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Energy Assessment of Building Integrated Photovoltaics and Fuel Cell Systems: Design Study for Building(s) of Mie, Japan

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Abstract

A building integrated energy system (photovoltaic (PV) and fuel cell (FC)) is proposed for assessment of the energy self-sufficiency rate in five cities of Mie prefecture in Japan. In this work, it is considered that the electricity requirement of the building is provided by the building integrated photovoltaic (BIPV) system and the gap between the energy demand and BIPV supply is fulfilled by the FC. The FC is powered by the electrolytic H_2 produced from the surplus power of PV. A design study of using the proposed system in five cities in Mie prefecture, which are in center part of Japan, has been performed. It has been observed that the monthly power production from BIPV is higher in spring and summer, while it is lower in autumn and winter at all considered locations. The self-sufficiency rate of the FC system is higher with decreasing households' number and it has been observed that the 12 households are more suitable for full cover of the electricity demand by the combined system of PV and FC. The relationship between the households' number and self-sufficiency rate of the FC system per solar PV installation area can be expressed by exponential curve. The coefficient of the exponential curve can predict the suitable city for the BIPV system with FC system utilizing electrolytic H_2 generated by using excess energy from the PV system.

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 is impacting on global climate. Renewable energy sources such as wind,

solar photovoltaic (PV), solar thermal, geothermal, bio-energy are drawing attention as alternative environment-friendly energy sources [1]. However, the energy density of these renewable energy sources is low. 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 [1]. In most of the developed countries, existing buildings are consuming around 40% of the total fossil fuel energy and they are contributing significantly in the greenhouse. The European Union's Energy Performance of Buildings Directive requires all new buildings to be nearly zero-energy by the end of 2020. The amount of energy that these buildings require comes mostly from the building integrated renewable energy sources (e.g. building integrated photovoltaic BIPV system).

Integrating renewable energy sources into the existing energy system network is an effective approach in the development of net zero-energy buildings' 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 [1]. The development of a smart city or a smart building requires harmonizing the renewable energy system with existing heat and power system infrastructures, and with new monitoring and control system [2].

Integrating/installing solar panels on the roof and/or side wall of the building is a typical way to make the building energy self-sufficient. Such kind of building integrated PV systems (BIPV) has been studied by many researchers [3]-[16]. According to some review papers [4] [5], 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 [6]. Most of the researches on BIPV focused on economic and environmental assessment evaluating by investment recovery with consideration of power generation performance [7], life cycle cost (LCC) and energy payback time (EPBT) [4] [11]. In addition, some studies investigated the effect of thermal management of PV module on the power generation performance of BIPV [12] [13].

Due to solar energy's intermittent nature, the BIPV system normally requires a sort of energy storage system and/or grid-connected mechanism [6] [17]. The typical energy storage system in integrated PV systems is battery bank and electrolytic H_2 can also be used for long term energy storage and these integrated systems have been studied numerically as well as experimentally [3] [16] [18]-[28]. The research on BIPV and energy storage system is a few [6] [17] [29] [30] [31], although the ice storage system combined with BIPV has been discussed in [16]. Though financial assessment on BIPV with energy storage system [29] [30] and a dynamic control procedure in a short time [31] have been discussed, the energy assessment that considers the BIPV with energy storage system in actual city for a long operational period has not been reported yet. In [6], the operational results of a zero-energy building (ZEB) house from the Southern

Norway have been reported only for the BIPV without any energy storage. Therefore, the optimization of BIPV with energy storage system and especially with long term energy storage in the form of electrolytic H_2 has not been investigated well.

In this paper, a design study has been performed on a proposed BIPV system with utilization of stored energy in the form of electrolytic H_2 through FC during the power production from the PV system. The proposed BIPV system consists of the solar PV array, water electrolyzer and fuel cell (FC). The H_2 required by the FC is provided from the stored electrolytic H_2 produced using the surplus power of the PV. The FC would therefore be able to buffer the intermittency (partly) between the building electricity demand (by the building) and the PV system. The BIPV power productions at the five cities in Mie prefecture, Japan have been evaluated using the meteorological data of the project "PV300" (period from August, 2013 to July, 2014 [32]). The BIPV power productions have been compared with the electricity demand data of households [33] and investigated for the optimum power supply in a way to overcome the intermittency of the electricity demand and PV system. The self-sufficiency rate of the proposed BIPV system to electricity demand has been estimated in the design study. In addition, the optimum number of households living in the building, *i.e.* the optimum size of the building, has been investigated.

2. Design Study

2.1. Estimation of Power Generation from the PV System

The building model, used in the design study, is 10 m width, 40 m length and 40 m height (=10 stories) [34] with 40 households [35]. The BIPV system has considered on the roof/top of the building and a FC using electrolytic H_2 produced when the surplus power from PV has been available [1].

The power generated by PV system is calculated by using the following equation [36]:

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

where E_{PV} is hourly electric power of PV system (kWh), H is hourly 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, hourly solar radiation: 1 kWh/m^2, module temperature: 25 degree Celsius) (kW/m^2). The instantaneous solar radiation data by 10 sec of the reference [32] are integrated as hourly data for calculating the hourly electric power of PV system.

In this study, the high-performance PV P250a Plus produced by Panasonic has been considered. This module has conversion efficiency and maximum power rating per module is 19.5% and 250 W [37]. The size of PV module is 1580 mm × 812 mm × 35 mm. P has been calculated by installing this PV module on the roof of the building model, which is 75 kW$_P$ (=300 solar modules). To calculate K, the performance value of state-of-the-art commercial devise is used. 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 [38]. 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) (degree Celsius), C is temperature correction factor which is 0.35 [39] (%/degree Celsius). The temperature characteristics of PV module which is adopted for this study are referred. T_m is calculated by using the following equation [40]:

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

where T_a is ambient air temperature (degree Celsius), U_m is wind velocity over module of PV (m/s). In this equation, the convection heat transfer by wind around the PV module is considered.

The meteorological data, such as solar radiation, the ambient air temperature, and wind velocity of some cities in Japan have been taken from the data base of the project "PV300" during the period from August, 2013 to July, 2014 [32]. Table 1 has listed a sample of PV300 data, 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. According to the previous study [1], the optimum tilt angle of solar panel installed on a roof/top of the building is 0 degree, resulting that the horizontal solar radiation has been used for calculating the power generated by the PV system in this study.

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

In this design study, it has been assumed that the surplus power generated by the PV system over the electricity demand of households [33] living in the considered building model, will be used for electrolytic H_2 production (*i.e.* long term energy storage in the form of electrolytic H_2). To optimize the size of BIPV system, number of households has been varied by 40, 20, 16 and 12 which correspond to 10, 5, 4 and 3 stories of the building, respectively. In this study, the building which has 4 households per floor is assumed. Then, the multiple number of 4 is based for assessment. To keep a building structure, the lowest limit of stories is set 3 which is the low height class building, indicating 12 households. The Type-S electrolyzer manufactured by IHT [41] [42] whose H_2 production rate, power consumption and electrolysis efficiency are 760 Nm³/h, 4.45 kHW/Nm³ and 79.5%, have been used in this design study. The amount of electrolytic

Table 1. Sample 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

H$_2$ could be produced by the surplus power generated from the PV system is calculated by the following equation [1]:

$$V_{H_2} = \frac{\eta_e E_s}{P_e} \tag{5}$$

where V_{H_2} is amount of electrolytic 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 (−). In this study, it is assumed that the electrolyzer can be operated following the power generation characteristics of PV system every time and the produced H$_2$ can be stored as well as used instantaneously.

It has been assumed that the H$_2$ produced by the electolyzer would be used to generate power through a polymer electrolyte fuel cell (PEFC) system [3]. H$_2$ is converted into electricity by FC following the below equation:

$$H_2 + 1/2 O_2 = H_2O + \eta_f Q \tag{6}$$
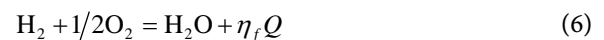
where η_f is power generation efficiency of latest PEFC stationary system based on lower heating value (=0.39) [43], Q is lower heating value of H$_2$ (=242) (kJ/mol). It is assumed that the energy loss for operating pump to preserve and provide gases is ignored.

In this study, a monthly self-sufficiency rate of the proposed combination system consisting of the PV and FC has been investigated for Tsu (Latitude: 34.43°N, Longitude: 136.30°E), Yokkaichi (Latitude: 34.57°N, Longitude: 136.37°E), Kuwana (Latitude: 35.03°N, Longitude: 136.41°E), Ise (Latitude: 34.29°N, Longitude: 136.42°E) and Owase (Latitude: 34.04°N, Longitude: 136.11°E). They are the main cities in Mie prefecture, Japan. The self-sufficiency rate is defined as the power supplied (from the combined PV and FC system) to the electricity demand of the households living in the building. The hourly time change in the self-sufficiency rate in the day, when the daily mean amount of horizontal solar radiation per month has been obtained and estimated.

3. Results and Discussion

3.1. Evaluation of Power Supply from the BIPV and the Building Electricity Demand for 40 Households Case

As described in earlier sections, this study has investigated the power production from the PV system using the meteorological data base of PV300 [32] including air temperature, solar intensity and wind speed at 10 sec intervals. Since the electricity demand of households [33] is available as hourly data, the power production from the PV system is summarized as hourly data by integrating the instantaneous data available at 10 sec intervals.

As an example, Table 2 has listed the hourly power from PV system (installed in Tsu for a year) which is shown to investigate the seasonal characteristics. In this table, the hourly time change in power of PV system in the day when the daily mean amount of horizontal solar radiation per month has been obtained and estimated. From this table, the hourly power of PV system increases from the morning up to the noon and decreases from the noon up to the evening as expected. In addition, it is obvious that the hourly power of PV system is higher in spring and summer, while it is lower in autumn and winter. The data shown in Table 2 has been summed for daily data and it has been multiplied by the total days for each month for using as monthly data. The monthly power production from the PV system is shown in Table 3 which is shown to investigate the seasonal and local characteristics. It has been observed that the monthly power of the PV system is higher in spring and summer, while it is lower in autumn and winter irrespective of the cities.

Table 4 has listed the hourly electricity demand of 40 households for a year which is shown to investigate the seasonal characteristics. In this study, the electricity demand profile, which depends on the city are not considered. It means that the same electricity demand profile has been used for the five cities as design study. When considering the electricity demand profile of other number of households, the data shown in Table 4 have been recalculated. It has been observed that the hourly electricity demand increases from the morning and keeps almost a constant value during a day. After that, the hourly electricity demand increases rapidly from the evening and keeps almost a constant value up to the midnight. In addition, it is obvious that the electricity demand is higher in

Table 2. Hourly power of PV system assumed to be installed in Tsu for a year (Unit: kWh).

Time (h)	Aug. 2013	Sep. 2013	Oct. 2013	Nov. 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014	Apr. 2014	May 2014	Jun. 2014	Jul. 2014
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	2	0	0	0	0	0	0	0	0	2	3	4
6	6	2	4	0	0	0	1	3	2	9	7	11
7	24	14	16	6	2	1	5	9	7	19	16	23
8	36	33	29	18	10	14	15	19	23	42	26	24
9	50	47	33	25	15	28	22	17	36	48	46	29
10	57	49	28	30	28	24	37	21	47	54	49	54
11	61	37	29	29	35	35	35	36	53	51	52	58
12	59	34	33	30	31	36	40	48	52	49	43	31
13	42	21	18	28	27	18	29	51	52	53	39	21
14	15	17	12	19	15	19	21	36	47	28	26	44
15	3	16	5	9	5	15	20	29	24	23	18	16
16	4	16	2	1	1	4	8	11	13	15	10	11
17	2	3	0	0	0	0	2	2	4	7	4	8
18	0	0	0	0	0	0	0	0	0	0	1	3
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Total	362	291	210	197	170	194	235	284	360	400	340	337

Table 3. Monthly power of PV system assumed to be installed in five cities (Unit: MWh).

City	Aug. 2013	Sep. 2013	Oct. 2013	Nov. 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014	Apr. 2014	May 2014	Jun. 2014	Jul. 2014
Tsu	11.2	8.74	6.50	5.90	5.27	6.02	6.59	8.80	10.8	12.4	10.2	10.5
Yokkaichi	11.7	8.37	5.04	4.44	4.19	5.58	6.39	8.20	7.82	9.65	9.93	7.77
Kuwana	10.8	7.92	6.36	5.00	4.04	6.43	7.01	8.34	9.88	9.16	10.3	7.91
Ise	8.03	7.10	5.00	5.87	4.66	4.05	4.13	7.81	6.92	9.95	9.01	7.79
Owase	10.7	7.14	3.27	6.93	5.67	7.07	4.85	5.43	9.42	13.3	7.84	5.89

Table 4. Hourly electricity demand data of 40 households (Unit: kWh).

Time (h)	Aug. 2013	Sep. 2013	Oct. 2013	Nov. 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014	Apr. 2014	May 2014	Jun. 2014	Jul. 2014
0	3	3	3	3	4	4	4	4	4	3	2	3
1	3	3	3	3	3	4	4	4	4	3	2	3
2	3	3	3	3	3	4	4	3	4	3	2	3
3	3	3	3	3	3	4	4	3	4	3	2	3
4	2	2	3	3	3	4	4	4	4	3	2	2
5	2	2	2	2	3	4	4	4	2	2	2	2
6	7	6	7	7	7	8	8	7	8	7	5	6
7	9	8	8	8	10	13	12	11	9	8	7	8
8	10	9	8	8	11	14	13	12	9	8	8	9
9	9	8	8	8	10	13	12	11	9	8	7	8
10	9	8	8	8	10	12	12	11	9	8	7	8
11	9	8	8	8	10	12	12	11	9	8	7	8
12	10	9	8	8	10	12	12	11	9	8	7	8
13	11	10	8	8	10	12	12	11	9	8	8	9
14	11	10	8	8	10	12	12	11	9	8	8	9
15	10	9	8	8	10	12	12	11	9	8	7	9
16	10	9	8	8	10	12	12	11	9	8	7	8
17	10	9	8	8	14	17	16	15	9	8	7	8
18	14	13	13	13	14	17	16	15	15	13	11	12
19	25	23	19	19	16	19	18	17	22	19	19	22
20	25	23	18	19	15	18	17	16	21	19	19	22
21	24	22	16	17	14	17	16	15	19	17	18	21
22	20	18	15	16	12	15	14	13	18	16	15	17
23	17	15	15	15	9	11	11	10	17	15	12	14
Total	257	232	208	214	220	272	259	240	237	211	192	221

summer and winter, while it is lower in spring and autumn. The data shown in Table 4 have been summed as daily data and it was multiplied by the total days for each month as monthly data.

Table 5 has listed the hourly power production for a year from the FC system, assumed to be installed in Tsu, which has been calculated by using the surplus power of PV system and the Equations (5) and (6). According to Table 2 and Table 4, the surplus hourly power of the PV system is high during the daytime, especially at the noon, while it is low from the evening to the early morning. When the hourly self-sufficiency rate of PV system is over 100 %, it means that the FC system has the capacity to generate the power due to the surplus power of PV system or the surplus energy can be stored in the form of electrolytic H_2. In this study, it has been assumed that the surplus power of PV system can be uti-

lized by the water electrolysis immediately and be stored as electrolytic H_2. It has been also assumed that the stored electrolytic H_2 can be utilized in the FC system for fulfilling the shortage of energy during the required time. In Table 5, hourly power productions from the FC system are used for finding daily power production from the FC system and it has been multiplied by the total monthly days for finding monthly power production from the FC system. The monthly power production profile of the FC system has been given in Table 6.

Table 6 has listed the monthly power production from the FC system which is shown to investigate the seasonal and locational characteristics. Figure 1 has shown the monthly self-sufficiency rate of the FC system which is also shown to investigate the seasonal and locational characteristics. The self-sufficiency rate is

Table 5. Hourly power of FC system assumed to be installed in Tsu for a year (Unit: kWh).

Time (h)	Aug. 2013	Sep. 2013	Oct. 2013	Nov. 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014	Apr. 2014	May 2014	Jun. 2014	Jul. 2014
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	1
7	3	1	2	0	0	0	0	0	0	2	2	3
8	5	5	4	2	0	0	0	1	3	7	4	3
9	9	8	5	4	1	3	2	1	6	8	8	4
10	10	9	4	5	4	2	5	2	8	10	9	10
11	11	6	4	4	5	5	5	5	9	9	9	10
12	10	5	5	5	4	5	6	5	9	9	7	5
13	7	2	2	4	4	1	4	8	9	9	6	3
14	1	2	1	2	1	1	2	8	8	4	4	7
15	0	1	0	0	0	0	2	5	3	3	2	1
16	0	2	0	0	0	0	0	4	1	1	1	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Total	56	41	29	26	19	18	26	36	56	64	53	49

Table 6. Monthly power of FC system assumed to be installed in five cities (40 households case; Unit: MWh).

| City	Aug. 2013	Sep. 2013	Oct. 2013	Nov. 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014	Apr. 2014	May 2014	Jun. 2014	Jul. 2014
Tsu	1.73	1.24	0.884	0.785	0.592	0.573	0.729	1.10	1.68	1.98	1.60	1.52
Yokkaichi	1.84	1.22	0.609	0.532	0.441	0.552	0.731	1.03	1.10	1.52	1.59	1.02
Kuwana	1.66	1.12	0.878	0.646	0.410	0.724	0.858	1.05	1.49	1.42	1.67	1.05
Ise	1.11	0.957	0.608	0.818	0.508	0.328	0.330	0.961	0.884	1.53	1.40	1.04
Owase	1.56	0.902	0.292	0.991	0.684	0.798	0.429	0.436	1.36	2.17	1.12	0.576
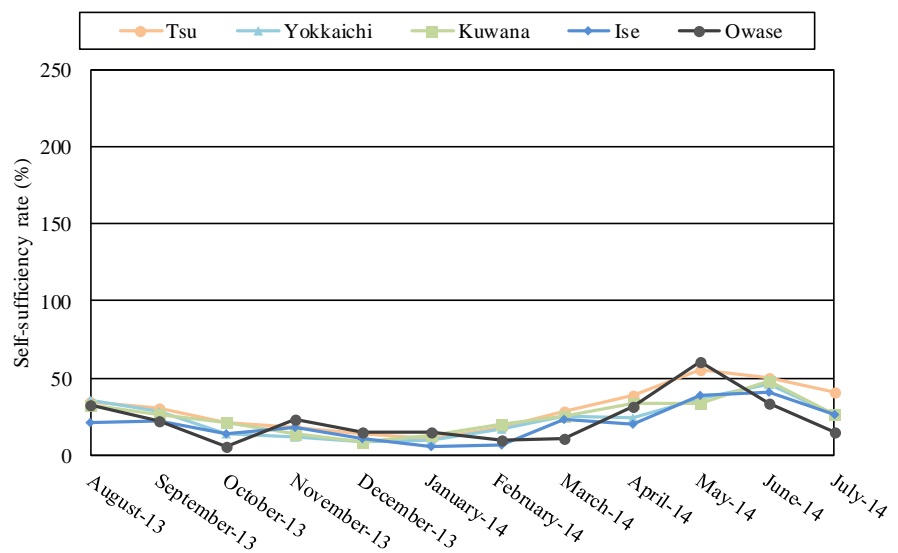
Figure 1. Monthly self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase (40 households case).

calculated by dividing the power produced by the FC system by the electricity demand, which is not covered by the PV system. If the self-sufficiency rate of the FC system is over 100%, then the proposed BIPV system with the FC system utilizing electrolytic H_2 generated by water electrolysis can cover the electricity demand of households living in the building.

According to Table 6, the monthly power of the FC system is higher in spring and summer, while it is lower in autumn and winter irrespective of cities. Also, it follows the power generation profile of the PV system.

It has been seen from Figure 1 that the monthly self-sufficiency rate of the FC system is below 100% irrespective of the cities. The annual self-sufficiency rate of the FC system assumed to be installed in the Tsu, Yokkaichi, Kuwana, Ise and Owase are 29%, 23%, 25%, 19% and 22%, respectively. Therefore, the proposed BIPV system with FC system utilizing the electrolytic H_2 generated by water electrolysis can't cover the electricity demand of 40 households living in the building. This study has investigated the optimum households number per same installment area of PV array in the next section.

3.2. Evaluation of Households Number for Proposed BIPV System with FC System Utilizing H_2 Generated by Water Electrolysis

The households number is changed to investigate the proper households number per same installment area of solar array on the roof/top of building. **Figures 2-4** have shown the monthly self-sufficiency rate of FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase for 20, 16 and 12 households cases, where the stories of buildings are 5, 4 and 3, respectively. These figures are shown to investigate the seasonal and locational characteristics under different households conditions.

It has been observed through **Figures 2-4**, the self-sufficiency rate of FC system is higher with decreasing households number, resulting that the self-sufficiency rate of FC system which is over 100% can be seen in spring and summer.
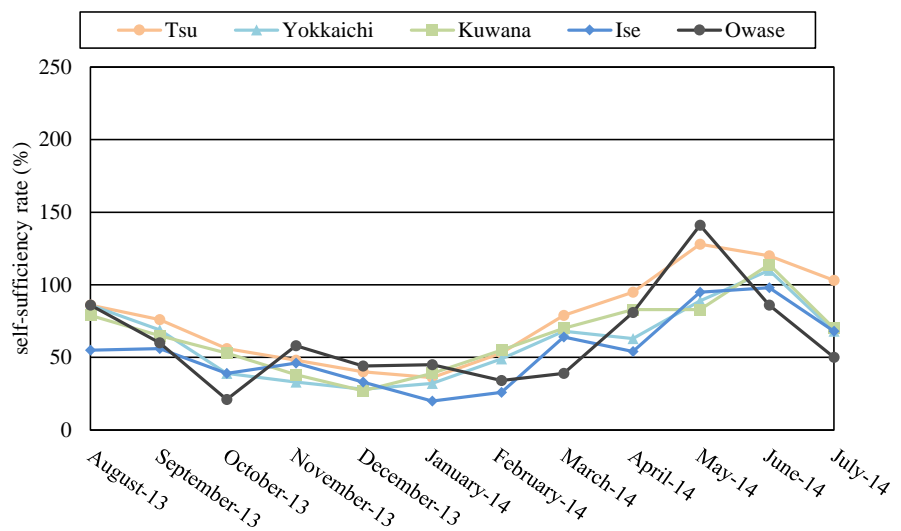
Figure 2. Monthly self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase (20 households case).
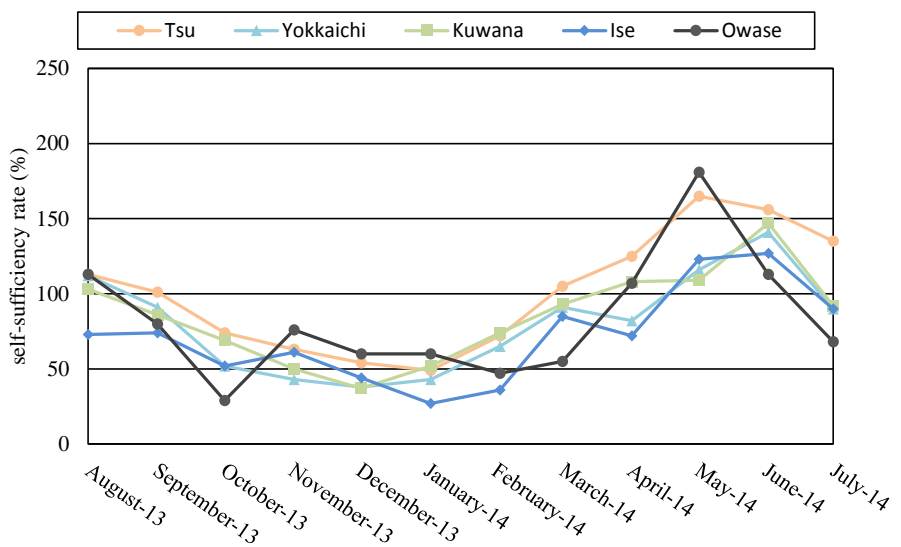
Figure 3. Monthly self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase (16 households case).
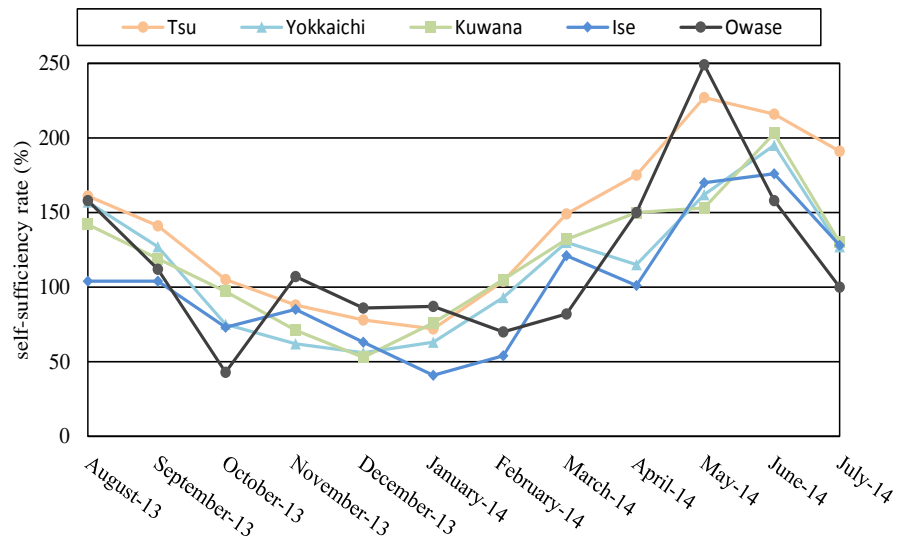
Figure 4. Monthly self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase (12 households case).

The annual self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase for 20 households design case are 74%, 60%, 63%, 52% and 61%, respectively. The annual self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase for 16 households design case are 98%, 79%, 83%, 69% and 81%, respectively. The annual self-sufficiency rate of the FC system assumed to be installed in Tsu, Yokkaichi, Kuwana, Ise and Owase for 12 households design case are 138%, 111%, 117%, 98% and 115%, respectively. From these results, 12 households are more suitable for full cover of the electricity demand by the combined system of PV and FC. Though it is expected that the smaller number of households below 12 indicates the larger self-sufficiency, it is necessary to consider the large electrolytic H_2 storage system for the excess power generated by the PV system instead. In addition, it is assumed that one story consists of 4 households. Consequently, this design study decides that 12 households is the optimum for the proposed BIPV system with FC system.

The relationship between the households number and self-sufficiency rate of FC system per solar PV installation area has been shown in Figure 5. It is observed that the relationship between the households number and self-sufficiency rate of FC system per solar PV installation area can be expressed by the exponential curve well. If the coefficient of the exponential curve is high, e.g. 0.6127 in Tsu case, it means that the self-sufficiency rate of FC system per solar PV installation area is high. Therefore, we can recognize that Tsu is more suitable for the installment of proposed BIPV system. Tsu is located at the center in Mie prefecture and obtain the large amount of solar radiation. In addition, the wind condition is also good to prevent the elevation of PV panel temperature since the mountain ranges are located at the northwest of Tsu. Consequently, the self-sufficiency rate for Tsu is the largest. On the other hand, since Ise is located in the southeast area in Mie prefecture and it is easy to rain, the amount of solar
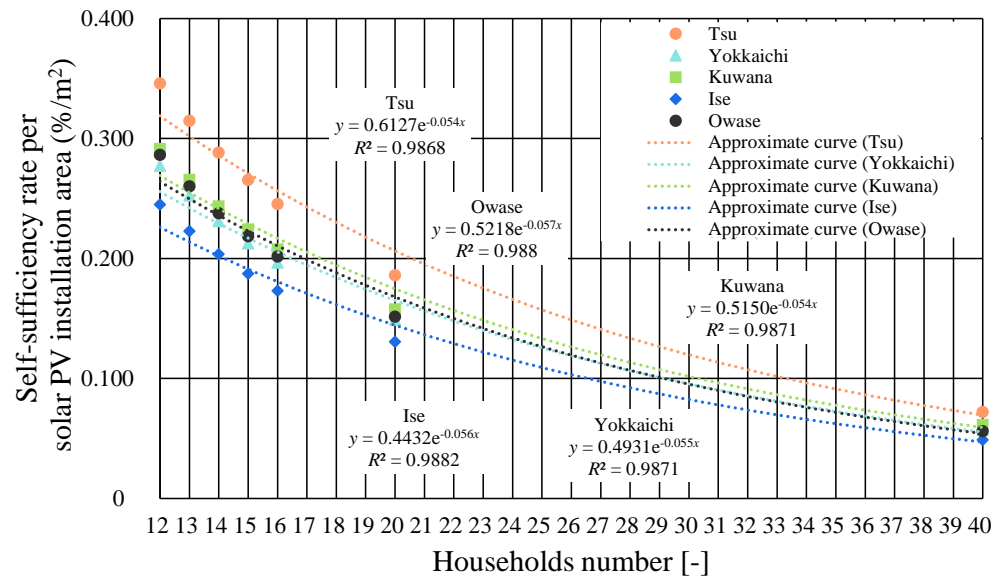
Figure 5. Relationship between the households number and self-sufficiency rate of FC system per solar PV installation area.

radiation is smaller than the other cities. Therefore, the self-sufficiency rate for Ise is the smallest. Owase is also located in the south area in Mie prefecture and it is easy to rain, resulting that the self-sufficiency rate becomes smaller. In the future work, the energy network system consisting of several BIPV system assumed to be installed in several cities will be investigated in order to cover the electricity demand of each other through H_2 transportation/infrastructure.

4. Conclusions

This study has proposed a combined PV and FC utilizing electrolytic H_2 produced with surplus power of PV for Japanese buildings. The self-sufficiency rates of the combination system of PV and FC have been investigated using meteorological data of five cities in Mie prefecture of Japan. As a result, the following conclusions have been drawn:

1) The power production of PV system increases from the morning up to the noon and decreases from the noon up to the evening. The monthly power of PV system is higher in spring and summer, while it is lower in autumn and winter irrespective of cities.

2) The monthly power of FC system is higher in spring and summer, while it is lower in autumn and winter irrespective of cities. It follows the power generation characteristics of PV system.

3) The self-sufficiency rate of FC system is higher with decreasing households number, resulting that 12 households are suitable for full cover of electricity demand by the combined system of PV and FC.

4) The relationship between the households number and self-sufficiency rate per solar PV installation area can be expressed by the exponential curve well. We can find the city, which is more suitable for the proposed BIPV system using the appropriate coefficient of the exponential curve.

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