing the renewable energy system with existing heat and power system infrastructure, and with new monitoring and control system [1].

Integrating renewable energy on the building has been investigated recently well. Many researches on building integrated that wind turbine has been conducted recently [2]-[7]. Some researches on building integrated solar thermal system have been also reported [8] [9] [10]. In addition, the research on building integrated ground heat pump has been investigated [11]. Furthermore, the hybrid building systems such as PV and wind turbine [12]-[17], PV and solar thermal systems [18]-[25], and PV and geothermal heat pump [26] have been studied well.

Integrating/installing solar panels on the roof and/or side wall of the buildings is a typical way to make the building energy self-sufficient. Such kind of building integrated that PV systems (BIPV) have been studied by many researchers [27]-[37]. According to some review papers [27] [28], BIPV installation is increasing every year and PV systems are integrated into different parts of the building such as roof, external building wall, façade, and windows, although the majority of installations is on roof-top [29]. Most of the researches on BIPV focused on economic and environmental assessment evaluating by investment recovery with consideration of power generation performance [30] [31], life cycle cost (LCC) [22] [32] and energy payback time (EPBT) [27] [33]. In addition, some studies investigated the effect of thermal management of PV module on the power generation performance of BIPV [21] [34]. Although the power generation performance of BIPV was investigated under several conditions of PV module orientation in some case studies [27] [35] [36], the optimum tilt angle of PV module installation on the roof of the building, which is believed to be very important to obtain the high power generation performance of BIPV, was not clarified well.

Due to solar energy's intermittent nature, the BIPV system normally requires a sort of energy storage system or grid-connected mechanism. The typical energy storage system in associated with normal PV systems such as battery bank and hydrogen produced by water electrolysis produced by the power of PV system are well known and these combination systems have been studied numerically as well as experimentally [37]-[47]. However, the research on BIPV and energy storage system is lack, although the ice storage system combined with BIPV was proposed [48]. In addition, there are some studies on the energy demand coverage performance of grid-connected BIPV without energy storage system [30] [31].

In this paper, a desktop case study has been conducted on a proposed BIPV system. The proposed BIPV system consists of solar panels and fuel cell (FC). The H_2 required by the FC are provided from the water electrolyzer with surplus power of PV. The FC would therefore be able to solve (partly) the gap between the electricity demand (by the building) and supply capacity of the PV panel due to the intermittent power generation of the PV system. As the PV panels were assumed to be installed on the roof of the building, the solar panel setting procedure is also investigated in this paper in order to clarify the maximum power could be generated from the BIPV. Compared the electricity demand data of household in Japan [49], the optimum power supply way to cover the electricity demand has been investigated. In addition, the self-sufficiency rate of power supply of the proposed BIPV system to electricity demand has been estimated in the case study.

2. Case Study

2.1. Estimation of Power Generation from the PV System

The building model used in the case study is 10 m width, 40 m length and 40 m height (=10 stories) [50]. It was assumed that 40 households lived in the building described in the reference [51]. The BIPV system assumed to be installed on the top of the building consists of solar panels and a FC using H_2 produced by water electrolysis with surplus power of PV.

The power generated by PV system is calculated by using the following equation [52]:

$$E_{PV} = H \times K \times P/1 \tag{1}$$

where E_{PV} is hourly electric power of PV system (kWh), H is amount of solar radiation (kWh/m^2), K is power generation loss factor (−), P is system capacity of PV (kW), 1 is solar radiation under standard state (AM1.5, solar radiation: 1 kWh/m^2, module temperature: 25 degree Celsius) (kW/m^2).

In this study, the high performance PV P250a Plus produced by Panasonic whose module conversion efficiency and maximum power per module are 19.5% and 250 W [53], respectively is adopted for PV system. The size of PV module is 1580 mm × 812 mm × 35 mm. P is calculated by installing this PV module on a roof of the building model, which is 75 kW$_p$ (=300 solar panels).K is calculated by using the following equation:

$$K = K_p \times K_m \times K_i \tag{2}$$

where K_p is power conversion efficiency of power conditioner (−), K_m is correction factor decided by module temperature (−), K_i is power generation loss by interconnecting and dirty of module surface (−). In this study, K_p and K_i are set at 0.945 and 0.95, respectively. K_p is assumed by referring to the performance of commercial power conditioning device VBPC259B3 manufactured by Panasonic [54]. K_m is calculated by the following equation:

$$K_m = 1 - \frac{(T_m - T_s)C}{100} \tag{3}$$

where T_m is PV module temperature (degree Celsius), T_s is temperature under standard test condition (=25 degree Celsius), C is temperature correction factor which is 0.35 [55] (%/degree Celsius). T_m is calculated by using the following equation [56]:

$$T_m = T_a + \left(\frac{46}{0.41U_m^{0.8} + 2}\right)H - 2 \tag{4}$$

where T_a is ambient air temperature (degree Celsius), U_m is wind velocity over module of PV (m/s).

The meteorological data, such as solar radiation, the ambient air temperature, and wind velocity of some cities in Japan are from the data base METPV-11 during the period from 1999 to 2009 [57] and the irradiation data of the project "PV300" during the period from August, 2012 to July, 2014 [58]. An example of meteorological data of METPV-11 for Tsu in Japan is shown in **Figure 1**. In this figure, a red circle, a green triangle and a flag symbol indicate the amount of horizontal solar radiation, the air temperature and a wind speed including direction, respectively. The solar radiation data for several tilt angles can be obtained from METPV-11 by changing configuration. **Table 1** also lists an example data of PV300, which shows the data of air temperature and amount of horizontal solar radiation at 10 sec intervals on 1st August, 2013 for Tsu in Japan.

It is important to consider the impact of shadow on power generation performance when PV system is installed. The longest shadow length which is obtained at AM 9:00 on the winter solstice is calculated by the following equation [52]:

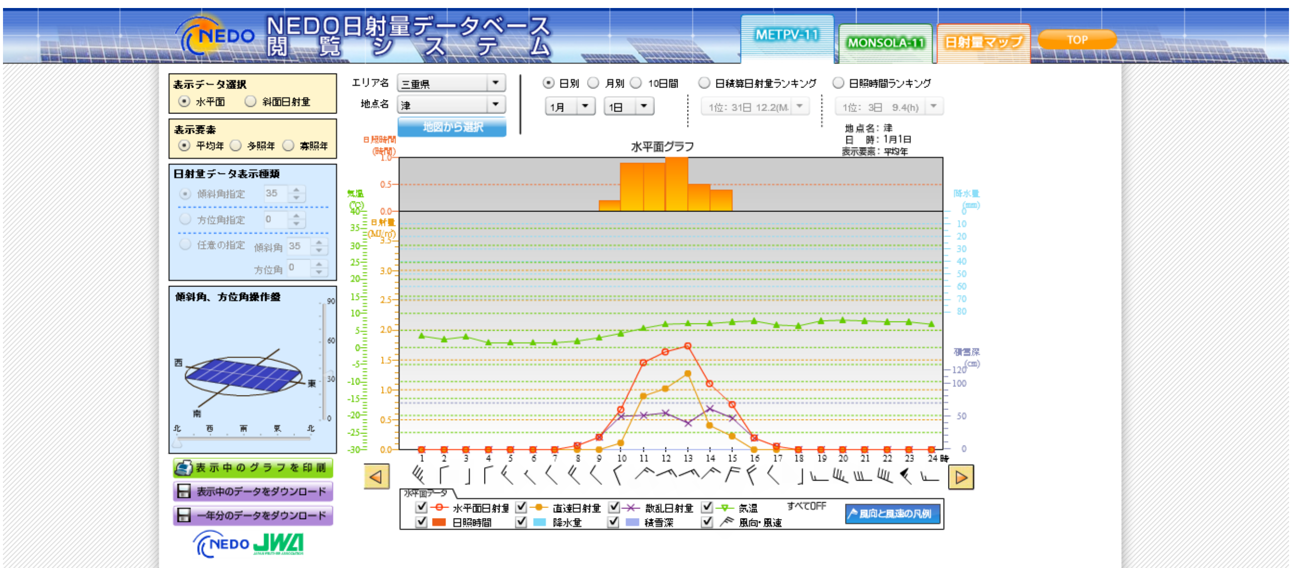

Figure 1. Example of meteorological data of METPV-11 (Tsu, Japan).

Table 1. Example data of PV300 on 1st August, 2013 for Tsu in Japan.

Year	Month	Day	Hour	Min	Sec	Amount of horizontal solar radiation (kW/m^2)	Air temperature (degree Celsius)
2013	8	1	9	0	0	0.1179	30.7
2013	8	1	9	0	10	0.1158	30.8
2013	8	1	9	0	20	0.1115	30.7
2013	8	1	9	0	30	0.1130	30.8
2013	8	1	9	0	40	0.1150	31.0
2013	8	1	9	0	50	0.1120	30.9
2013	8	1	9	1	0	0.1107	30.8
2013	8	1	9	1	10	0.1123	30.8
2013	8	1	9	1	20	0.1166	31.0
2013	8	1	9	1	30	0.1179	30.9
2013	8	1	9	1	40	0.1183	30.8
2013	8	1	9	1	50	0.1194	30.8
2013	8	1	9	2	0	0.1229	30.8
2013	8	1	9	2	10	0.1249	30.6
2013	8	1	9	2	20	0.1267	30.5
2013	8	1	9	2	30	0.1270	30.3
2013	8	1	9	2	40	0.1262	30.1
2013	8	1	9	2	50	0.1258	30.1
2013	8	1	9	3	0	0.1298	30.4

$$L = \frac{1}{\tan \alpha} \times \cos \beta \times h \tag{5}$$

where L is the longest shadow length of solar panel to north direction (mm), α is solar altitude (degree), β is solar azimuth angle from north and south direction (degree), h is height of solar panel (mm).

In other words, the solar panels need to keep L distance apart in N-S direction to avoid the shadowing each other. The number of solar panels, which can be installed on the roof of building without shadowing other panels, was estimated with various tilt angles.

2.2. Estimation of Power Generated by FC System Using H_2 Produced by Water Electolysis

In this case study, it is assumed that the surplus power generated by PV system over the electricity demand of households [49] living in the building model would be used for water electrolysis. The Type-S electrolyzer manufactured by IHT [59] whose H_2 production rate, power consumption and electrolysis efficiency are 760 Nm^3/h, 4.45 kWh/Nm^3 and 79.5%, is used in this case study. The amount of H_2 could be produced by the surplus power generated from PV system is calculated by the following equation:

$$V_{H_2} = \frac{\eta_e E_s}{P_e} \tag{6}$$

where V_{H2} is amount of H_2 produced (Nm^3), E_s is surplus power generated by PV system (kWh), P_e is power consumption (kWh/Nm^3), η_e is electrolysis efficiency (−).

It is assumed that the H_2 produced by the electolyzer would be used to generate power through a polymer electrolyte fuel cell (PEFC) system. H_2 is converted into electricity by FC following the below equation:

$$H_2 + 1/2O_2 = H_2O + \eta_f Q \tag{7}$$

where η_f is power generation efficiency of latest PEFC stationary system based on lower heating value (=0.39) [60], Q is lower heating value of H_2 (=242) (kJ/mol).

In this study, 4 monthly values of the self-sufficiency rate of the proposed combination system consisting of PV and FC was investigated, which are representative of four seasons for Tsu city in Japan. The self-sufficiency rate is defined as the power supplied (from the combined PV and FC system to electricity demand of the building), in this study. The hourly time change in the self-sufficiency rate in the day when the daily mean amount of horizontal solar radiation per month was obtained was estimated.

3. Results and Discussion

3.1. Optimum Installment Procedure of Solar Panel on the Roof of the Building Model

At first, the optimum tilt angle for installment of solar panel on the roof is investigated using the hourly meteorological data base [57] for several cities in Japan. After that, the instant time change in power generation characteristics of PV system under the optimum tilt angle (a_t) condition is investigated using the meteorological data base of PV300 including air temperature, solar intensity and wind speed at 10 sec intervals [58]. Compared the power generation characteristics of PV system with the electricity demand data of households in Japan [49], the surplus and deficit between power supply (from PV) and the electricity demand in the building were estimated. The power generation characteristics of FC system using H_2 produced by water electrolysis with the surplus power of PV system is investigated to bridge the gap between the power supply and the electricity demand.

To clarify the optimum a_t of solar panel installed on the roof of the building model universally in Japan, this study investigates the daily power energy of PV system averaged per month for five cities in Japan such as Tsu (north latitude: 34 degrees; east longitude: 136 degrees), Fukushima (north latitude: 37 degrees; east longitude: 140 degrees), Tokyo (north latitude: 35 degrees; east longitude: 139 degrees), Sapporo (north latitude: 43 degrees; east longitude: 141 degrees) and Naha (north latitude: 26 degrees; east longitude: 127 degrees) using the hourly meteorological data METPV-11 including air temperature, solar intensity and wind speedat 1 hour interval [57]. Tsu is located in the center of Japan. Fukushima is the city which is necessary to be rebuilt overcoming the big earthquake damage. Tokyo is the capital in Japan. Sapporo and Naha are located in the farthest north area and the farthest south area in Japan.

Figures 2-5 show the relationship between daily power energy of PV system averaged per month and a_t of solar panel installed on the roof of the building model. In these figures, January, April, July and October are selected as the months which are representative of four seasons in Japan, respectively. In addition, **Figure 6** shows the relationship between annual power energy of PV system and a_t of solar panel installed on the roof of the building model for five cities. From these figures, it is revealed that the optimum a_t is 0 degree irrespective of city as well as season. Though the optimum a_t of solar panel installed on the ground is approximately 20 - 30 degrees in Japan generally [57], the optimum a_t of solar panel installed on the roof of the building is 0 degree due to the limitation of the rood area of the building.

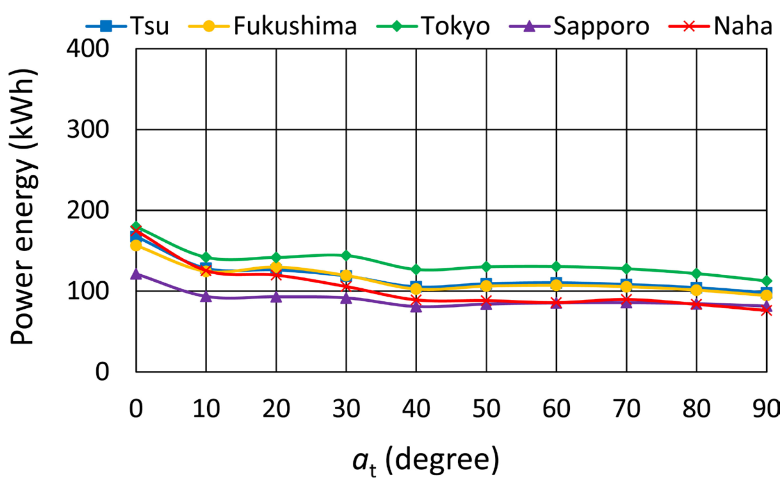

Figure 2. Relationship between daily power energy of PV system averaged per month and tilt angle of solar panel installed on the roof of the building model (January).

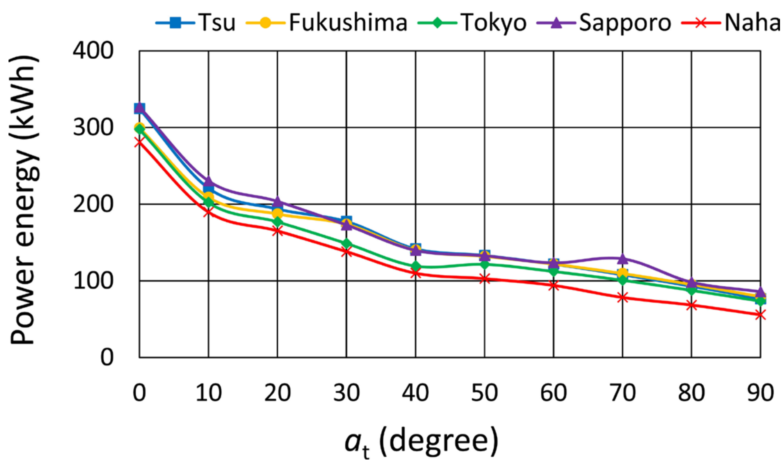

Figure 3. Relationship between daily power energy of PV system averaged per month and tilt angle of solar panel installed on the roof of the building model (April).

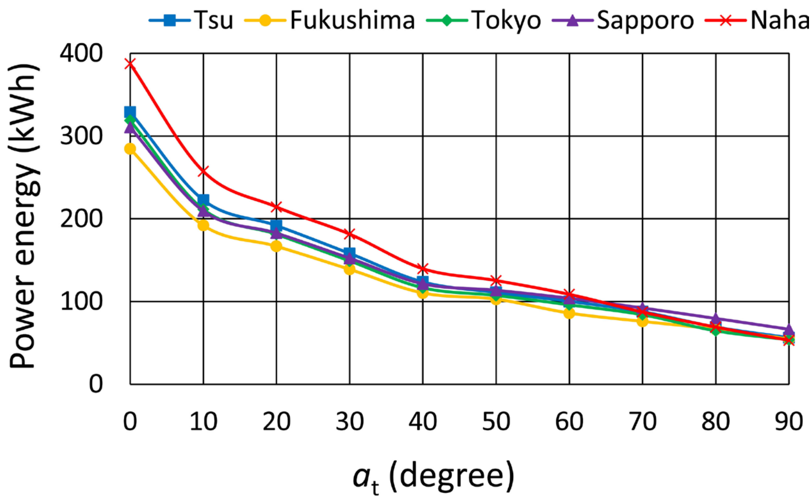

Figure 4. Relationship between daily power energy of PV system averaged per month and tilt angle of solar panel installed on the roof of the building model (July).

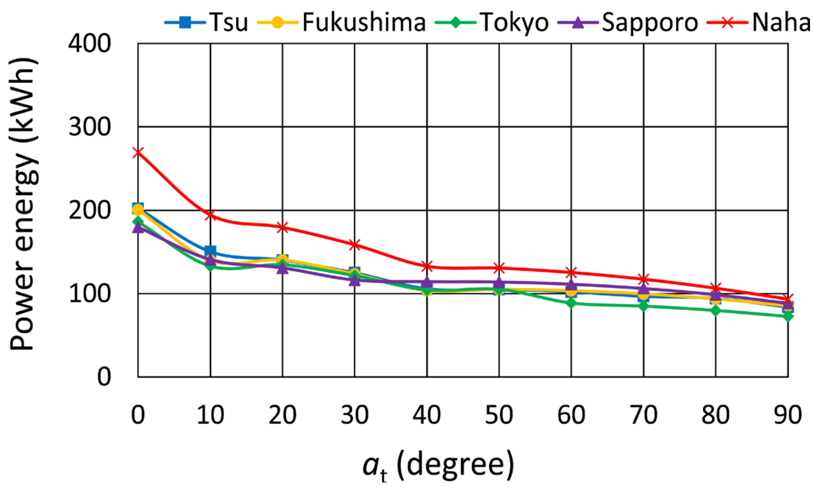

Figure 5. Relationship between daily power energy of PV system averaged per month and tilt angle of solar panel installed on the roof of the building model (October).

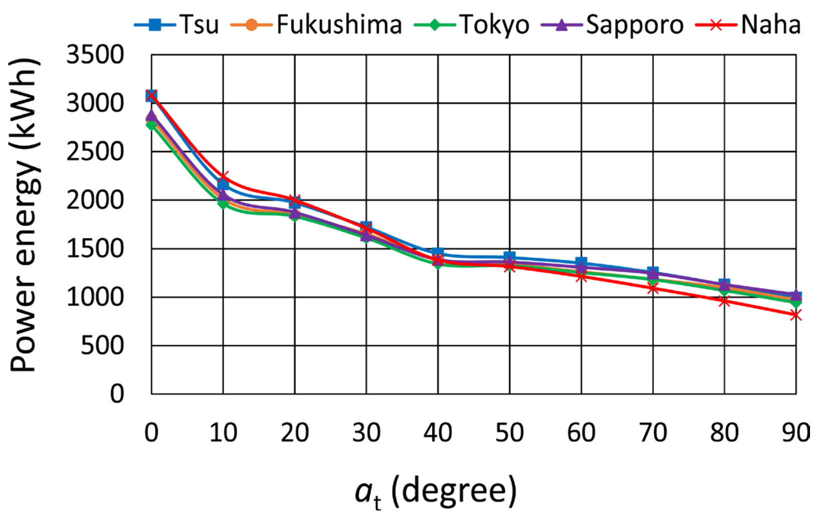

Figure 6. Relationship between annual power energy of PV system and tilt angle of solar panel installed on the roof of the building model.

Table 2. The number of installable solar panel with consideration of shadow impact.

a_t (degree)	0	10	20	30	40	50	60	70	80	90
L (mm)	0	312	615	898	1155	1376	1555	1688	1770	1796
N_s (−)	300	200	175	150	125	125	125	125	125	125
N_s/N (−)	1.00	0.67	0.58	0.50	0.42	0.42	0.42	0.42	0.42	0.42

Table 2 lists the number of installable solar panel on the roof of the building model with consideration of shadow impact. In this table, the relationship between a_t and number of installable solar panel is shown. N_s and N mean the number of installable solar panel with consideration of shadow and that without consideration of shadow, respectively, when N is 300. From this table, N_s decreases with increase in a_t. Since the roof area of the building is limited, N_s decreases with increase in a_t due to shadow extension. According to the review by this study, there is no report concluding that 0 degree is the optimum a_t for installing solar panel on the roof of the building. Since the effect of shadow and restricted area of roof of building on the power generation performance of PV system is not considered at the same time in the past studies, it is believed that this new finding is obtained. It is thought that the dust impact on the power generation of PV system is afraid when a solar panel is installed at a_t of 0 degree for the roof of the building actually. However, this study suggests cleaning up the dust by water for the case of a_t of 0 degree.

3.2. Evaluation of Characteristics of Power Supply from BIPV and Power Demand in the Building in Tsu City

Figures 7-10 show hourly power generated from proposed BIPV system and energy demand of 40 households assumed living in the building model in Tsu city in Japan. Hourly power generated by PV system was estimated for the standard day in the month with the mean amount of horizontal solar radiation of the month using the meteorological data base of PV300 [58]. In these figures, January, April, July and October are selected as the months which are representative of four seasons, respectively. The hourly self-sufficiency rate of PV system (R_{PV}) is also shown in order to reveal the power supply surplus or deficit in a particular hour.

From Figures 7-10, it is obvious that the generation of PV system increases in the morning up to the noon and decreases after noon to the evening due to solar trajectory, while the electricity demand keeps almost constant during the day and increases from the evening until the midnight. Due to the mismatch between the power generation and electricity demand, R_{PV} is over 100% during the daytime and is 0% during the night-time. Moreover, R_{PV} during the daytime in April and July are higher than those in January and October. Since the amount of horizontal solar radiation in spring and summer are higher than those in autumn and winter in Japan, the R_{PV} are higher in April and July than those in January and October.

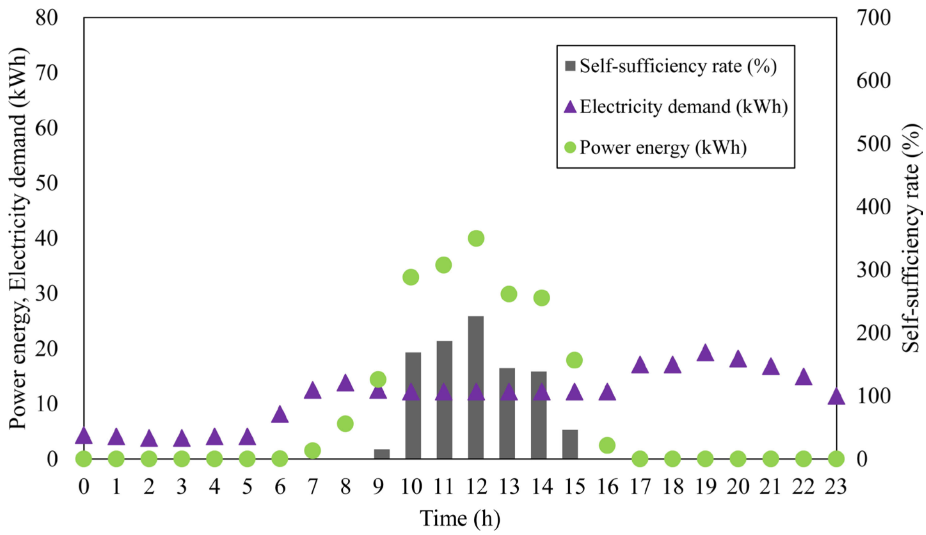

Figure 7. Comparison between hourly power energy of PV system and electricity demand (January).

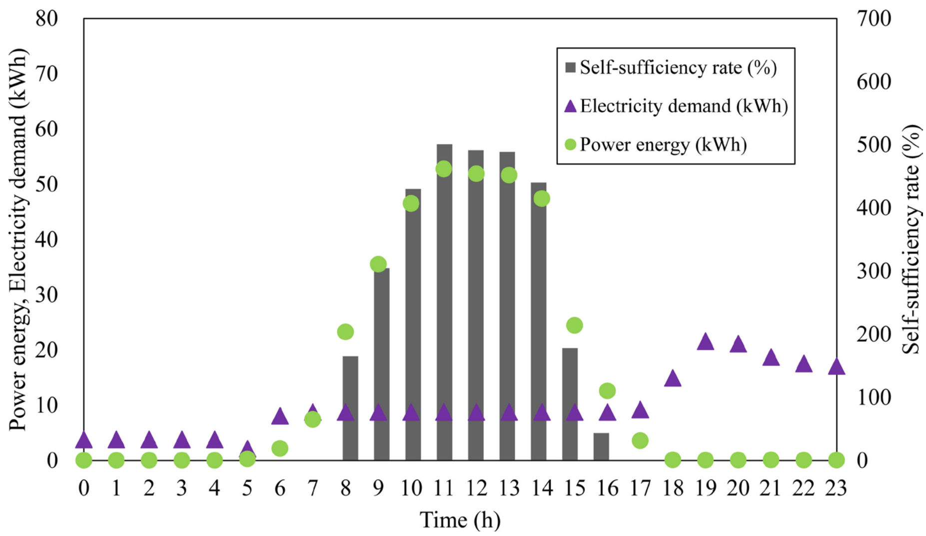

Figure 8. Comparison between hourly power energy of PV system and electricity demand (April).

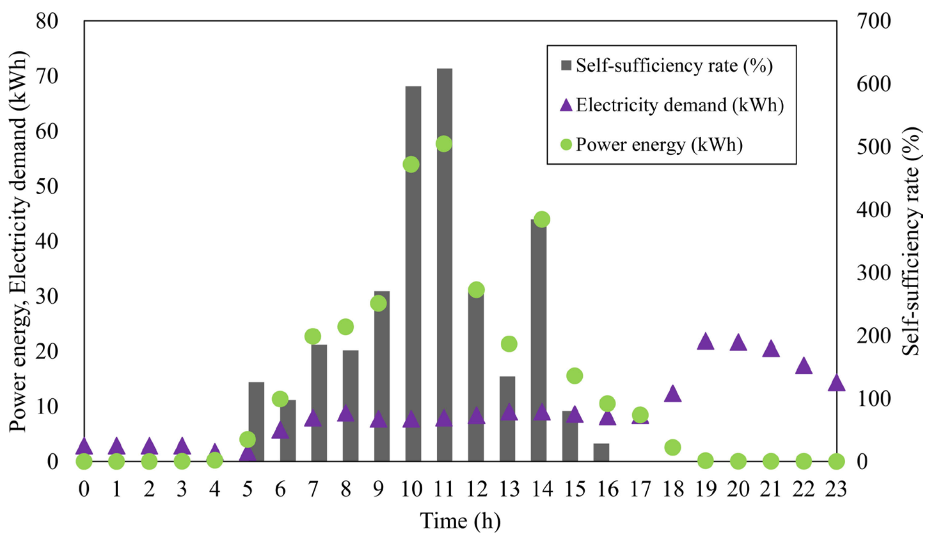

Figure 9. Comparison between hourly power energy of PV system and electricity demand (July).

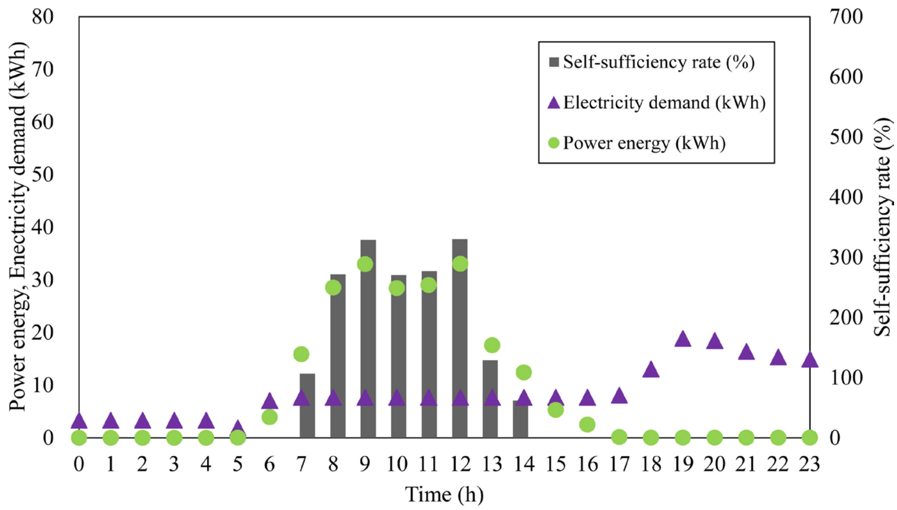

Figure 10. Comparison between hourly power energy of PV system and electricity demand (October).

It was assumed that the surplus electricity generated was used for water electrolysis to produce H_2 which is fed into the FC system. The self-sufficiency rate of the FC system (R_{FC}) is defined as the ratio of the power generated by FC system to the electricity demand which is not covered by PV system. The average daily R_{FC} in representative months is calculated and it is given in Table 2. In this table, E_{FC} is the power energy of FC system using H_2 generated by water electrolysis with the surplus power of PV system, and E_D is the electricity demand which is not covered by PV system. In addition, E_{FC}, E_D and R_{FC} were calculated as a daily value by summing up the hourly values for the day when the mean amount of horizontal solar radiation was obtained per month in January, April, July and October.

From Table 3, it is known that R_{FC} is in the range of 15% - 38%. Since the power energy is high in January and the power energy is low in October, R_{FC} for these two months are lower. However, it is implied that the power generation of FC system using H_2 generated by the surplus power of PV system is effective for bridging the gap between the power supply of PV system and electricity demand of households.

Table 4 shows the change in R_{FC} in a week which from three days ago to three days after the day when the mean amount of horizontal solar radiation was obtained per month in Tsu city using the meteorological data base of PV300 [58]. It is seen from Table 3 that R_{FC} changes following the daily meteorological condition. For example, in a cloudy or rainy day when R_{FC} is 0%, indicating that the surplus power of PV was not obtained and R_{FC} can be as high as 49% in a good sunny day.

As we know that the electricity demand/consumption depends on the number of households in the building, Table 5 and Table 6 give the self-sufficiency rates in a week calculated by the meteorological data base of PV300 [58] and the electricity demand data of households in Japan [49] under the assumptions that there were 20 and 12 households in the building with the same roof areas (*i.e.*

Table 3. Self-sufficiency rate of power energy of FC system to the electricity demand which is not covered by PV system.

	E_{FC}(kWh)	E_D (kWh)	R_{FC} (%)
January	24	186	13
April	56	149	35
July	49	130	38
October	29	138	21

Table 4. Change in daily self-sufficiency rate of FC system in a week (40 households in the building).

	January (%)	April (%)	July (%)	October (%)
3 days ago	15	13	41	38
2 days ago	0	35	18	37
1 day ago	10	18	12	41
Mean solar radiation day	13	35	38	21
1 day after	9	31	19	0
2 days after	15	47	0	33
3 days after	15	49	14	40

Table 5. Change in daily self-sufficiency rate of FC system in a week (20 households in the building).

	January (%)	April (%)	July (%)	October (%)
3 days ago	38	28	66	61
2 days ago	0	64	34	59
1 day ago	29	38	29	65
Mean solar radiation day	33	65	59	35
1 day after	28	56	39	1
2 days after	36	80	6	53
3 days after	38	83	30	63

Table 6. Change in daily self-sufficiency rate of FC system in a week (12 households in the building).

	January (%)	April (%)	July (%)	October (%)
3 days ago	46	40	100	93
2 days ago	1	85	55	90
1 day ago	36	52	39	99
Mean solar radiation day	40	86	98	56
1 day after	33	82	49	2
2 days after	46	114	9	81
3 days after	46	118	42	97

same amount of solar panels installed), respectively.

According to Table 5, it is seen that the R_{FC} increases compared to Table 4, but still falls below 100% for each day investigated.

Table 6 shows R_{FC} in a week in the case of 12 households who live in the building with 12 m height (=3 stories), when the mean amount of horizontal solar radiation was obtained per month in Tsu city using the meteorological data base of PV300 [58]. It can be seen, in this case, the R_{FC} over 100% are obtained in some days in April and high R_{FC} near 100% are obtained in some days in July and October. The surplus H_2 in the days when R_{FC} is over 100% can be stored and used for the days when R_{FC} is less than 100%. Although Tables 3-6 show the assessment result of one city (Tsu) only, it is expected that the proposed combined PV and FC system has potential to achieve the 100% self sufficient supply for buildings in Japan, especially in good solar resource areas.

In addition, the proposed systems in different buildings with different energy demands may be connected in future, so the surplus electricity generated from PV and/or H_2 can be transferred between buildings. Moreover, H_2 as an energy storage medium has longer term storage efficiency than secondary battery.

4. Conclusions

This study has investigated the proper solar panel setting procedure to be installed on the roof of the building. This study proposed a combined PV and FC utilizing H_2 produced with surplus power of PV for Japanese buildings. The PV's installation angles and performance of the system have been studied with meteorological data of several cities in Japan. The (energy) self-sufficiency rates of the combination system of PV and FC are also studied with meteorological data for Tsu city in Japan. As a result, the following conclusions have been drawn:

1) The optimum installation angel for solar panel on the roof of the building is 0 degree irrespective of city or season due to the limitation of the roof area of building.
2) Due to the mismatch between the power supply and electricity demand, R_{PV} is over 100% during the daytime while it is 0% during the night-time. R_{PV} during the daytime in April and July is higher than that in January and October since the amount of horizontal solar radiations in spring and summer are higher than those in autumn and winter in Japan.
3) It is revealed that R_{FC} is in the range of 15% - 38% for the day for a big building (*i.e.*, with 40 households).
4) For the smaller buildings with 20 or 12 households, the R_{FC} over 100% could be possible in April and high R_{FC} near 100% is possible in July and October in the case of 12 households (=3 stories).

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