TECHNO-ECONOMIC ANALYSIS OF A HYBRID SOLAR-HYDROGEN-BIOMASS SYSTEM FOR OFF-GRID POWER SUPPLY

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Abstract

Japan is facing a severe challenge regarding the heavy dependence on fossil fuel after the Great East Japan Earthquake. Fossil fuels currently account for 89 % of the total energy consumption in Japan, which approaches the level of the oil shock in 1973. To tackle this challenge, the government of Japan needs to develop and utilize renewable energy sources to increase its energy self-sufficiency rate and reduce the environmental impacts of the increased use of fossil fuels.

Since the renewable energies are from the natural environment, they are all-weather dependent, which makes them vulnerable in developing a stable power system. The hybridization of variable renewables can allow for smooth, durable, and reliable output to power grids to improve the safety, reliability, and stability of dispatched power, which is cheaper than investing in single renewable technologies. Therefore, Hybrid Renewable Energy System (HRES) can be considered as one possible solution which can combine two or more renewable energy sources to produce power continuously, without interruption.

A hybrid renewable energy system (HRES) is defined as a combination of several renewable technologies which can operate as a self-sustaining power system with higher efficiency than a single renewable power generator such as solar or wind system. If the proposed HRES does not guarantee the production of energy during extended periods, energy storage requirements should be considered to bridge the lean times. Battery storage can be considered as a solution. However, the concerns with the battery storage include its cost and lifetime. Beyond battery storage, a feasible solution is adding a hydrogen-based storage system, including a hydrogen producer, storage tank, and hydrogen consumer such as a fuel cell. Currently, there are several hydrogen production technologies such as water electrolysis, natural gas reforming, photochemical and thermochemical splitting of water, and also a fermentation process which can be used as the hydrogen producer in a HRES. Biomass gasification via biochemical or thermochemical conversion processes are also the most practical technologies for HRES applications. However, the main concern with the gasification process is the formation of ash and tar, which causes severe technical problems such as fouling and slagging in the gasification process. As an alternative to the conventional gasification, the supercritical water gasification (SCWG) process uses water over 22 MPa and 374 C (critical point) as the gasifying agent to decompose the wet biomass feedstock, allowing to achieve a much higher ratio of gasification and hydrogen generation.

In this study, Firstly, an innovative HRES will be introduced with specific emphasis on the integration of renewable generation into the power grid. The proposed HRES is based on the combination of hydrogen generation from two sources: (1) SCWG process of the residential kitchen waste and organic wastewater and (2) solar water electrolysis process which uses the surplus electric power generated by the solar cells. The fuel cell converts hydrogen into

electrical power, which can be used during the periods when the sunlight is not available. So, the proposed HRES forms a composite energy system capable of all-weather conditions. Secondly, a detailed techno-economic-analysis of the proposed HRES is carried out to estimate the cost of electricity generation from the system to meet the electrical load requirements of a selected household area in a subject district around the Shinchi station which is located in Shinchi-machi in this prefecture.

The techno-economic-analysis includes simulation and optimization models. The simulation model is based on the technical design of the system to evaluate the hourly power generation from the proposed HRES, using real meteorological data available in the selected residential area. The optimization model's main goal is set to find the optimal configuration of the system subject to satisfying the required load (electricity) in the selected household area, based on introducing two different optimization criterions: 1) minimization of the total cost of the system and 2) maximization of the total profit obtained from using renewable electricity and selling surplus solar electricity to the grid, considering the Feed-in-Tariff (FiT) scheme in Japan. The optimization method is based on the PSO algorithm, which is one of the meta-heuristics methods to find out the pseudo solution. The model was employed to perform sensitivity analyses of the Levelized Cost of Energy (LCOE) with respect to three scenarios of: 1) cost minimization with unlimited biomass feedstock, 2) cost minimization with the limited biomass feedstock and 3) profit maximization with the limited biomass feedstock.

As indicated by the model results, the proposed HRES can generate about 47.3 MWh of electricity in all scenario which is needed to meet the external load requirement in the selected study area. The LCOE of the system in scenario 1, 2 and 3 is estimated about 48.89 JPY/kWh, 55.92 JPY/kWh and 56.47 JPY/kWh, respectively. Comparison between scenario 1 and scenario 2 showed that the capacity of electrolyzer and PV module with limited biomass feedstock increases. The limited availability of biomass feedstock resulted in increasing the share of the PV panels from 45% to 90% in electricity generation mix and decreasing the share of the fuel cell from 55% to 10%. The major part of the generated electricity from the solar panels was consumed in the electrolyzer to support the required level of hydrogen consumption in the fuel cell. Comparison between scenario 2 and scenario 3 revealed the role of PV module in increasing the profit through selling back the surplus electricity to the grid, using the FiT mechanism. The model was employed to perform sensitivity analyses of the LCOE with respect to the size of solar-powered hydrogen generation system (Solar PV + electrolyzer). The result of the sensitivity analysis shows that the substitution of biomass hydrogen with solar hydrogen can significantly influence the LCOE of the system. By increasing the amount of hydrogen produced by the electrolyzer, the total cost of the system increases. Therefore, the reduction of the cost of the solar hydrogen system turns out to be by far the most important cost driver. However, under the profit maximization scenario with limited biomass feedstock, the capacity of the solar electricity increases under FiT mechanism.

Keywords: HRES (Hybrid Renewable Energy Systems), Optimization, PSO, SCWG, Solar, Biomass, FiT(Feed-in-Tariff), LCOE

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Introduction

Chapter 1: Introduction

1.1 The energy situation in Japan

The renewable energy resources have a pivotal role in achieving sustainable social development. After the Great East Japan Earthquake, Japan reduced the dependence on nuclear power because of the nuclear power accident that happened in Fukushima. The energy mix before-after the earthquake is shown Fig. 1. [1] The ratio of nuclear power in the power generation in Japan declined to 2% or less by national public trust.

Japan is one of the world's most energy consuming countries, however the energy self-sufficiency rate was significantly less than 10% in 2017 (shown Fig. 2[1]) which has become a major problem in energy security. The dependence on fossil fuel in Japan accounts for 87.4% of total energy consumption [2]. This value will reach the level of first oil shock around 1973.

Furthermore, Japan emits a lot of carbon dioxide due to use of petroleum resources. Most of carbon dioxide is emitted from industrial factories, refineries and power plants. Fig. 3 shows the transition in CO_2 emissions by each sector [3].

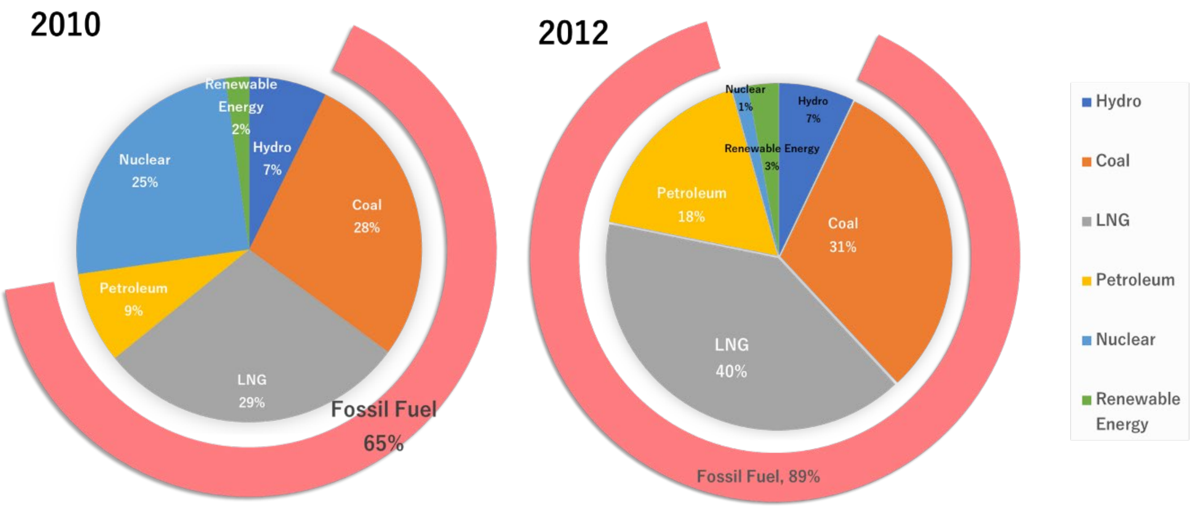


Fig. 1 Energy mix in Japan

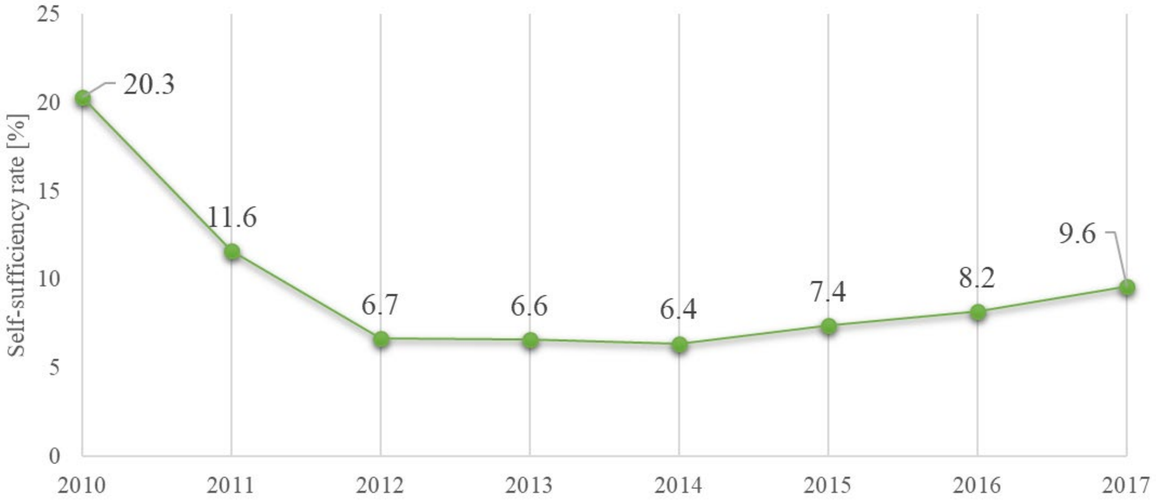


Fig. 2 Energy self-sufficiency in Japan [1]

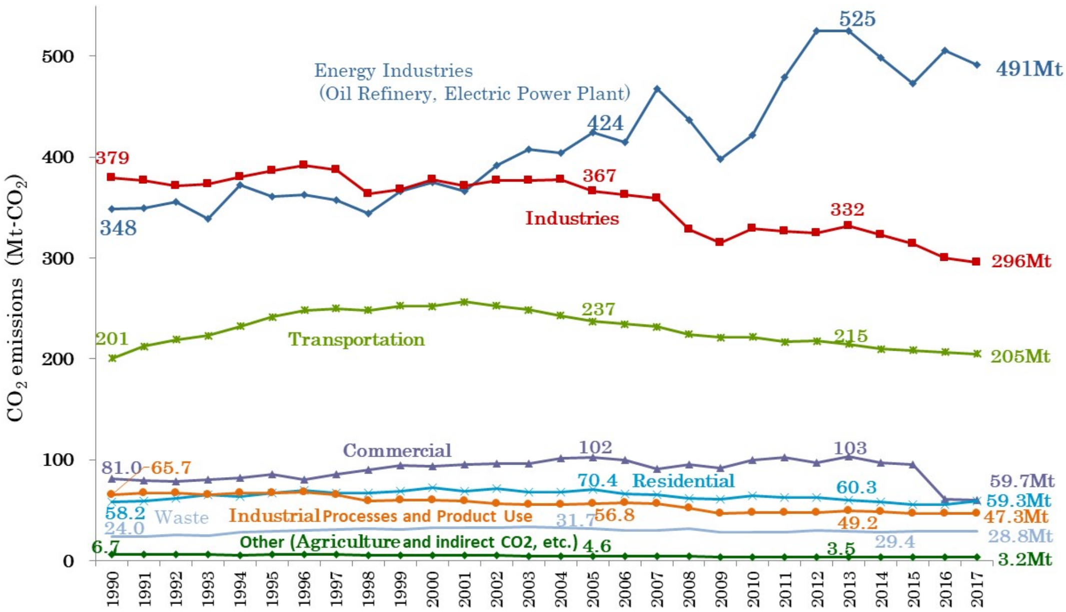


Fig. 3 Sector-wise GHG emission in Japan

Fig. 4 shows the annual solar radiation is approximately 1,000 to 1,500 kWh/m^2 around Japan, especially the relatively good sunshine environment is available in the Pacific coast and the stable power generation from solar photovoltaic (PV) can be expected in that place. The Japan government has introduced the Feed-in-Tariff scheme since 2012 in which the owners can sell back the surplus electricity generated from their installed solar panels to the grid with a fixed Tariff. Fig. 5 represents the annual introduction and installed capacity of PV in Japan. As a result, the solar power installed capacity increased to 42GW in Japan Fig. 6 shows the annual power generation per 1kW installed capacity in each prefecture in Japan [4]. The annual average power generation from residential PV modules is approximately 1,000 kWh/kW, which varies from 10% to 30% depending on the region and year.

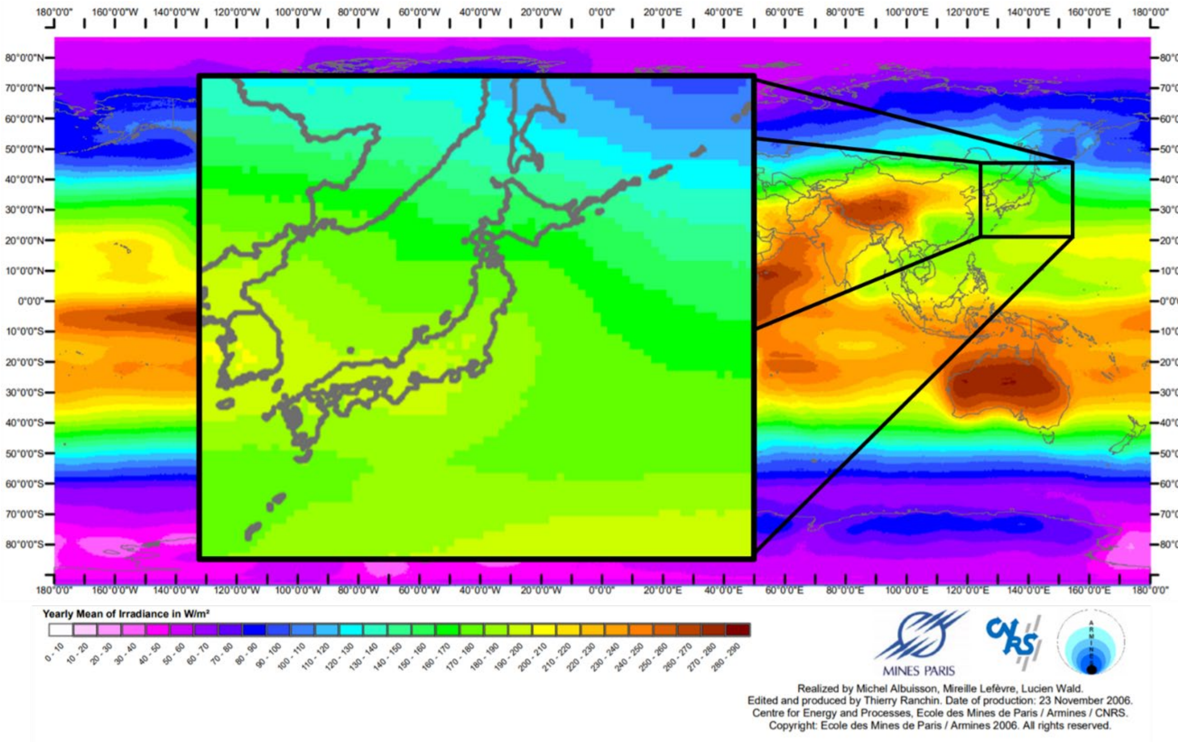


Fig. 4 Average solar radiation in Japan [5]

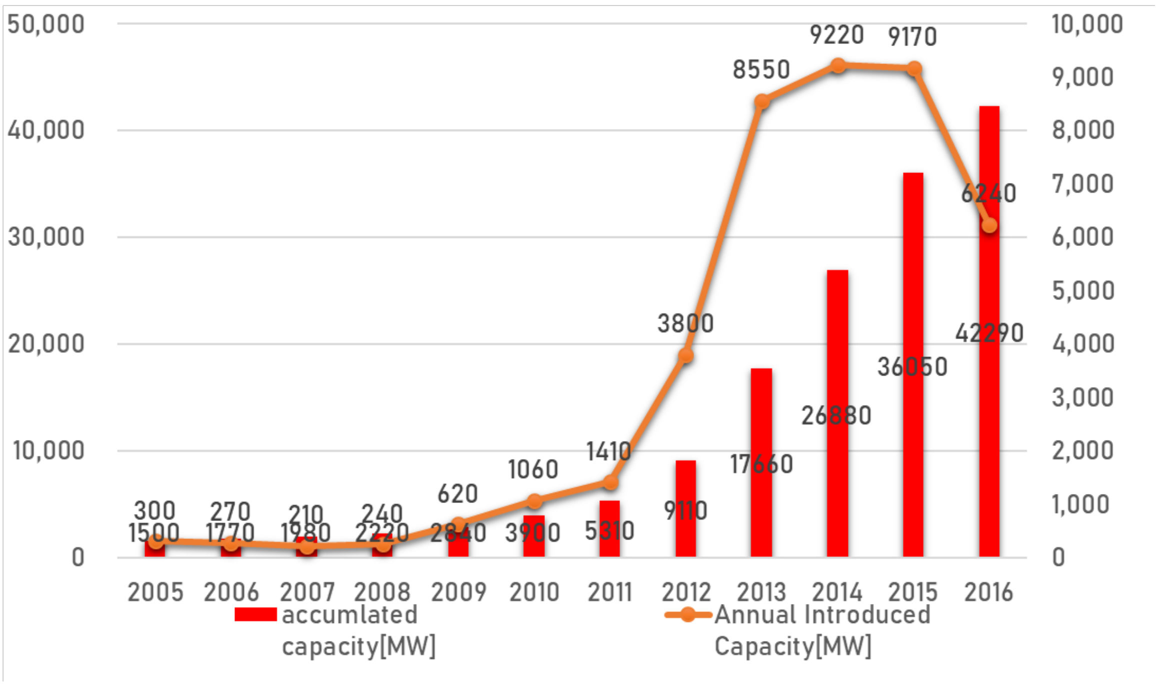


Fig. 5 The accumulated and annual installation of PV system in Japan

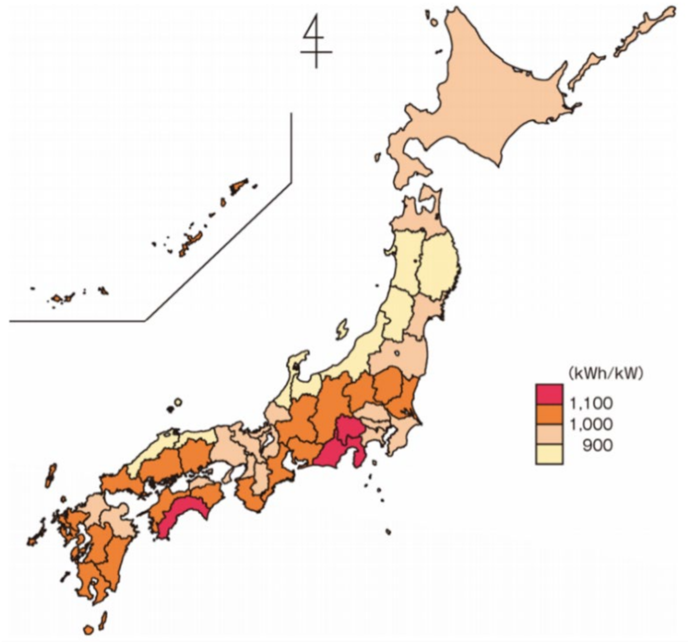


Fig. 6 Annual power generation per PV module-1kW [4]

The wind potential map in Japan (onshore and offshore) is shown in Fig. 7. Japan has an onshore area with an average 7m/s wind speed, which is less than other countries. The coastal areas which have suitable condition for a strong wind speed are located in Hokkaido, Tohoku, Kanto and Kyushu regions. The installed capacity of onshore wind turbine is reported about 290GW by METI and 280GW by MOE [1]. Hokkaido has the largest potential and accounts for about 30% of the total wind potential, followed by Tohoku area 23%, and Kyushu 11% [4]

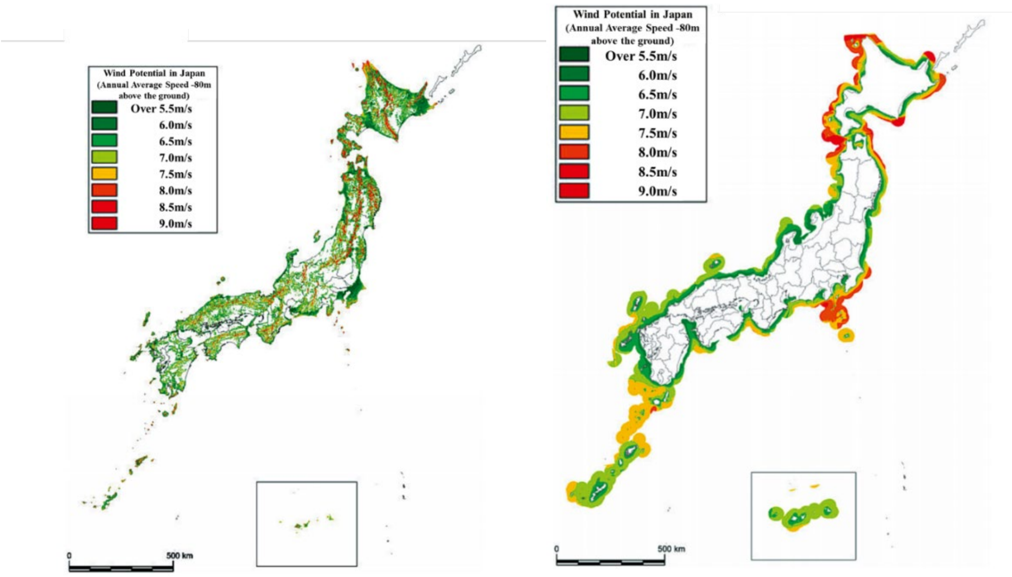


Fig. 7 The wind potential around Japan (left: Onshore, Right: Offshore) [6]

IEA reported the potential of biomass energy in all over the world [7]. According to this report, the technical biomass potential is approximated 50 - 1,500 EJ/year in 2050 which will be about 10% of the demand energy [4].

According to NEDO, the biomass energy potential is estimated to 510 PJ/year in Japan which only accounts for 3% of primary energy supply (19.8 EJ/year) and much lower than other countries. In other references, the potential of biomass energy is estimated about 530 PJ/year, and the potential of production resource crop is about 240 PJ/year [8]

1.2 Background and motivation for this study

Renewable energy resources have the possibility to become the key solution for increasing the energy self-sufficiency in Japan, through replacing fossil fuels.

Since renewable energies are from the natural environment, they are all weather dependent, which makes them vulnerable in developing a stable power system. The hybridization of variable renewables can allow for smooth, durable, and reliable output to power grids to improve the safety, reliability, and stability of dispatched power, which is cheaper than investing in single renewable technologies. Therefore, Hybrid Renewable Energy System (HRES) can be considered as one possible solution which can combine two or more renewable energy sources to produce power continuously, without interruption. Furthermore, when the HRES is connected to a storage system like battery or hydrogen storage, the excess energy generated by the renewable energies such as solar or wind can be stored and then utilized during the period when there is no sunshine and wind and electricity is not being generated. Therefore, compared to a single renewable technology, the HRES works more efficiently in all operating conditions. For example, when electricity generation exceeds demand electricity, the surplus electricity is converted to hydrogen by using electrolyzer, and stored hydrogen tank.

Some researchers have reported the different HRES which combined several components. They have categorized the HRES based on the system components, modeling approach, and solving algorithms which are showing following sentence.

Farzaneh reported a standalone power system which can provide electricity, thermal energy, hydrogen and water to the 10 detached houses in Shinchi-machi as case study. [9] This HRES includes a supercritical water gasification system for hydrogen production from wet biomass feedstock such as the aqueous sludge, kitchen waste and organic wastewater. Other components of this HRES are PV module, electrolyzer, fuel cell and hydrogen storage. The proposed HRES can provide about 47.3 MWh of electricity and about 2.6 ton of hydrogen from 98 ton of wet biomass feedstock for annual. The Levelized Cost of Energy including electricity and heat was indicated 0.38$/kWh, and reduction of carbon dioxide emission is about 21 ton for annual.

Pao et al discussed the economic analysis of HRES which consists of the biomass fermentation in order to develop standalone power system independent on weather condition. [10] This Bio-HRES can provide electric power, thermal energy and hydrogen and includes fermentation system, PV module, wind-turbine, electrolyzer, hydrogen storage and fuel cell. As a result, the total electric power available from the proposed system was estimated about 31,343 kWh per annum (19,146kWh from PV module, and 12,197kWh from wind). In addition, the thermal energy generation was estimated about 8,408kWh.The cost analysis indicated a LCOE of 0.793$/kWh including both electrical and thermal energies. Rohit et al developed a techno economic analysis for a proposed HRES which consists of a small hydro-power, solar, PV, bio-diesel and batteries in a remote village in Palari, India. [11] Their results showed that the best configuration of HRES with LCOE of 0.420$/kWh can be obtained by using PV array 14%, hydro 76% and Bio-diesel 10%. However, the hydro power has a large-scale fluctuation dependent on weather condition.

Mohammed et al implemented the PSO algorithm in order to find out the best configuration of HRES which consists of Wind turbine, Tidal turbine, PV module, Battery. [12] That system was designed to make a power balance between supply and demand with standalone operation in Brittany, France. In this report, PSO algorithm has the possibility to achieve the optimal solution, it could find out the best configuration at a time rate better than 80% of the conventional method. The optimize function was defined by several scenario of the cost minimization such as COE (Cost of Energy) and TNPC (Total Net Present Cost). This result of one scenario is based on Wind, Solar, Tidal and battery HRES, and the cost minimization result showed the COE at 0.094$/kWh.

Masoud et al reported the optimal design of HRES results based on using PSO method, including the multi-objective optimization problem such as the total cost of system, unmet load and fuel emission. [13] HRES consists of a wind turbine, PV panels, diesel generator, batteries, fuel cell, electrolyzer and hydrogen tank. They conducted the sensitivity analysis of different parameters to the developed model. The PSO method was implemented to find out the total cost minimized configuration. The results of one scenario in this study revealed the total cost of 93,487€ for 25 years, the annual supply energy of 13,407 kWh and gas oil consumption of 562 litter/year under the 4.5% of load loss probability Tab. 1 shows the references about HRES analysis that has already reported so far.

Tab. 1 Summary of the literature review about HRES

Authors	System Components								Objective Function	Method	
	WT	PV	FC	Biomass	Battery	H_2 Tank	Electrolyzer	Diesel other			
H. Farzaneh		✓	✓	✓		✓	✓		Total cost	Simulation	[9]
L.C. Pao	✓	✓	✓	✓		✓	✓		Total cost	Simulation	[10]
Mohammed	✓	✓			✓			✓	COE NPC	PSO	[12]
Masoud	✓	✓	✓		✓	✓	✓	✓	Total Cost/ CO2 Emission/ Unmet load/	PSO	[13]
Garyfallos	✓	✓	✓		✓	✓	✓	✓	Total cost	SA	[14]
Rodolfo	✓	✓	✓		✓	✓	✓	✓	Total cost/ CO2 Emission/ Unmet Load	MOEA GA	[15]
Abedi	✓	✓	✓			✓	✓	✓	Total cost/ CO2 Emissions/ Unmet Load	Fuzzy technique	[16]
Motaz	✓	✓			✓			✓	Total cost	PSO	[17]
Yashwant	✓	✓		✓	✓			✓	Total cost	GA/PSO	[18]
Orhan	✓	✓			✓				Total cost	SA	[19]
Raquel	✓		✓		✓	✓			LEC	LP + Heuristic	[20]
Akella	✓	✓		✓					Operation Cost	LP	[21]
Eliliston	✓	✓		✓	✓				Annualized Cost	GA	[22]
Bernal	✓	✓	✓		✓	✓	✓	✓	Total cost	GA	[23]

In the case of the economic analysis, the total cost of system (including investment cost, operation and maintenance cost and fuel cost) and LCOE (Levelized cost of electricity) is considered as the objective function. The LCOE is a standard index that is calculated based on the estimated power generation during the operation lifetime by adding up the costs and profits necessary for power generation such as investment cost, operation and maintenance cost and fuel cost.

This research aims at introducing a novel HRES which consists of a solar panel, a gasifier system which works based on the Supercritical Water Gasification (SCWG) of biomass feedstocks, a hydrogen tank, a water electrolyzer and a fuel cell which is fed by the Hydrogen to provide power and heat. The proposed system was designed to minimize the mismatch between electricity demand and supply in a selected household area in Shinchi-machi of Fukushima-Prefecture, Japan. To this aim, a mathematical model based on the Techno-Economic Analysis (TEA) was developed which can be used to verify the balance of electricity and hydrogen generation for securing the operation feasibly during system lifetime.

In this study, the hydrogen is considered to function as an energy storage medium, by storing renewable energies, until the fuel cell converts it to electricity. The Hydrogen provided from two sources feed the fuel cell: 1) a water electrolyzer and 2) a SCWG which generates hydrogen from biomass gasification via hydrothermal conversion route [24]. The SCWG uses water as the gasifying agent at its supercritical condition to decompose the organic biomass such as kitchen waste and organic biomass to hydrogen, carbon dioxide, carbon monoxide, and methane gas, allowing to achieve very high volumetric hydrogen ratio.

In addition, SCWG can resolve some problems facing the conventional biomass gasification. The steam reforming and fermentation are typical as the conventional methods for biomass gasification. However, in the case of steam reforming, the water content of the biomass feed influence on the efficiency of the gasification, since this method needs to dry process for the biomass. [25] The fermentation is implemented by microbiota that decomposes organic substance. It needs time because of the ability of decomposition by microbiota is limited. Then, the smell when microbiota decompose the organic substance is also problem. SCWG process can breakthrough such problems.

This thesis is structured as follows: First chapter addresses the energy situation in Japan and background and motivation for this study, in the Second chapter, the technical design and system simulation of the HRES is introduced in detail. In the Third chapter, the designing of the HRES beyond economic optimization will be discussed based on using the PSO algorithm and forth chapter addresses the case study for the HRES operation and cost analysis. In the end of this chapter, the results of techno-economic analysis show the best configuration of this HRES. Finally, Chapter 5 shows the summary of this study and discussion about economic analysis results of this study.

Chapter 2

Technical design and system simulation of the HRES

Chapter 2: Technical design and system simulation of the HRES

2.1 Classification of HRES based on Hydrogen generation

HRES often has the hydrogen supply chain for adjusting the generated electricity and demand. For example, the PV module as the main power generators of HRES generates more electric power during the daytime, however the peak time of demand electricity is the nighttime. It is required to store surplus power in the battery storage banks or producing hydrogen by using water-electrolyzer.

Furthermore, HRES has other flexibility for producing hydrogen from other resources. There are four hydrogen production ways mainly: 1) water-electrolyzer, 2) Steam reforming with fossil fuel, 3) biomass gasification, 4) byproducts from industrial factory. The most reasonable way to produce hydrogen in a standalone HRES is biomass gasification. The classification of hydrogen production is shown in Fig. 8 .

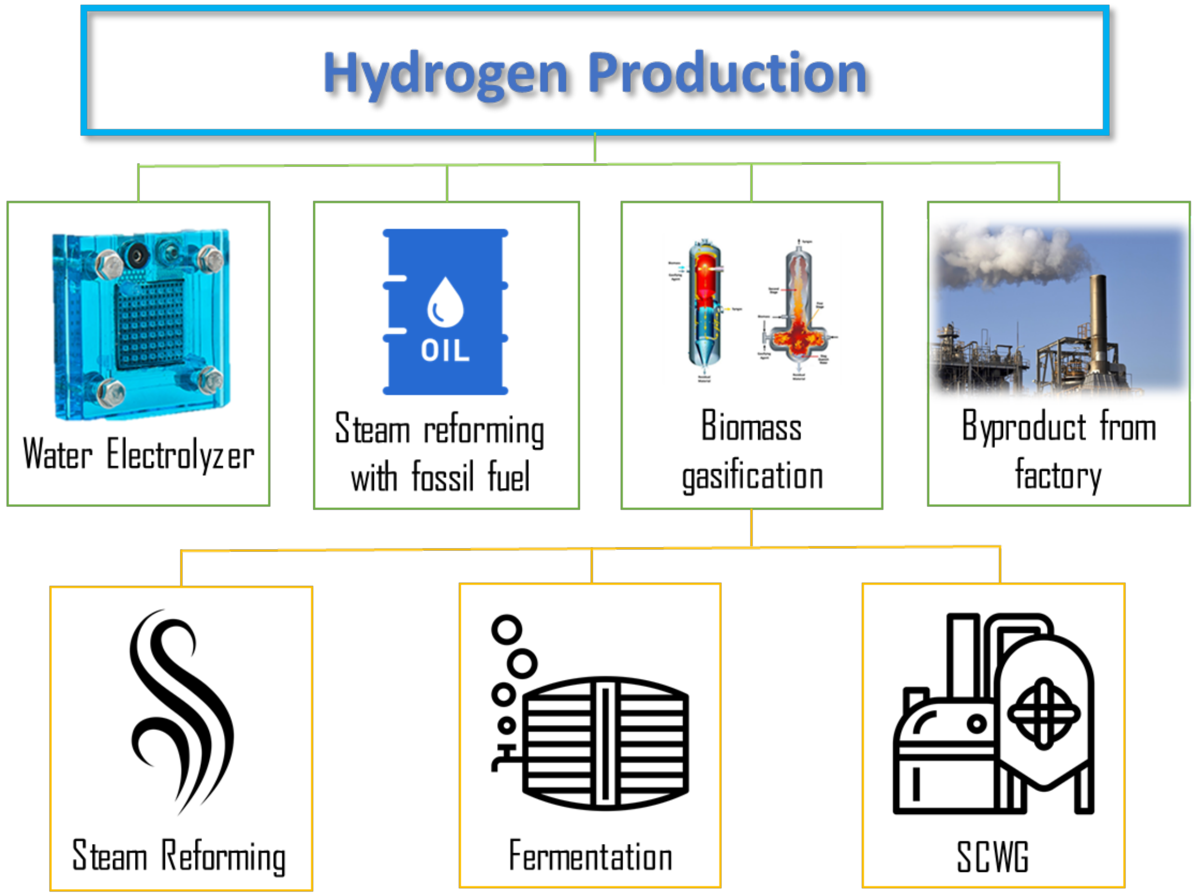


Fig. 8 Classification of hydrogen production method

The traditional methods for hydrogen production from biomass include: 1) the thermal decomposition under high temperature and 2) fermentation technology under anaerobic conditions. In thermal decomposition process, the biomass feedstock is heated up to 1073K-1273K [26]. To increase the hydrogen production efficiency, pretreatment and drying process should be considered in this method.

The fermentation technology is an anaerobic decomposition process of biomass to produce hydrogen. There are two problems with this method 1) long-time process and 2) Difficulty of residue and waste water treatment.

One of the recent technologies which is used to produce hydrogen from biomass feedstock is Supercritical Water Gasification (SCWG). This process gasifies biomass feedstock in the supercritical water which reaches to its critical point (374°C, 22MPa) to produce the syngas including carbon dioxide, carbon monoxide, methane and hydrogen. This technology has possibility to decompose completely biomass, without using any treatment system for residue and waste water. Therefore, this technology is one of the suitable options which can be used for hydrogen production in HRES.

2.2 System integration in this study

The system configuration of the proposed HRES in this research is depicted in Fig. 9.

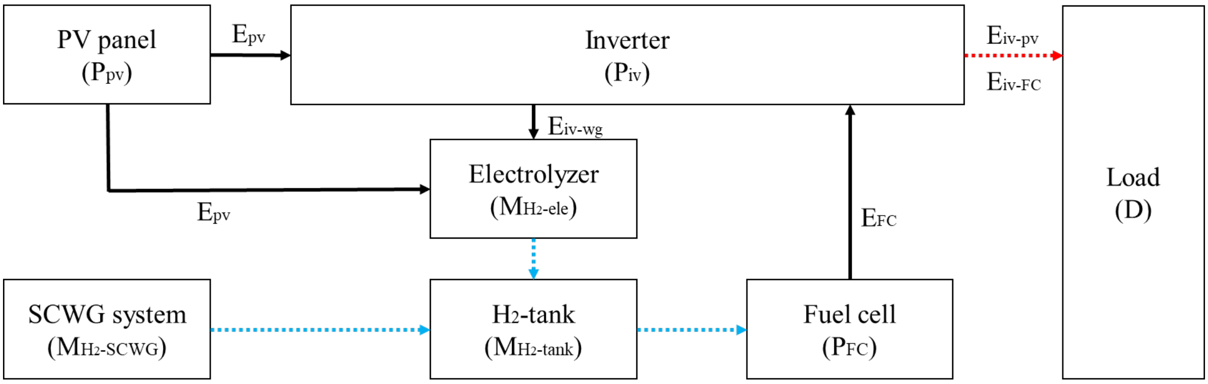


Fig. 9 Proposed system configuration

The proposed HRES is based on the combination of hydrogen generation from two sources: 1) SCWG process of the residential kitchen waste and organic wastewater and, 2) solar water electrolysis process which uses the surplus electric power generated by the solar cells. The fuel cell converts hydrogen into electrical power, which can be used during the periods when the sunlight is not available. So, the proposed HRES forms a composite energy system capable of all-weather conditions.

1) The solar PV supplies sufficient generated energy. The use of this energy to supply the load has preference over using the Fuel Cell. The extra energy generated by the solar PV is used in the water electrolyzer to generate hydrogen which will be stored in the hydrogen storage. 2) Electrolyzer can convert the surplus electricity from PV module to hydrogen by electrolysis of water. 3) Fuel cell has a pivotal role to make the energy balance to produce the electric power from hydrogen when the solar electricity is insufficient to match the load. There are different types of fuel cell including: PEMFC (Proton Exchange Membrane), SOFC (Solid Oxide), PAFC (Phosphoric Acid) and MCFC (Melting Carbon). In this research, PEM is considered as

a suitable type of fuel cell.

4) SCWG (Supercritical Water Gasification) uses water over 22 MPa and 374 ^{0}C (critical point) as the gasifying agent to decompose the wet biomass feedstock, allowing to achieve a much higher ratio of gasification and hydrogen generation. Organic wastewater and kitchen waste are considered as possible sewage sludge which do not need any drying step, resulting in economically beneficial characteristics of the hydrogen production. However, the SCWG analysis need information which includes moisture content and the mass fraction of biomass. Followings are main steps in a SCWG system:

a) Collecting waste material source of Biomass

b) Pre-treatment for biomass

c) Decomposing biomass feed to gases (CO, CO2, CH4, H2)

d) Purification for hydrogen

The hydrothermal gasification in SCWG needs the large amount of water, which needs to be heated. The heat required to reach, e.g. 873 K can exceed the energy content of the applied biomass and which should be provided by the HRES, itself

5) Hydrogen tank: The hydrogen generated from water-electrolyzer to use the surplus electricity from renewable energy device and SCWG system process can be stored in a hydrogen storage. There is various method for hydrogen storage such as the compressed, liquification, and absorption to mixed metals.

In comparison with other stand-alone power systems, the main superiorities of the proposed HRES can be addressed as follows:

The HRES, itself can provide the electric power which is needed for the pre-treatment devices and auxiliary systems (i.e., pumps, mixer, etc.),

•the off-gas produced by the SCWG includes a rich mixture of carbon monoxide and hydrogen which can be used to bring the feedstock to the required reactor inlet temperature,

•the surplus electricity from the HRES is available for export or other in-plant uses.

2.3 Simulation Module

2.3.1 PV module

The photovoltaic effect is the generation of electric power in a material exposure to light and is a physical and chemical phenomenon. This reaction is happened in the interface of semiconductor which has a rectification effect, for example the p-n junction of semiconductor and the Schottky barrier junction between semiconductor and metal materials. These interfaces have an internal electric field. The conducting electron increases by the light to the interface (Internal photoelectron effect), these electrons are separated from electron-hole by the internal electric field. These carriers can be configured photoelectron flow from pole to outside. Here, we explain the p-n junction of semiconductor reaction in detail.

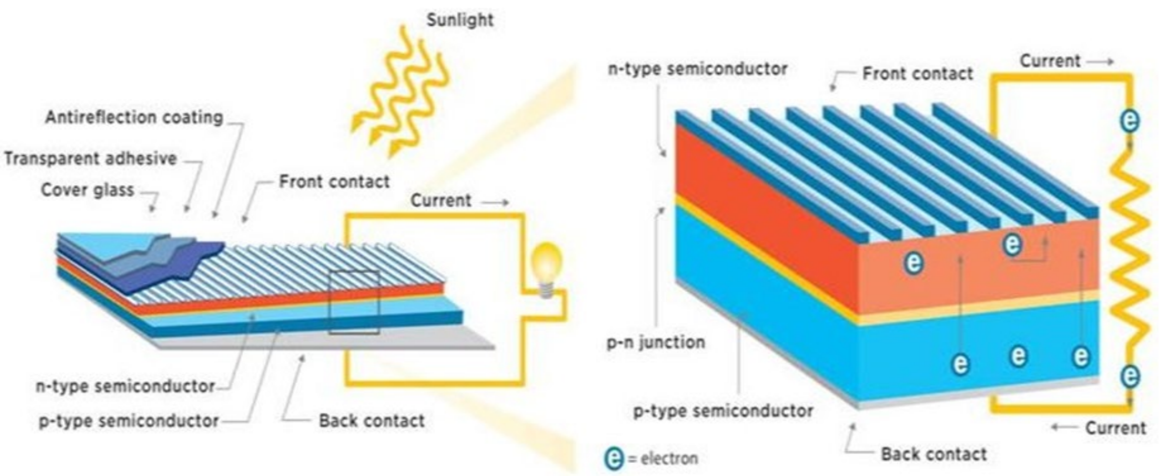


Fig. 10 Conceptual diagram of photovoltaic effect [27]

1. When the combine p-type semiconductor and n-type semiconductor, the conduction electron and the electron carriers are combined. Then, these masses are diffused, and the diffused current flow happens.
2. As a result, the combination of electron and hole, the area in which there are a few carriers in is appeared around the interface. Moreover, internal electric field force to move each carrier back to the original area (p or n).
3. In the state of thermal equilibrium, diffusion current flow balance to drift current flow. And then, fermi-level become constant.
4. When the light which has bigger energy than bandgap of semiconductor irradiates to p-n junction, the electron on balance band absorb it. After that, the electron is excited over band gap and becomes a conduction electron(photoelectron). The electron hole remains after the reaction. The drift current flow is increased by appearing photoelectron, and the thermal equilibrium cannot keep the balance. Through series of reactions, photoelectrons are moved to n-type semiconductor, the electron holes are moved to p-type semiconductors by the internal electrical field which is formed in the depletion layer. The electromotive is happened by these carriers moving.
5. If we attach pole to n and p-type semiconductors, we can get the direct current flow into the outside of these semiconductors.

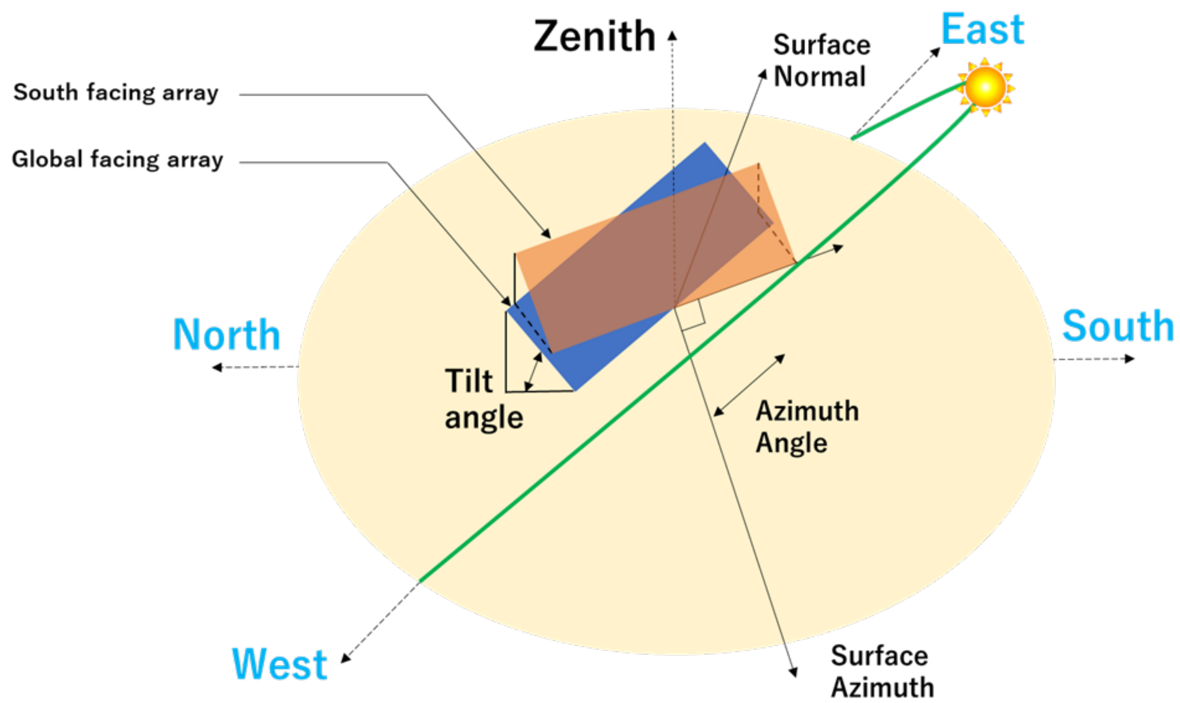


Fig. 11 Relationship between sun path and plate angle

The PV array power output can be calculated using the following formula [28]:

$$P_{out}=P_{max}F_{PV}\left(\frac{\bar{I}_T}{\overline{G_{T,STC}}}\right)\left[1+\alpha_p(T_c-T_{c,STC})\right] \tag{1}$$

$$T_c=T_a+G_T\left(\frac{T_{c,\,NOCT}-T_{a,\,NOCT}}{G_{T,NOCT}}\right)\left(1-\frac{\eta_{cell}}{\tau\alpha}\right) \tag{2}$$

Where, P_{max} is the rated capacity of a PV module under standard test conditions, and F_{PV} is the PV derating factor which is dependent to PV surface conditions such like clearness. $\overline{I_T}$ is the incident radiation to the PV surface, and $\overline{G_{T,STC}}$ is the incident radiation under standard conditions; which equals to 0.8 kW/m^2 [28]. α_p refers to the cell temperature coefficient [%/°C]. T_c is the cell temperature inside PV module in each time step which is calculated by Eq. 2. $T_{c,STC}$ is the PV cell temperature under standard conditions (25°C); T_a indicates the ambient temperature; $T_{c,\,NOCT}$ is the nominal operating cell temperature of the PV module; $T_{a,\,NOCT}$is the ambient temperature at which the NOCT (Nominal Operating Cell Temperature) is defined which value equals to 20°C [28]; η_{cell} is cell efficiency which can be assumed to equal to the maximum power point efficiency η_{max} .

The incident radiation to the PV surface is a function of the ambient condition, time, and period of earth revolution which can be calculated by using below equations [29]

$$I_T=I_{grobal}\left\{\left(\cos\theta+\mu\cos\frac{\psi}{2}\right)+\rho\left(\cos\kappa+\mu\sin^2\frac{\psi}{2}\right)\right\} \tag{3}$$

Where, I_{grobal} is global irradiance on a surface perpendicular to the vector of sunlight; μ is diffuse portion constant for calculation of diffuse radiation as a part of incident radiation; ψ is the tilt angle between the ground which is parallel to horizon and PV panel; ρ is the reflection index that is dependent to ground condition; θ is the angle between the solar rays and κ which is the sun zenith angle; these values are calculated by using the following equations:

$$\cos\theta = \cos\psi\cos\kappa + \sin\psi\sin\kappa\cos(\lambda\text{-}\zeta) \quad 4$$

λ and ζ indicate sun azimuth on the celestial sphere and plate azimuth angle. (Radians East >0 and West <0)

$$\cos\kappa = \sin\delta\sin\gamma + \cos\delta\cos\gamma\cos\alpha \quad 5$$

$$\tan\lambda = \frac{\sin\alpha}{\sin\gamma\cos\alpha\text{-}\cos\gamma\tan\delta} \quad 6$$

$$\delta = -23.45\cos\left(\frac{360}{365}\times(d+10)\right) \quad 7$$

$$\alpha = 360/24\times(24T-12) \quad 8$$

$$T = \text{Local Time}+EOT\text{-}4L_{local}+60T_{zone} \quad 9$$

$$EOT = -9.87\sin 2\beta + 7.53\cos\beta + 1.5\sin\beta \quad 10$$

$$\beta = \frac{360}{364}\times(d\text{-}81) \quad 11$$

Where, δ is the solar declination angle on the celestial sphere, which is concerned sun altitude; γ is the latitude in the observed point; α is the solar angle; *d* is the day number when January 1st in each year is 1; T is the solar time and identified by Eq.9. *Local Time* is the local standard time in observed point; EOT is the equation of time to express the relationship earth's revolution speed around the sun (minutes); L_{local} is longitude in observed point and T_{zone} is the time difference to GMT (Greenwich Mean Time). Fig. 12 shows the flowchart of PV module calculation in this study.

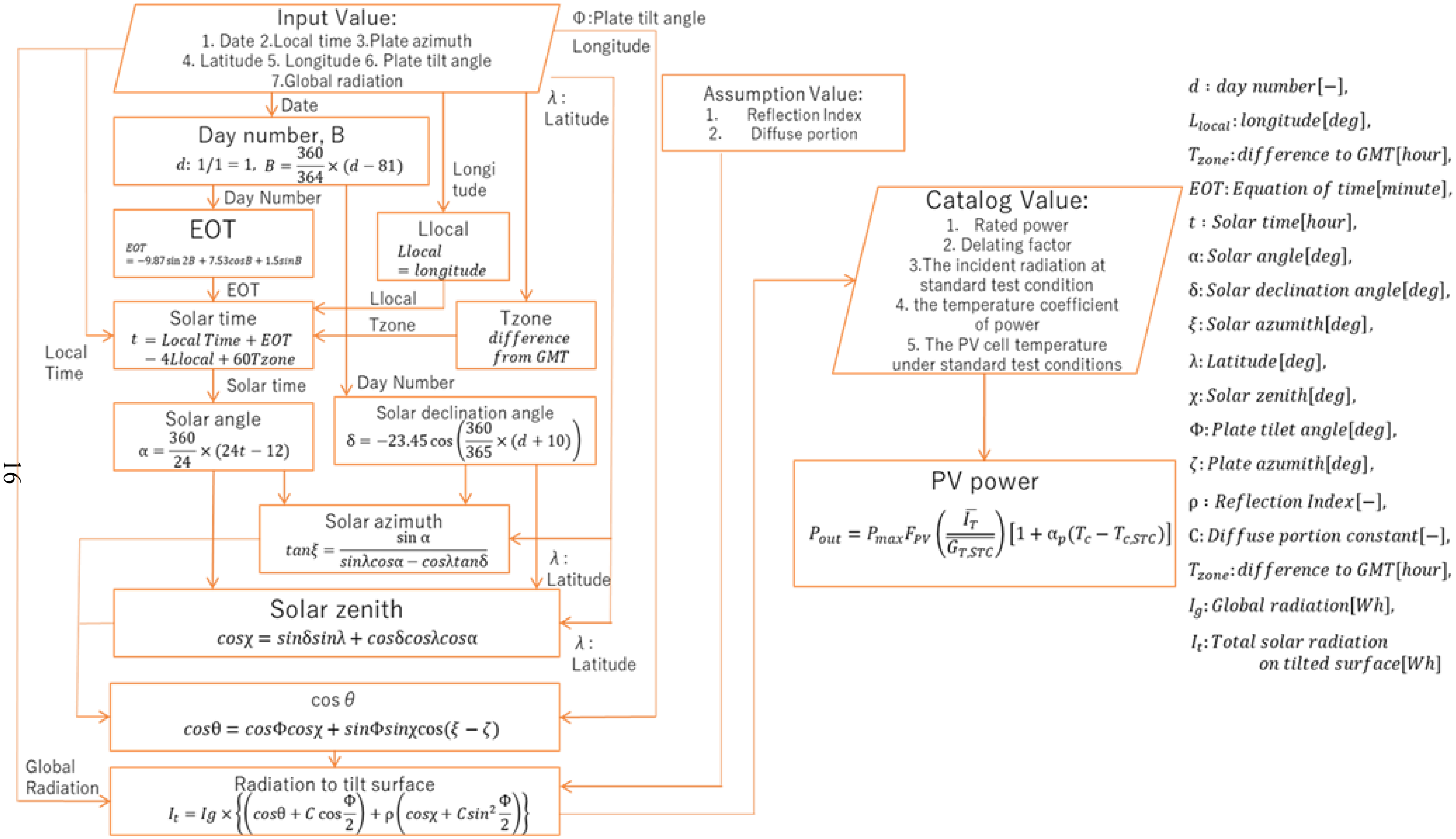


Fig. 12 Flowchart of PV module calculation

2.3.2 Fuel Cell

Proton Electrolyte Membrane Fuel Cell (PEMFC) is one of the represented methods in field of the fuel cell technology. Recently, PEMFC is used for several applications such as automotive, aerospace power and residential fuel cell. Fig. 13 shows the PEMFC typical schematic representation based on water using and acidic polymer membrane as the electrolyte. [30] The basic construction of PEMFC is fuel pole as negative, polymer membrane, air pole as positive.

In the fuel pole, the fuel such as the hydrogen and methanol are provided and the chemical reaction that decomposes from molecular to electron and proton. After that, the proton passes through the electrolyte membrane, and electron is released for load wire as electric current and moving air pole. Generally, the platinum is used as the catalyst in this fuel cell and this is the main reason that PEM cost is expensive.

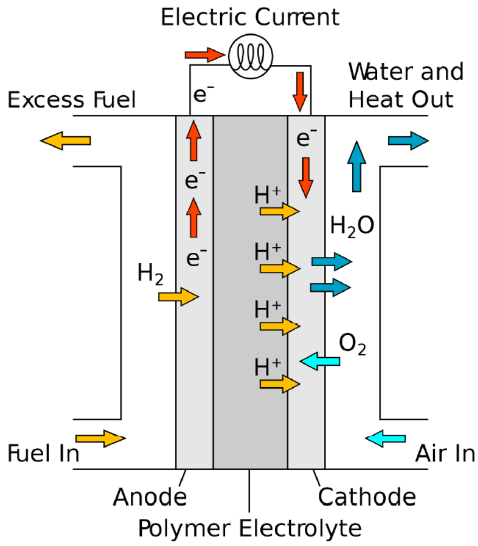


Fig. 13 Schematic of PEM fuel cell

Polymer membrane has a behavior that the generated proton in the fuel pole moves to the air pole. In the membrane, protons are hydrated and move on sulfonic acid groups. Therefore, moisture in the membrane moves from the fuel electrode to the air electrode. Therefore, fuel pole needs to include moisture, and this property makes to be difficulty in PEMFC operation if the working temperature is over 100 degree, or less than 0 degree.

In the air pole, the proton comes from the electrolyte membrane and the electron comes from conductor wire are reacted with oxygen in the air and producing water. It performs the following chemical reaction.

$$\mathbf{4H^+}O_2\text{+}4\mathbf{e^-} \rightarrow \mathbf{2}H_2O \qquad 12$$

However, this oxygen and 4-electron reduction is not efficient, it becomes the reason to drop down the electromotive of the fuel cell, in fact.

The fuel cell can obtain about 1.2 V in theoretical approach, there is loss of electro pole reaction and it causes the voltage to become 0.7 V in actual [31]. However, PEMFC has these advantages; 1) The starting time is short because of the start-up is occurred in standard temperature 2) The cell and stack size are compact 3) High safety with the working temperature is low. It is the reason to use PEM for residential power resources.

The fuel cell which converts the chemical energy of hydrogen and oxygen to electrical energy operates as a backup of the main power components such as the PV panel and Wind turbine in a HRES. The output power of the fuel cell is proportional to the rate of hydrogen consumption

(m_{H_2}) [31]:

$$P_{FC}=N\cdot I_{FC}\cdot E_{FC} \quad (13)$$

N is the number of cells, and I_{FC} is the current flow of cells. E_{FC} refers to the electromotive energy of fuel cell which is calculated as follows:

$$I_{FC}=\frac{2F\left[\frac{s\,A}{mol}\right]}{N[-]\cdot \upsilon[-]\cdot M\left[\frac{g}{mol}\right]} m_{H_2}\left[\frac{g}{s}\right] \quad (14)$$

$$E_{FC}[V]=E_0-b(\log(i)+3)-R_{ohmic}i-me^{8i} \quad (15)$$

Where, F is Faraday constant; υ is the stoichiometry of the reaction; M is the molecular mass of hydrogen; i is the current flow density which is a function of the reaction area (A) as follows:

$$i=I/A \quad (16)$$

And b is the Tafel slope: The equation shows Eq. 17

$$b=\frac{1}{2}\frac{nF}{RT} \quad (17)$$

n is the number of exchanged electrons in the reaction; T is the working temperature of fuel cells. Generally, the range of working temperature of PEM (Polymer Electrode Membrane) Fuel cells is between 353.15[K] (80[°C]) to 393.15[K] (120[°C]).

In Eq. (16), E_0 is the open-circuit voltage (OCV). This value is dependent on the working cell temperature:

$$E_0= -G/nF \quad (18)$$

$$G[kJ/mol]= 0.052T[K]-244.277\left[\frac{J}{mol}\right] \quad (19)$$

When working temperature increases, the absolute value of Gibbs free energy decreases. The ohmic loss in Eq. 20 can be calculated by using the below equations

$$R_{ohmic}=r_m[\Omega\ cm]L_{mem}[cm] \quad (20)$$

Where, r_m refers to the specific resistivity for the flow of hydrated protons, and L_{mem} is the thickness of the polymer membrane as given in [32].

$$r_m=\frac{181.6\cdot(1+0.03i+0.062\cdot\left(\frac{T}{303}\right)^2\cdot i^{\frac{5}{2}})}{(\lambda-0.634-3i)\cdot\exp(4.18\cdot(\frac{T-303}{T}))} \quad (21)$$

$$\lambda=\begin{cases} 0.043+17.81\cdot a_{H_2o} -39.85\cdot a_{H_2o}^2+36.0\cdot a_{H_2o}^3, & 0<a_{H_2o} <1 \\ 14+1.4\cdot(a_{H_2o} -1) & 1<a_{H_2o} <3 \\ 2 & a_{H_2o} >1 \end{cases} \quad (22)$$

$$a_{H_2O}=P_{H_2O}/P^{sat}{}_{H_2O} \quad (23)$$

$$\log_{10}P^{sat}{}_{H_2O}=-2.179+0.040\cdot(T-273.15)-9.184\cdot10^{-5}\cdot(T-273.15)^2+1.445\cdot10^{-7}\cdot(T-273.15)^3 \quad (24)$$

The coefficient m is estimated by the following equation.

$$m=\begin{cases} 1.1\times10^{-4}-1.2\times10^{-6}\times(T-273.15), & 312.5[K]<T \\ 3.3\times10^{-3}-8.2\times10^{-5}\times(T-273.15), & 312.5[K]>T \end{cases} \quad 25$$

Fig. 14-Fig. 16 show the I-V curve for a PEMFC. It can be observed from Fig. 14 that voltage decreasing with the current flow increasing. Fig. 15 shows the voltage loss breakdown of the fuel cell. The ohmic loss is linearly proportional to the current flow density function. The voltage dropping down of the fuel cell is caused by the delaying the gas diffusion at the electric pole. This phenomenon is dependent on the reaction area internal one fuel cell.

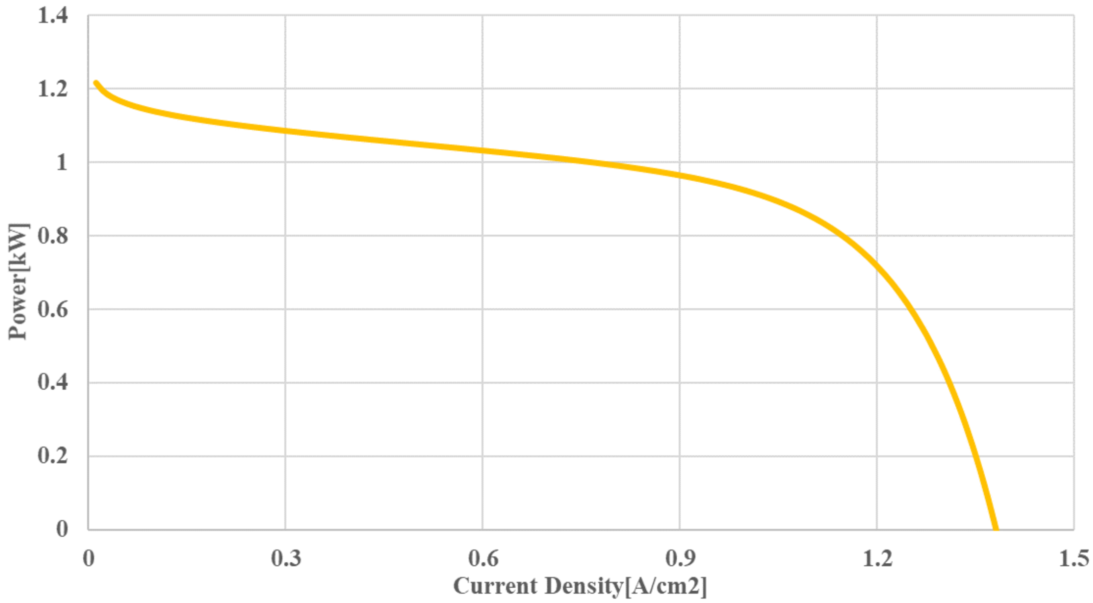


Fig. 14 I-V curve of the fuel cell

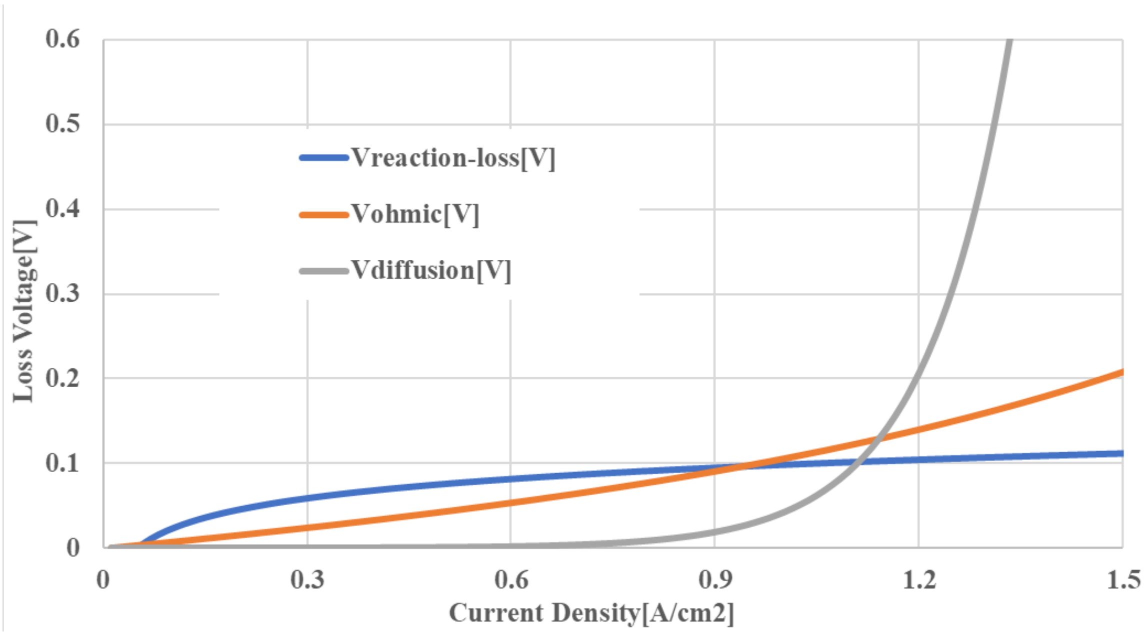


Fig. 15 Loss voltage of the fuel cell

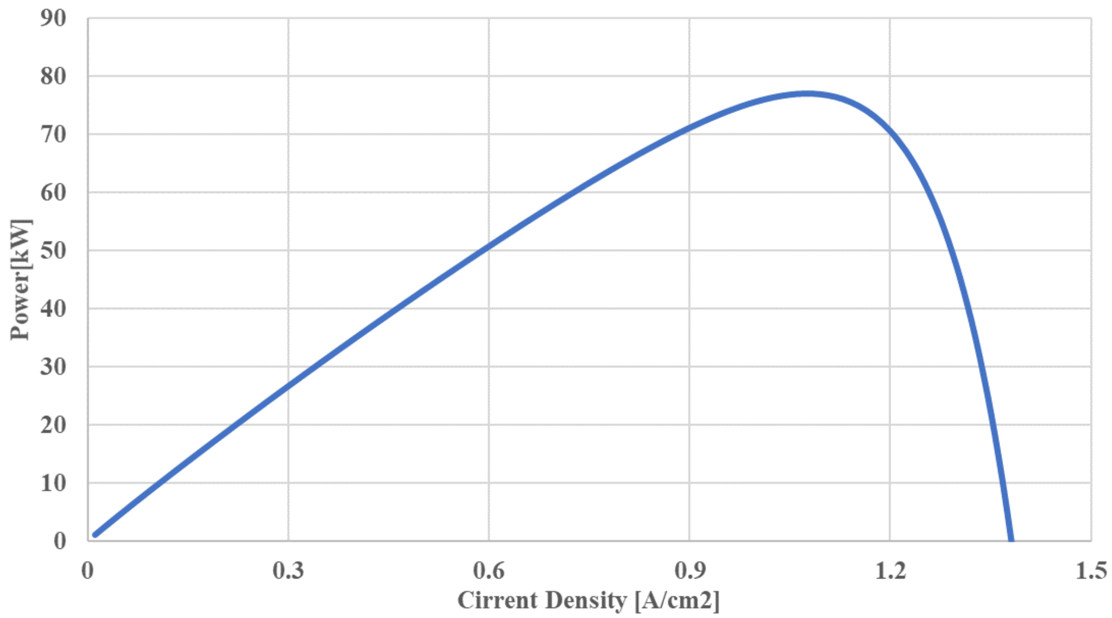


Fig. 16 The power curve of the fuel cell

2.3.3 Electrolyzer

In a water electrolyzer, water is spitted into hydrogen and oxygen by using electricity. The electricity consumption ($Elec_{EL}$) of the electrolyzer is identified as a function of rated hydrogen flowrate ($Q_{n\text{-}H2}$) and actual hydrogen flowrate (Q_{H2}) [33]:

$$Elec_{EL}=A_E Q_{n\text{-}H_2}+B_E Q_{H_2} \quad 26$$

Where, A_E and B_E are the electricity consumption curve coefficients of the electrolyzer. The efficiency of electrolyzer is calculated as follows:

$$\eta_{El} = (Q_{H_2} \times HHV_{H_2}) / Elec_{EL} \quad (27)$$

Where, HHV_{H_2} = 39.4 [kWh/kg], $A_E = 20$[kWh/kg] and B_E = 40[kWh/kg] from Ref. [33]

2.3.4 Hydrogen tank

The amount of hydrogen in the storage tank at each time step t is dependent to hydrogen quantity at a previous step (t-1), the hydrogen inflow from the electrolyzer and SCWG at time step t(Q_{H2}), and hydrogen outflow to the fuel cell at the time (t) [34]:

$$H_{2_{level}}(t) = H_{2_{level}}(t-1) + Q_{H_2}(t) - m_{H_2}(t) / \eta_{H_2\text{-tank}} \quad (28)$$

$\eta_{H_2\text{-tank}}$ is hydrogen tank efficiency when releasing hydrogen to fuel cell. And the hydrogen tank has the minimum ($H_{2\text{-min}}$) and the maximum limit ($H_{2\text{-max}}$) of hydrogen level; $H_{2\text{-min}}$ can be assumed 5%, and $H_{2\text{-max}}$ is 90% of this capacity of hydrogen tank.

2.3.5. SCWG

Hydrogen is primarily produced by using the steam reforming method from hydrocarbons such as natural gas. Steam reforming is a chemical method for producing syngas which is mixed hydrogen and carbon monoxide. Methane reformer is generally used in industry to make hydrogen. This method is one of the most energy efficient ways to produce hydrogen. The reason is that hydrogen yield from steam reforming is generally higher than 50% at the temperature higher than 600°C. However, this method requires an external heat source, using fossil fuels. [35]. Another way of hydrogen production is fermentation that can be considered for hydrogen production. This method is the fermentative conversion of organic substrates to hydrogen which called biohydrogen. The conversion is affected by bacteria and protozoa. But this method is faced some problems such as long-time process and bad smell.

The physical properties of water at supercritical condition are shown in Fig. 17 [36]. In the case of water, the critical point is around 374°C and 22.1MPa. Over the temperature and pressure of this point, the characters of each parameter change slightly. The hydrocarbon solubility increases immediately over the 350°C and the inorganic solubility decreases over the 380°C. At the supercritical condition, the lower density of water enables SCWG reactor to decompose the biomass feedstock at a faster rate than ideal gases, resulting in the production of hydrogen and methane-rich gases. To reach the supercritical condition, an external thermal source is required SCWG produces syngas , including methane and carbon monoxide as the byproduct of the gasification reaction which can be burned in a fired heater to provide the required thermal energy for the supercritical gasification of water. [9]

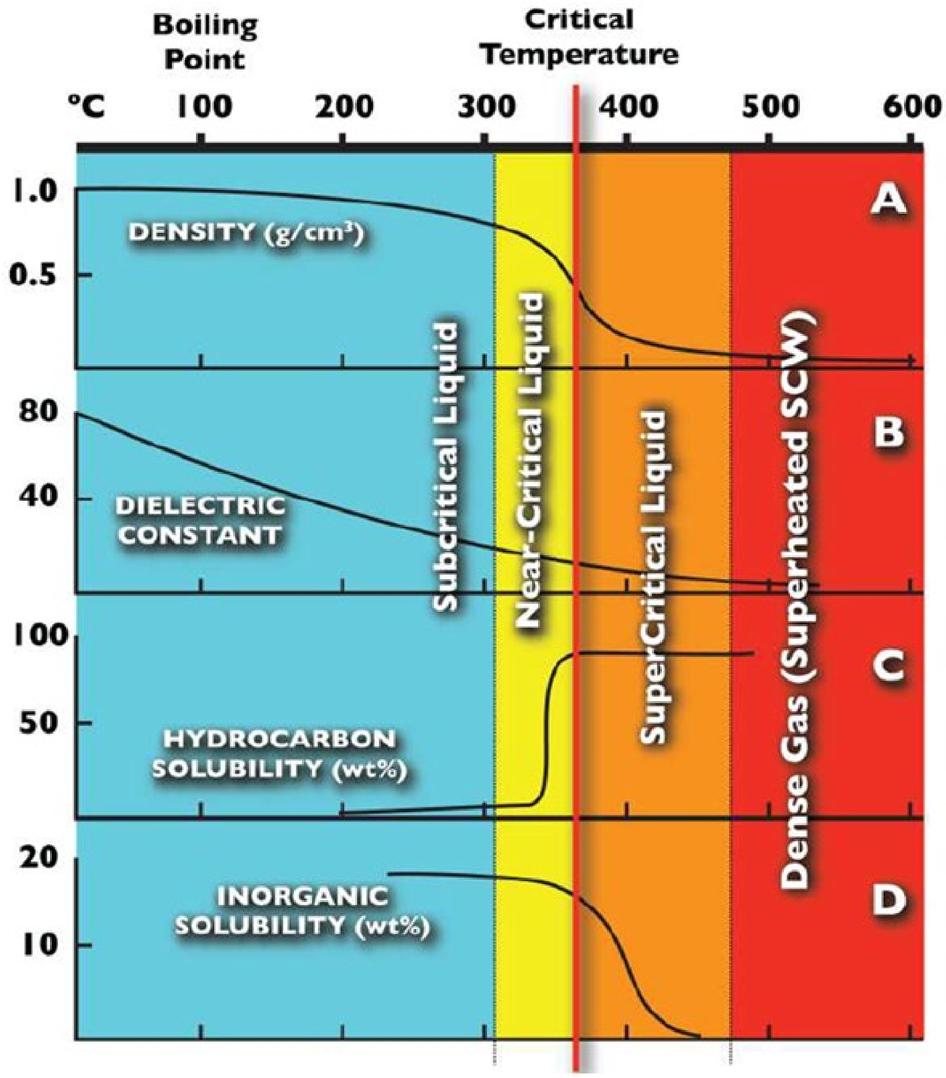


Fig. 17 Physical property of Supercritical water [36]

The K-value model is used to determine the species and their amounts of the biomass supercritical gasification reaction in the equilibrium state at a specific temperature and pressure: which is expressed by the following equation. [37]

$$\boldsymbol{K_i = \prod_{j=1}^{N} a_j^{v_j}} \quad (29)$$

The calculation of hydrogen production is required the mass composition of products from reaction and the biomass feedstock in detail. The assumed basic reaction kinetic of glucose in a SCWG reactor is represented below:

$$C_cH_xO_y + wH_2O \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4H_2O + x_5CH_4 \quad (30)$$

Where c, x, and y are given as mole fractions of the biomass feedstock such as glucose. w refers to the mass flow rate of water used in the gasification reaction. The element balances of carbon, hydrogen, and oxygen elements are given below:

$$x_1 + x_3 + x_5 - c = 0 \quad (31)$$

$$x + 2w - 2x_2 - 2x_4 - 4x_5 = 0 \quad (32)$$

$$y + w - x_1 - 2x_3 - x_4 = 0 \quad (33)$$

Since there are just three element equations for five variables, two more equations would be needed here. In this study, two thermodynamic equilibrium reactions of water-gas shift and methanation are considered, and their equilibrium constants are defined as the function of their partial pressures [38]:

$$\mathbf{K_1}=\frac{x_{H_2}x_{CO_2}}{x_{H_2O}x_{CO}} \quad 34$$

$$K_2=\frac{x_{CH_4}}{\left(x_{H_2}\right)^2} \quad 35$$

The values of K_1 and K_2 are dependent on working temperature under SCW (SuperCritical Water) reaction. In the SCWG, K-values can be also expressed by Eq. 32 – 33 as follows:

$$\ln K_1=\frac{7082.848}{T}+(-6.567)\ln T+\frac{7.466\times10^{-3}}{2}T+\frac{-2.164\times10^{-6}}{6}T^2+\frac{0.701\times10^{-5}}{2T^2}+32.541 \quad 36$$

$$\ln K_2=\frac{5870.53}{T}+1.86\ln T-2.7\times10^{-4}T+\frac{58200}{T^2}-18.007 \quad 37$$

Here, the feedstock is assumed as kitchen garbage from households. The result of ultimate analysis for a food waste sample with a moisture content at 70 % and includes the mass compositions of: C=48%, H=6.4% and O=37.6% [38]. The chemical formula from above composition shows $C_{108}H_{171}O_{63}$ from the amount of 1 mol wasted foods. (dry basis)

Then, general equation of this reaction is shown Eq. 27, where, C =108, H=171 and O=63 in this study. And w is the molecular quantity of water per 1 mol. $x_1 - x_5$ shows stoichiometric number of each substance; 1. carbon monoxide 2. hydrogen 3. carbon dioxide 4. Methane 5. Water; In this study, nitrogen is not considered in the reaction equilibrium. [38] The flowchart how to calculate SCWG model is shown in Fig. 18.

The influence of reaction temperature and biomass feedstock moisture content on SCWG product gas are depicted in Fig. 19 and Fig. 20 It can be observed from this figure that, by increasing the reaction temperature, the concentration of hydrogen and carbon monoxide in the product gas increases. The results also revealed that as the feedstock moisture content increases from about 20 wt.% up to 80 wt.%, carbon dioxide and hydrogen yields increase remarkably.

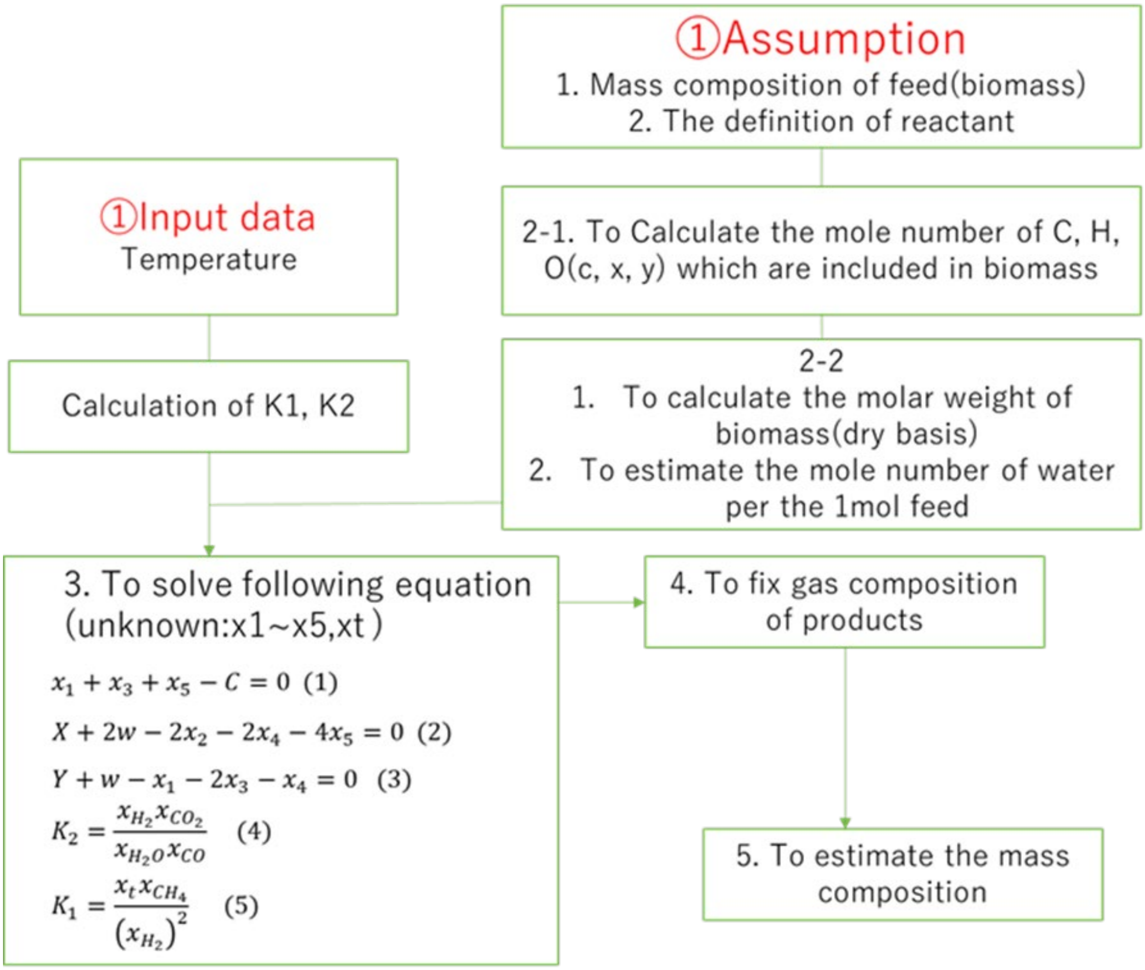


Fig. 18 Calculation flowchart of SCWG

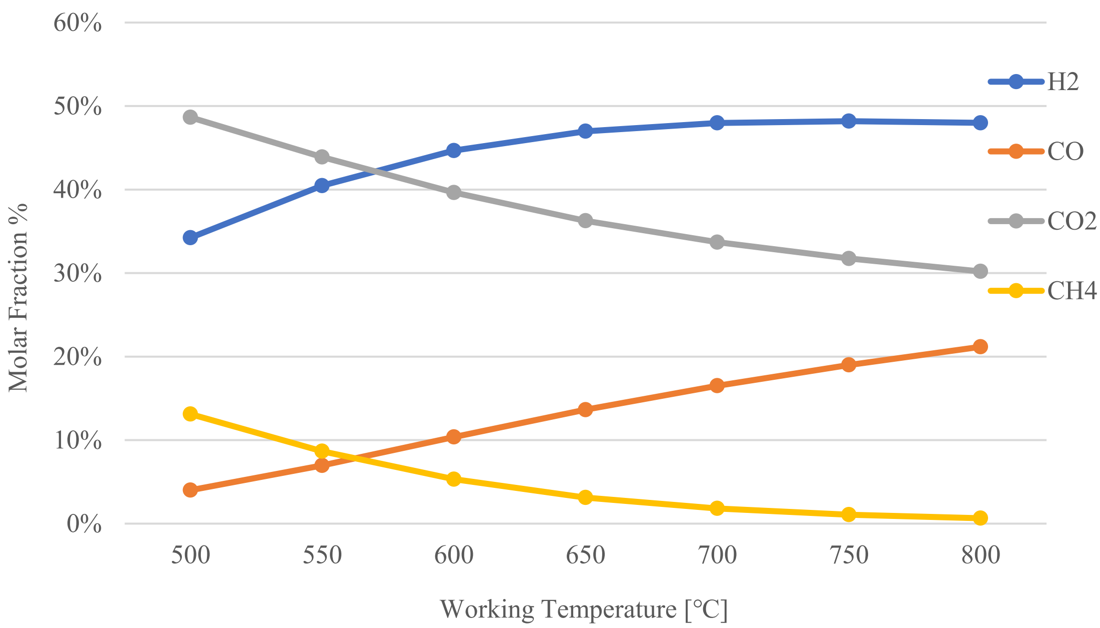


Fig. 19 Products molar fraction Vs. Working Temperature

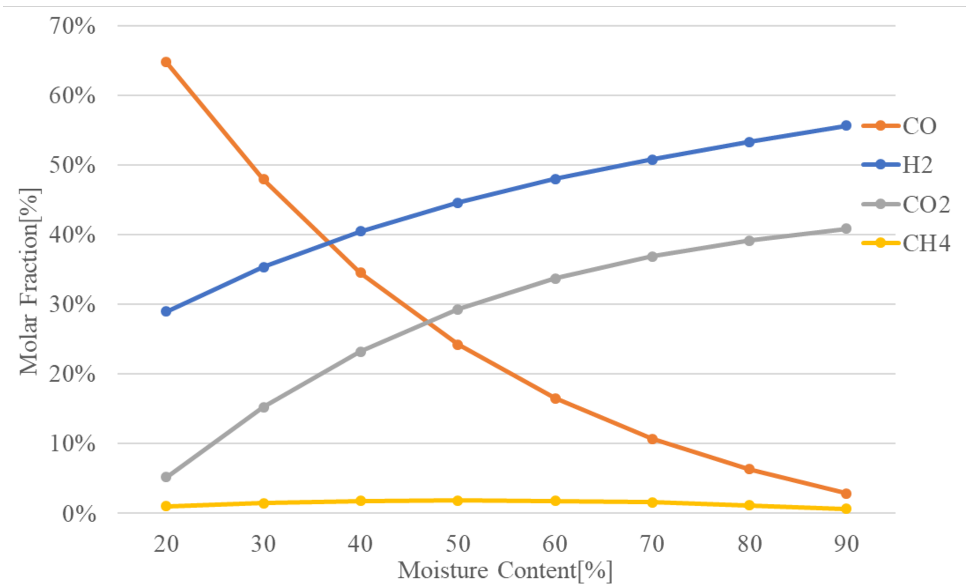


Fig. 20 Moisture Content Vs. products molar fraction

Fig. 20 shows changing of hydrogen, carbon monoxide and carbon dioxide is slightly with water content increasing. Because of the water gas shit reaction is made by balance between a) carbon monoxide, b) water content and c) hydrogen, d) carbon monoxide. Hence, these substances affected by the water content. Fig. 21 shows the variation of K-values with working temperature.

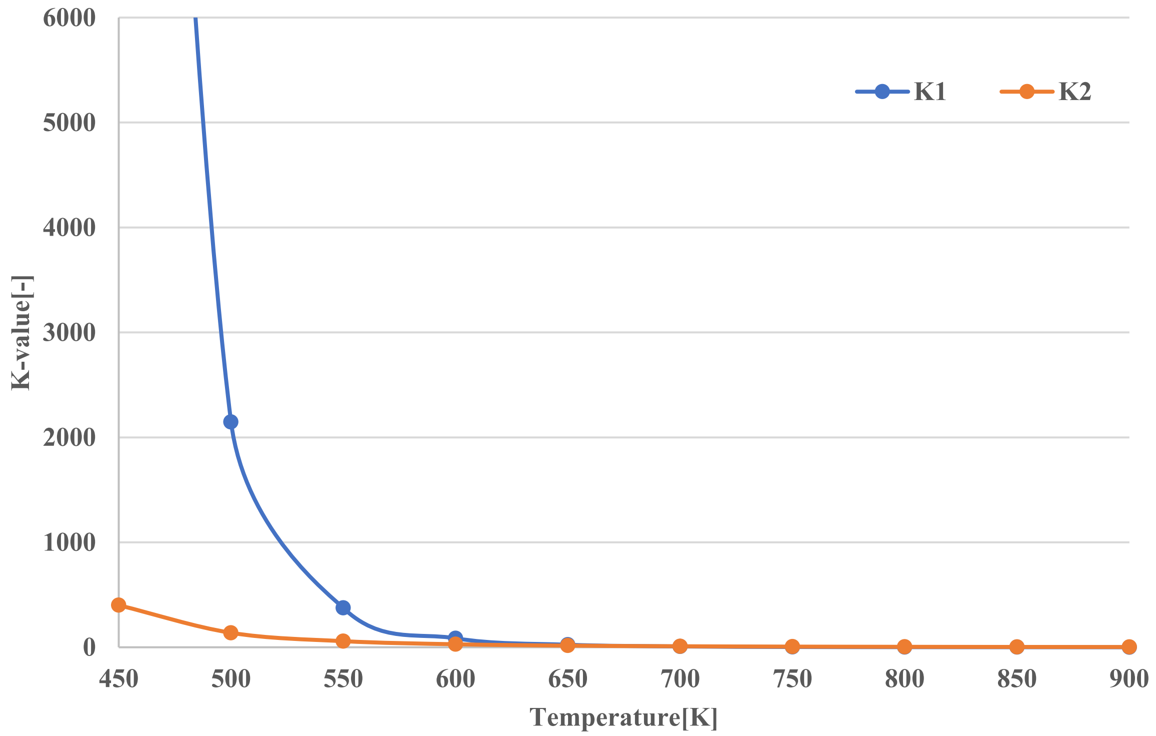


Fig. 21 K-value variation with the working temperature

2.4 Control strategy in the proposed HRES

Fig. 22 shows the management strategy, which is used to control the amount of power and hydrogen generated by the different components in the proposed HRES.

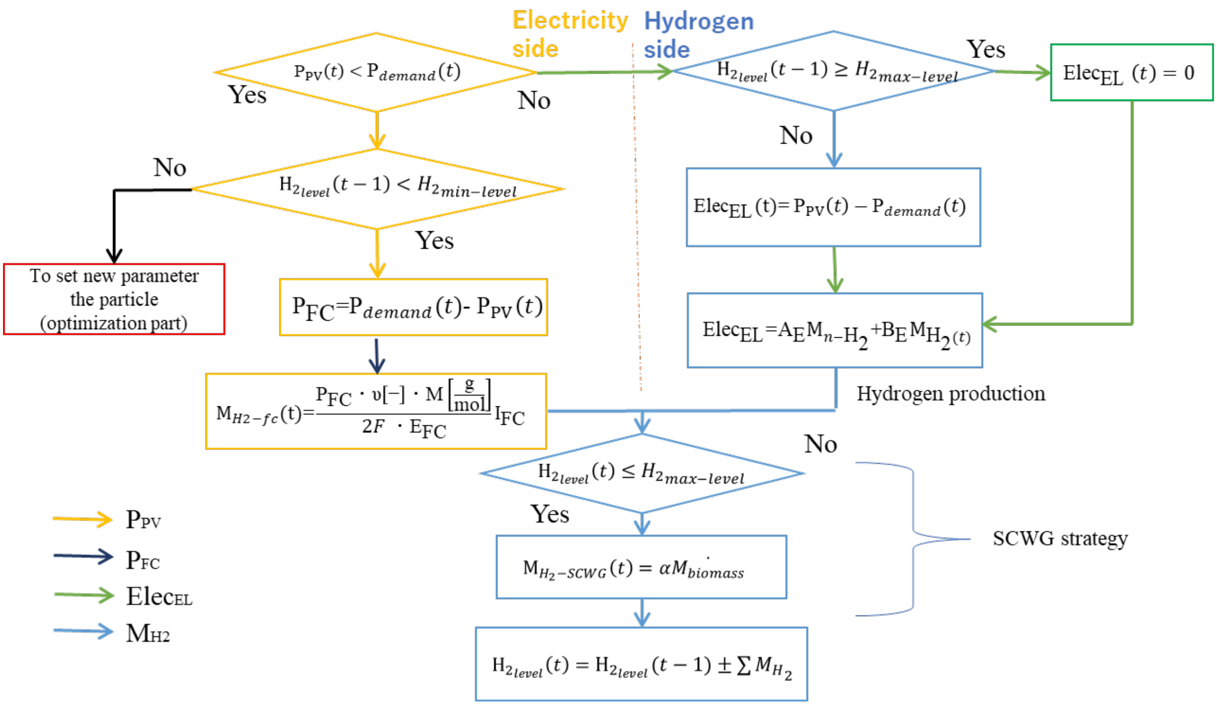


Fig. 22 Calculation flowchart of electricity and hydrogen generation

In this approach, the renewable energy sources (Biomass & solar) plus the energy stored in the hydrogen storage are used to meet the load requirement. The fuel cell is switched on as a backup source when solar energy is not sufficient to supply the load. For each hour step, the simulation program compares the required energy demand and the supplied energy, and according to the difference, a decision to operate the water electrolyzer and SCWG or to charge the hydrogen or discharge it will be taken. The electricity balance in each time steps is shown by the following equation:

$$\mathbf{P_{FC}(t) + P_{PV}(t) = P_{demand}(t)} \quad 38$$

$$\mathbf{P_{PV}(t)} - \mathrm{Elec_{EL}(t)} = \mathbf{P_{demand}(t)} \quad 39$$

Where, P_{pv} is the output electricity from PV module in each timestep, P_{FC} is the output electricity from the Fuel cell, P_{demand} is demand of electricity in each timestep, $Elec_{EL}$ is the electricity consumed by the water-electrolyzer. In this study, the SOC (State Of Charge) of hydrogen tank is assumed to be 95% as was addressed by in [20]

Chapter 3

Design of the HRES beyond economic optimization

Chapter 3: Design of the HRES beyond economic optimization

In this study, the development of an optimization model will be discussed which its goal is to find the optimal configuration of the system subject to satisfying the required load (electricity) in the selected household area.

3.1 Objective Function

In this study, the optimization model was founded based on introducing two different criterions: 1) Minimization of the total cost of the system 2) Maximization of the total profit from electricity generation. Eq.37 shows the objective function for total cost minimization problem [39]

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n}(I_t+M_t+F_t)/(1+r)^t}{\sum_{t=1}^{n}E_t/(1+r)^t} \quad 40$$

Where, I_t is investment cost in year t, M_t is operation and maintenance costs in year t, F_t is fuel costs, E_t is electricity generation in year t, r is discount rate, and n is the lifetime of each component.

$$\text{Total Cost} = \sum_{i}^{5} \mathrm{LCOE}_i \times P_i \quad 41$$

The total cost of the system includes the investment and operation and maintenance cost. The profit maximization problem describes the situation that the surplus electricity generated from the solar panel can be sold back to the grid. Therefore, profit maximize function includes the difference between the revenue from both surplus electricity generated from the solar panel which can be sold back to the grid and total renewable electricity which is generated from the HRES and the total cost of the system, as follows:

$$\text{Profit} = \alpha E_{dem} + \beta E_{sur} - \text{Total Cost} \quad 42$$

Where, α is electricity tariff for residential in Japan which is equal to 26 JPY/kWh [40], E_{dem} is demand of electricity in one household which can be net by the HRES, β is FIT (Feed In Tariff) which is equal to 28 JPY/kWh [8], E_{sur} is surplus electricity from PV module.

3.2 Optimization Strategies

3.2.1 PSO algorithm

PSO (Particle Swarm Optimization) algorithm is one of the meta-heuristics algorithm to find the approximate solution in the case of a combinatorial optimization problem. The behavior of this algorithm comes from characteristic of collective organisms: under giving the objective function as the searching target, particles move around with information communication in searching space to find the optimal solution. This algorithm has several advantages such as 1. Algorithm simplicity 2. Flexible operation 3. No gradient information required. The model of PSO shows Fig. 23

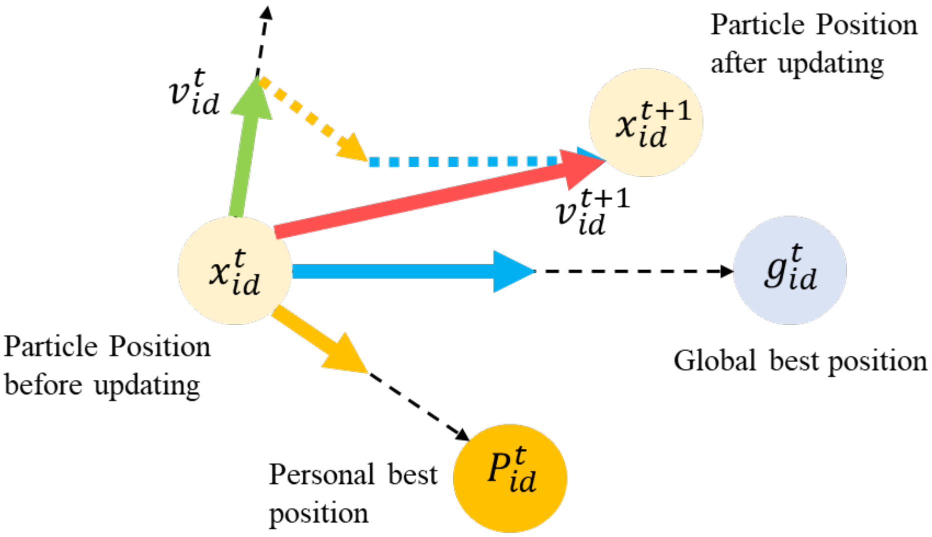


Fig. 23 Position updating in PSO

All particle has the position information, vector information and personal best information: personal best information means their best position so far which based on the objective function. The updating equation for particles shows Eq. 40 - 41

$$\overrightarrow{v_{id}(t+1)} = \omega \cdot \overrightarrow{v_{id}(t)} + C_1 \cdot \left(\overrightarrow{P_{id}(t)} - \overrightarrow{x_{id}(t)}\right) + C_2 \cdot \left(\overrightarrow{g_{id}(t)} - \overrightarrow{x_{id}(t)}\right) \quad 43$$

$$\overrightarrow{x_{id}(t+1)} = \overrightarrow{x_{id}(t)} + \overrightarrow{v_{id}(t+1)} \quad 44$$

Where, $v_{id}(t+1)$ is particle vector after updating, $v_{id}(t)$ is particle vector before updating, ω is inertia weight of vectors which control the vector size: This value should be set the range of [0.5, 1] because of this value is lower than 0.5, the particle will implement local searching, or value is higher than 1, particles are difficult to converge the optimum solution. Here, ω is set as 0.7. [41] And both referring value C1 and C2 are set 1.0 and 0.5.

3.2.2 Detail Design of PSO

1) Topology of PSO: The PSO model needs the detail design such as boundary control the topology: this is the shape of the communication between each particle in this model. In the field of PSO modeling, the topology is classified by threee types (Fig. 24 shows).

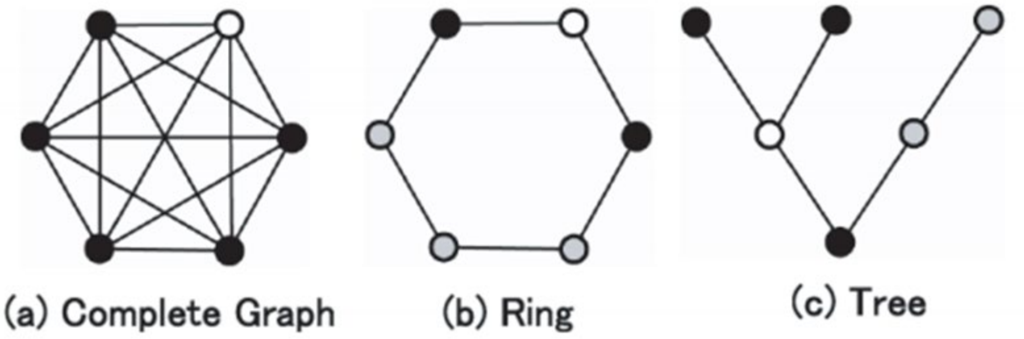


Fig. 24 Type of topology of PSO [42]

a) Complete Graph: This topology the all of particle can communicate with each other to share the global best score and position in each timestep. This method helps to converge the results earlier. Besdies, the topology needs definition of the vector elements because if its scalar value is low, the particles lose the diversity in optimization.

b) Ring: The method is a particle exchange information with only the next particle. The advantage of this topology is to reduce calculation cost for the number of exchanging information is less than other topology. However, all particle activity will spread slowly when some particle descent down the local optimum in the multimodality problem.

c) Tree: In the optimization problem, it is necessary to make a balance between diversity and convergence of the particles. The tree topology makes the balance both of the particles. Otherwise, tree topology is complicated to adopt the system

In this study, the adopted topology of PSO is a) Complete Graph for implementing easily and high convergence of particles: it helps to reduce calculating cost with optimization.

2) Boundary Condition of PSO:

In the PSO simulation, there are four other types of a boundary condition in the case of the particle is going to be outside of simulation space. Fig. 25 shows the classification of the boundary condition of each type.

a) absorbing: In the case of the particle flying to outside the searching space in one dimension, to reset the velocity component in that dimension is equal to zero.

b) Reflecting: In the case of the particle flying to outside the searching space in one dimension, to set the reverse the sign of velocity component in that dimension, and vector length keeps the previous timestep one.

c) Damping: In the case of the particle flying to outside the searching space in one dimension, to set the reverse the sign of velocity component in that dimension, and vector length is updated as previous timestep one-time uninformed random number [0,1].

d) Invisible: In the case of the particle flying to outside the searching space in one dimension, the fitness of this particle is set at infinite when optimizing minimum or infinitesimal when optimizing maximum.

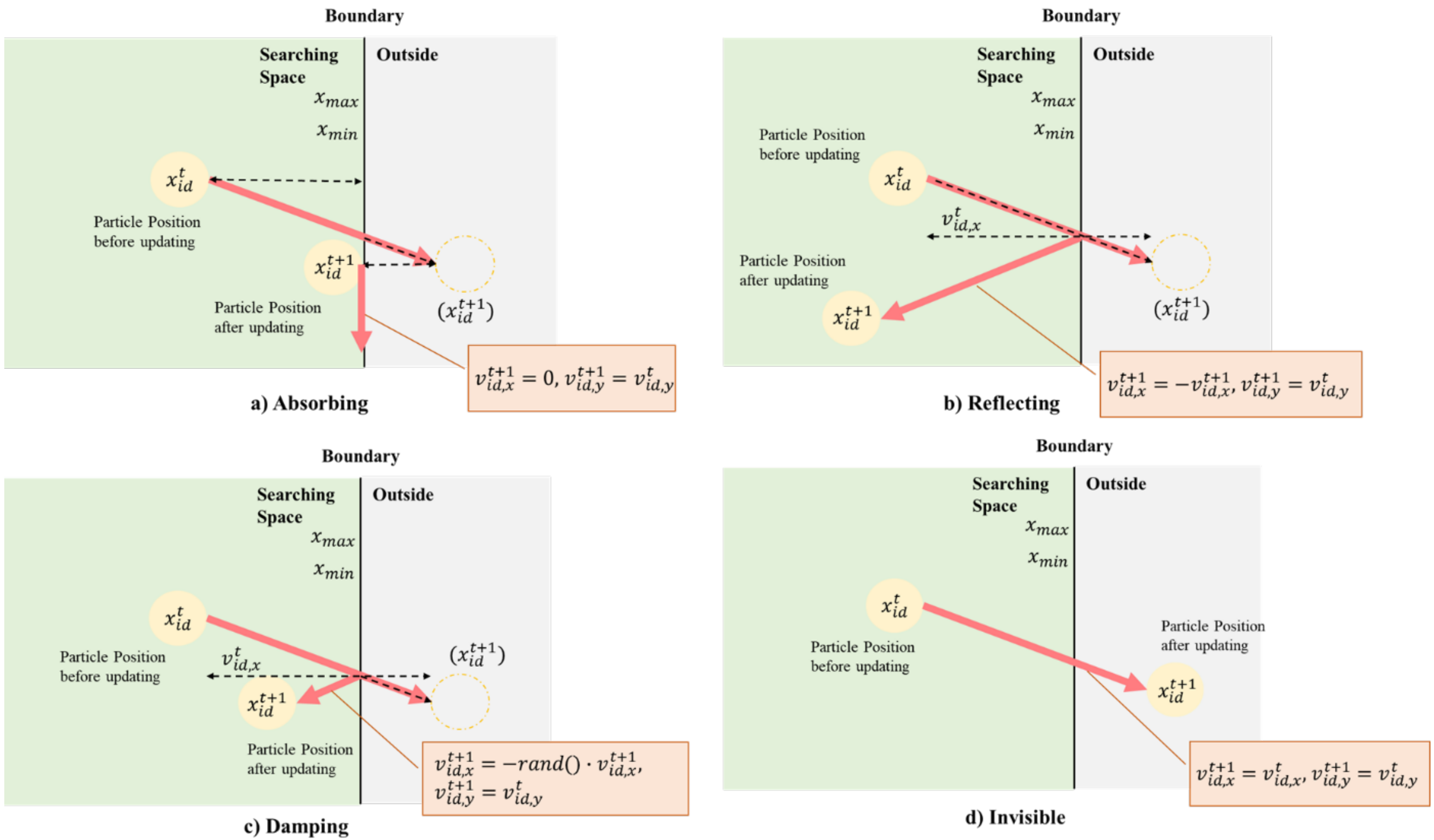


Fig. 25 Four types of boundary condition

In this study, the PSO method implemented c) damping method as boundary condition treatment. And vector length and updating position are defined the following equation with assuming α= 1.

$$x_{id}^{t+1} = x_{id}^{t} + |x_{id}^{t} - x_{max}| - \left(v_{id,x}^{t} - \alpha\, |x_{id}^{t} - x_{max}|\right)$$

$$= x_{id}^{t} - v_{id,x}^{t} + 2|x_{id}^{t} - x_{max}| \quad |v_{id,x}^{t}| > |x_{id}^{t} - x_{max}| \text{ or } |v_{id,x}^{t}| > |x_{id}^{t} - x_{min}| \qquad 45$$

Fig. 26 shows particle updating in detail. Where, α is the elastic modulus of the boundary, it assumed as α=1 in this study. If the particle will get off the searching space, the particle position updates like hitting the boundary as the wall and bounces back to searching space. At that time, the length of another dimension vector keeps ordinary vector scale.

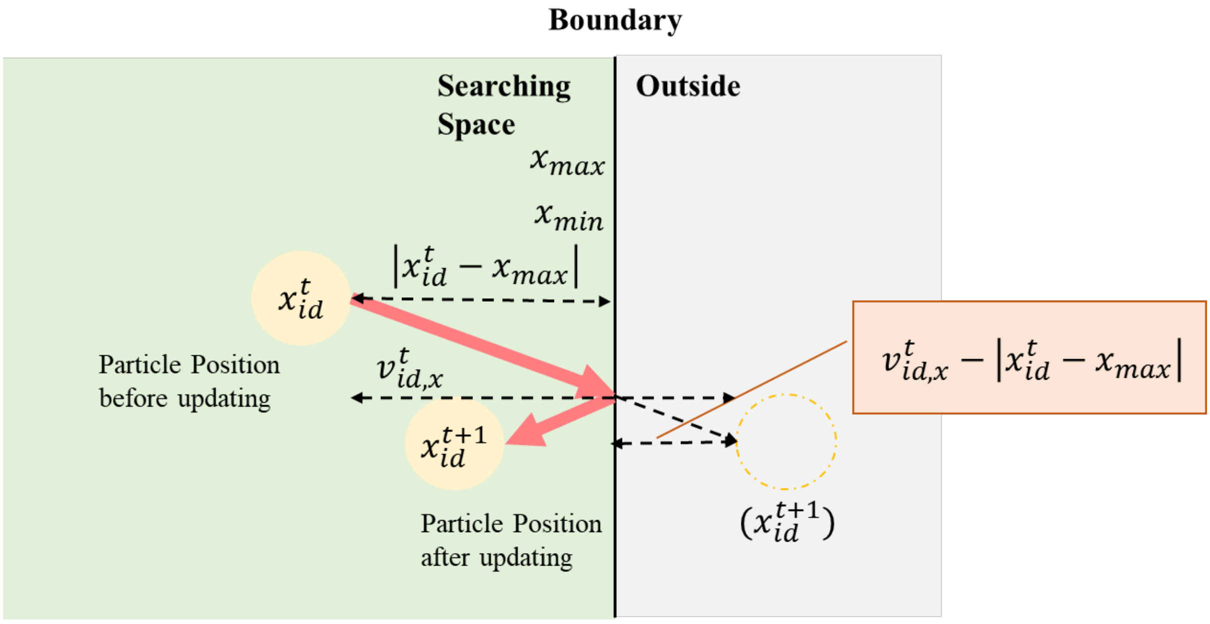


Fig. 26 Improved damping method

3.2.3 Connection between the simulation and optimization parts

The simulation part can calculate the hourly hydrogen and electricity generation over a year by giving the load requirement and weather data (temperature, global radiation).

Fig. 27 shows the connection between PSO optimization part and simulation model. The fitness values of optimization model are the installed capacity of each component of HRES such as PV module, fuel cell, electrolyzer, hydrogen tank and SCWG reactor.

The particle of the optimization part has the information about fitness value, and they try to find the optimal configuration with updating this information. Firstly, the information of each capacity information is sent to simulation part and the annual energy and hydrogen balance is checked based on this information. If the balance is met, the score is defined by the objective function based on each scenario. The fitness function is a particular type of objective function to find the best solution from among all feasible solutions. In the PSO part, the constraints can also be included in the fitness function. Therefore, the PSO optimization part will evaluate the fitness of each particle and update individual and global best fitness and position through updating velocity and position of each particle. Each particle remembers the best fitness value which the minimum total cost of the system which has achieved during the operation of the algorithm. The particle with the best fitness value compared to other particles is also calculated and updated during iterations. The process is repeated until some stopping criteria, such as the number of iterations or predefined target fitness values are met.

The complete flow of the algorithm applied for techno-economic analysis of the HRES is given below:

Step1) Initialization.

- ✓ Load meteorological data (hourly wind speed, solar radiation, and ambient temperature during one year)
- ✓ Load component's characteristics
- ✓ Load economic parameters
- ✓ Upper bound and lower bound of nominal operation of each components

Step 2) Update iteration variable.

Step3) Update inertia weight.

Step4) Update velocities.

Step5) Update positions.

Step6) Apply the updated values of the objective function to find LCOE and profit

Step7) Update individual best position.

Step8) Update global best position.

Step9) Stopping criterion. If the number of iterations exceeds the maximum number of iterations then stop; otherwise go to step 2.

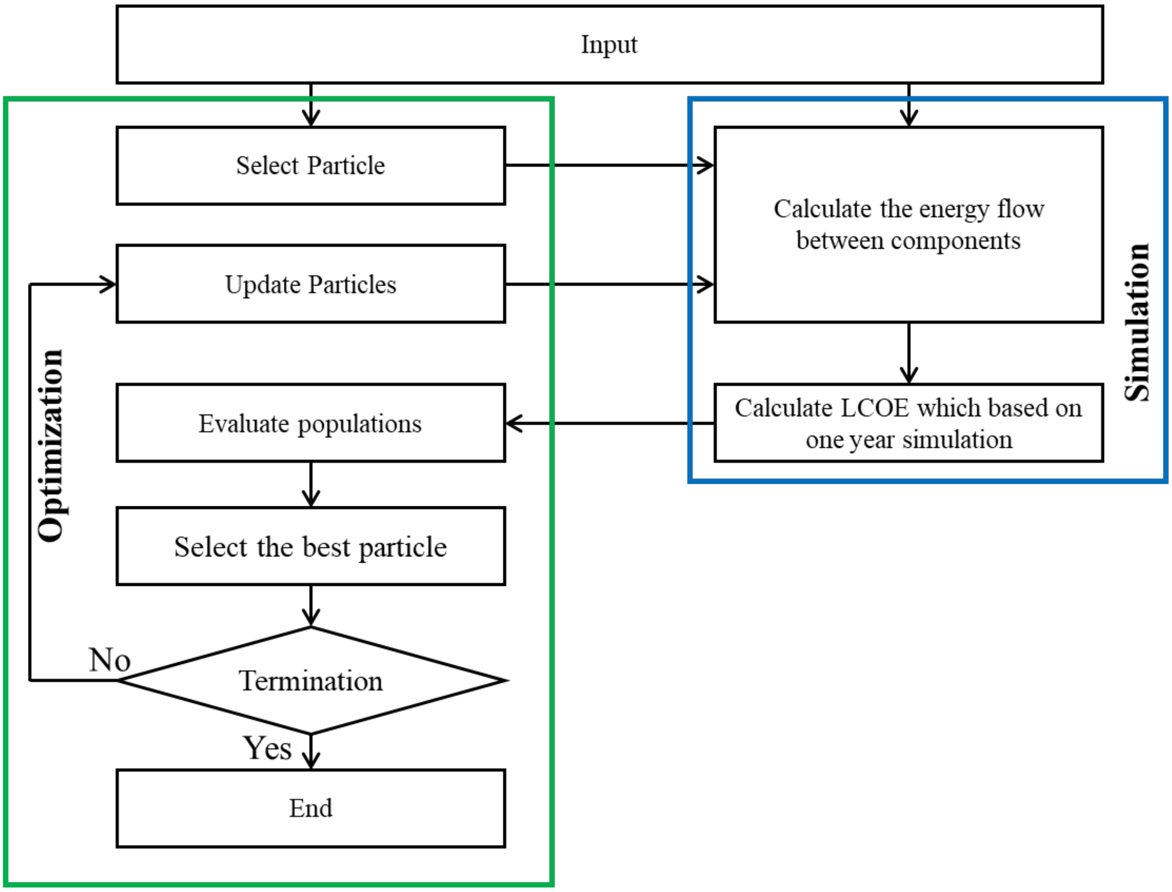


Fig. 27 The connection between the optimization and simulation sections

Chapter 4

Techno-Economic Analysis of the Proposed HRES in Fukushima

Chapter 4: Techno-Economic Analysis of the Proposed HRES in Fukushima Prefecture

This chapter gives the detail of the application of the developed model in a typical residential area in Shinchi-machi, Fukushima Prefecture in japan.

4.1 Case Study

The case study considered in this research is a residential area located in a subject district in Shinchi-machi of Fukushima-Prefecture, Japan. This district belongs to the Tohoku region, which the Great East Japan Earthquake happened there [43]. A small thermal power plant provides the electricity load requirements in this district, using imported LNG as fuel. The hourly load curves of the selected household in each season are shown in Fig. 28. As can be observed from this figure, the first ramp takes place between 5:00 am to 8:00 am when people are starting to work in the morning, followed with the second ramp between 4: 00 pm to 8: 00 pm when people are getting back to their homes in the evening. Furthermore, electricity consumption is tending to be higher during winter when the air-conditioner usage increases because of a severe cold comes every winter in this district. The air temperature and daily average global irradiation in Fukushima are shown in Fig. 29 and Fig. 30 [44]. In general, during the spring time in Japan, it is possible to obtain the most solar radiation. and from April to June, the global radiation has the largest value. In August, the global radiation decreases slightly. Because the Tohoku region is affected by seasonal wind the weather condition in this area, especially in summer is variable.

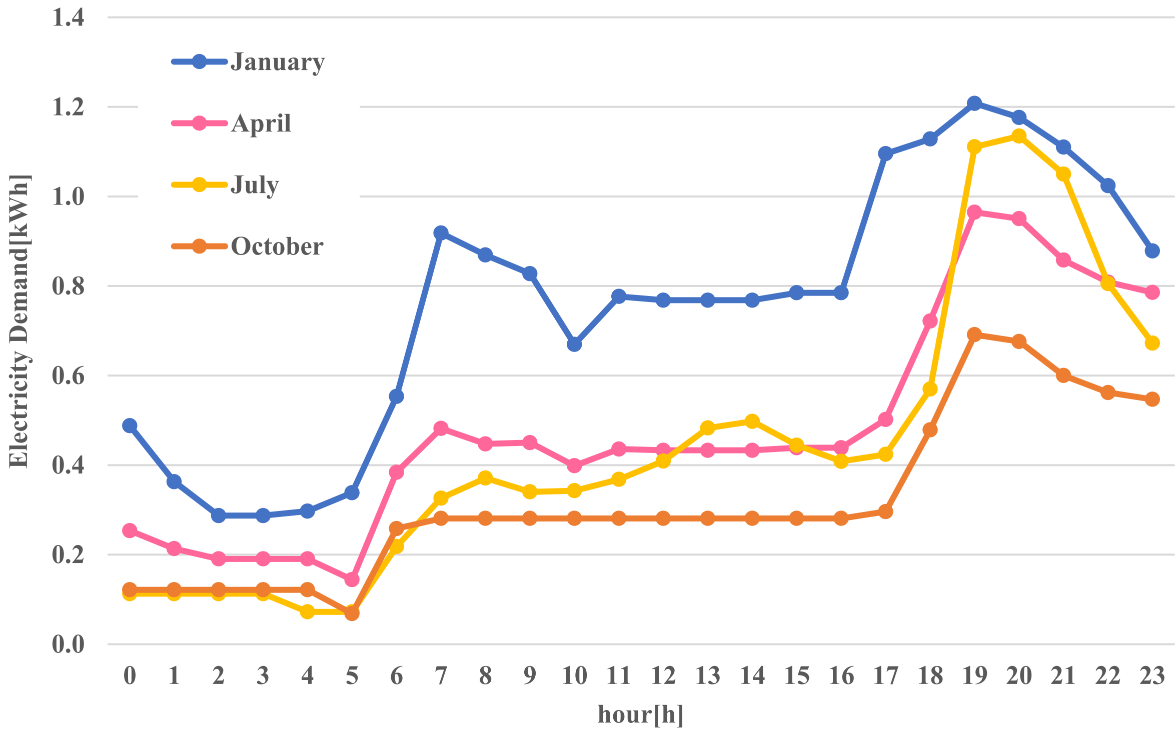


Fig. 28 Electricity demand in the selected residential area in Shinchi-machi

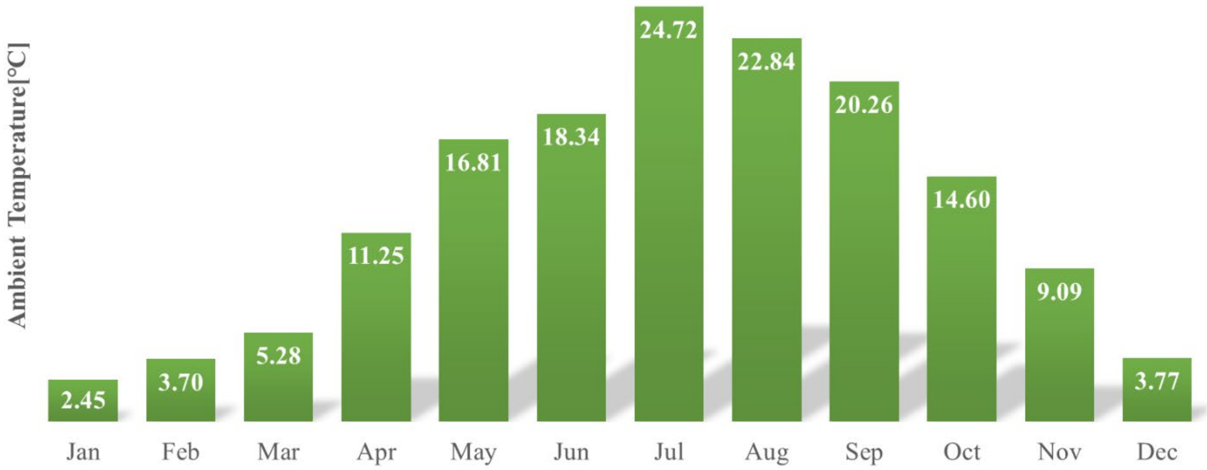


Fig. 29 Monthtly average temperature in Fukushima

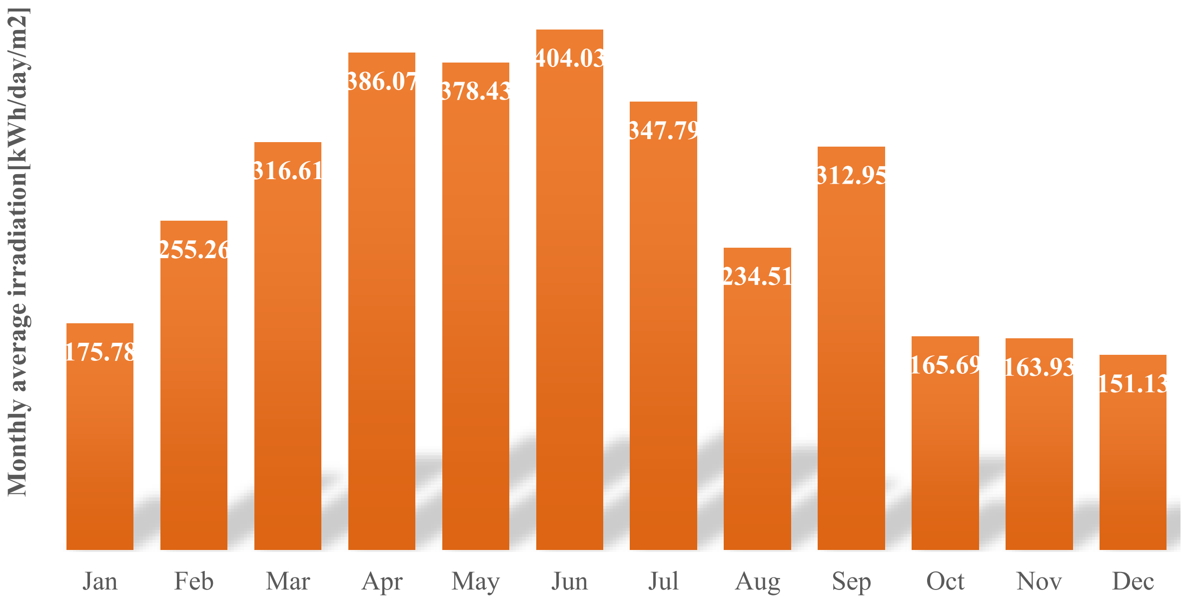


Fig. 30 Monthly average solar irradiation in Fukushima

4.2 Cost analysis of the HRES

1) PV module: The installation cost of the PV module is around JPY 230/W for the residential rooftop and the annual operation and maintenance cost was estimated at 5% of the installation cost with a lifetime of 20 years.

2) Electrolyzer: The electrolyzer can be classified into two categories: alkaline electrolysis and PEM (polymer electrolysis membrane). The alkaline electrolysis is adopted the mature technology; therefore, the cost of this equipment is lower than other type, and with a longer lifetime. In addition, the installation volume is larger than PEM because its efficiency is lower than the PEM. The installation cost of the alkaline water-electrolyzer is estimated at JPY 170/W. [10] The PEM technology has the advantage of high efficiency to produce hydrogen. However, its installation cost is around USD 5,000/kW. [45] In order to reduce the system cost, the alkaline electrolyzer was selected in this study with a total lifetime of 10 years, and annual operation and maintenance cost of JPY 3,000 / kW.

3) Fuel cell: Fuel cell can generate both electricity and heat (byproduct) in the HRES. This equipment cost differs based on the type of electrolyte used in the system. Polymer Electrolyte Membrane operates in a temperature range from 80 ℃ to 100℃. Generally, PEM doesn't produce the heat as byproducts because its working temperature is lower than other types. The PEM installation cost was estimated at 400/W with a total lifetime of 10 years. [46] The operation and maintenance cost of PEM fuel cell was considered 1 % of the installation cost. and operation and maintenance costs of JPY 20,000 per year

4) Hydrogen Tank: The installation cost of hydrogen tank was estimated about JPY 150,000 yen per kilogram of Hydrogen with a total lifetime of 20 years. And operation and maintenance costs of JPY 9,000 yen/year. [10]

5) SCWG reactor: The cost of SCWG reactor breakdown shows Tab.2 which has been reported some scholars. The unit cost of SCWG-reactor in this study is assumed 42,000 JPY/(kg/day) based on Tab.2.

Tab. 2 SCWG cost breakdown [9]	**Feedstock (t/d)**	**Cost (MJPY)**	**Reference**
SCWG-plant (recycle reactor) + Purified H2	9	650	[47]
SCWG-plant (recycle reactor) + Purified H2	90	3100	[47]
SCWG-plant (recycle reactor) + Purified H2	180	2600	[47]
SCWG-plant + Purified H2	180	3000	[47]
SCWG-plant + rich gas	5	210	[48]

4.3 Results

4.3.1 Scenario 1: Total Cost minimization with unlimited biomass feedstock for SCWG

The technical parameters which are needed to be considered in calculation of the PV power output are reported in Tab. 3 to Tab. 4.

Tab. 3 The calculation parameter of incident radiation

Place	Soma
-Longitude	140.9189
-Latitude	37.7973
Plate azimuth angle	0(South)
GMT	9
Tilt angle of PV surface	30

Tab. 4 The products value of PV panel [49]

Product	VBHN325SJ47(Panasonic)
Temperature Coefficient[%/deg]	-0.258
Maximum efficiency [-]	0.2176
Rated Power[W]	325
Nominal operation cell temperature [°C]	44
Nominal operation ambient temperature [°C]	20
Incident radiation under test condition[W/m2]	1000
Derating Factor	0.9
Cell temperature under test condition [°C]	25

The results of the optimization model for this scenario is shown in Fig. 31, and Tab. 5. As it is shown in Tab. 5, the annual electricity demand in the selected residential area in Shinchi-machi is about 4.37[MWh], which can be met by a combination of the solar electricity generation (36%) and fuel cell electricity generation (64%);

The hourly electricity supply-demand in this scenario based on using historical weather data in 2018 is shown in Fig. 32.

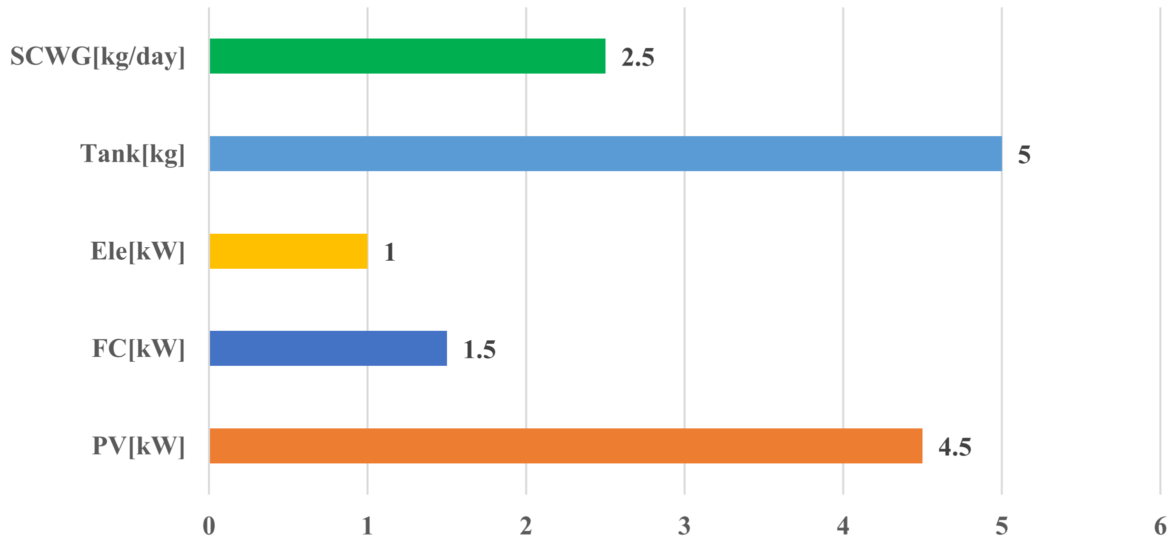
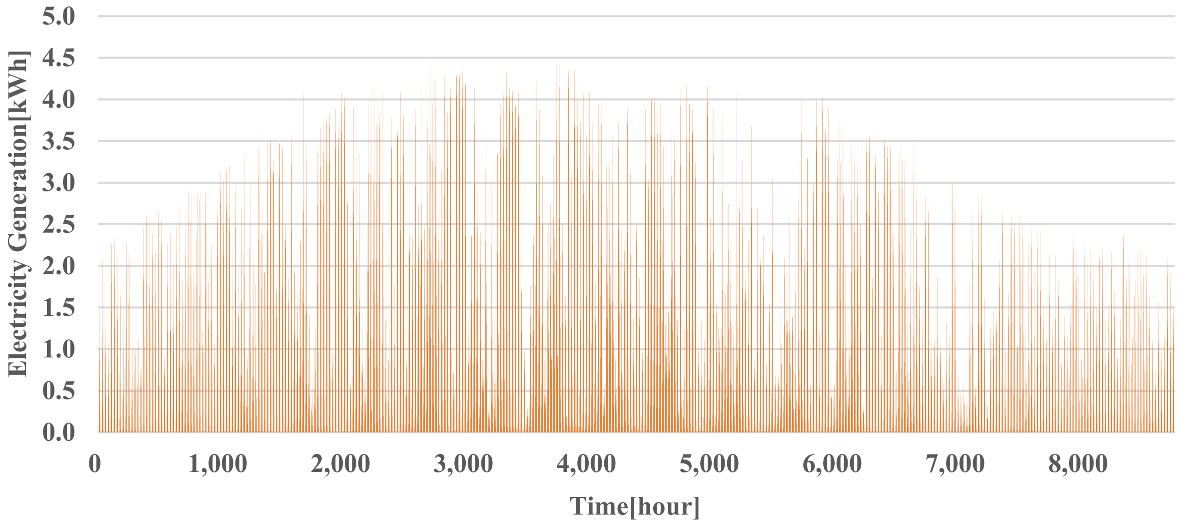


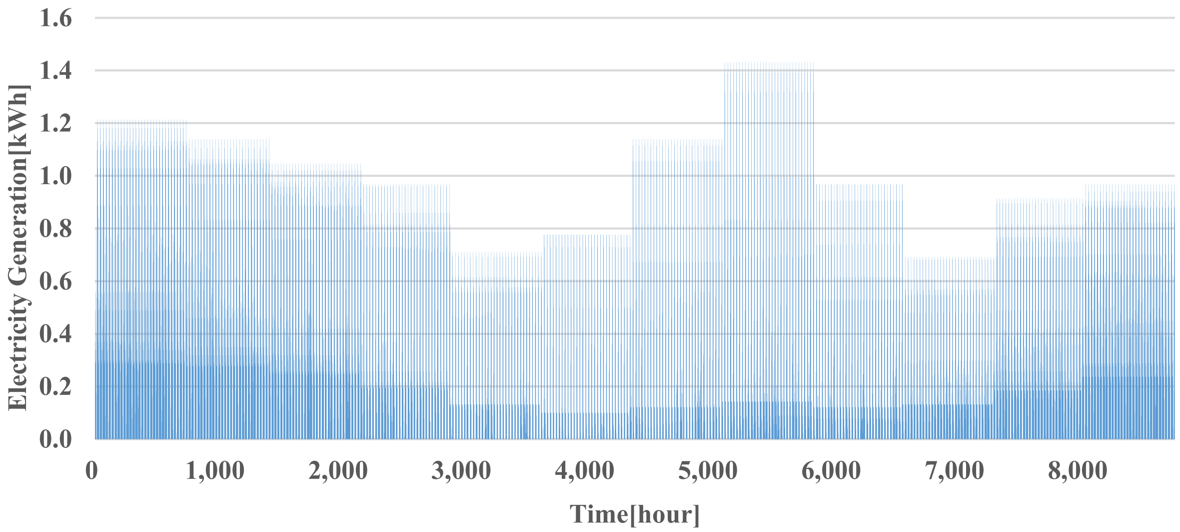
Fig. 31 Optimal configuration of the HRES in scenario 1

Tab. 5 Electricity supply-demand balance in Scenario 1

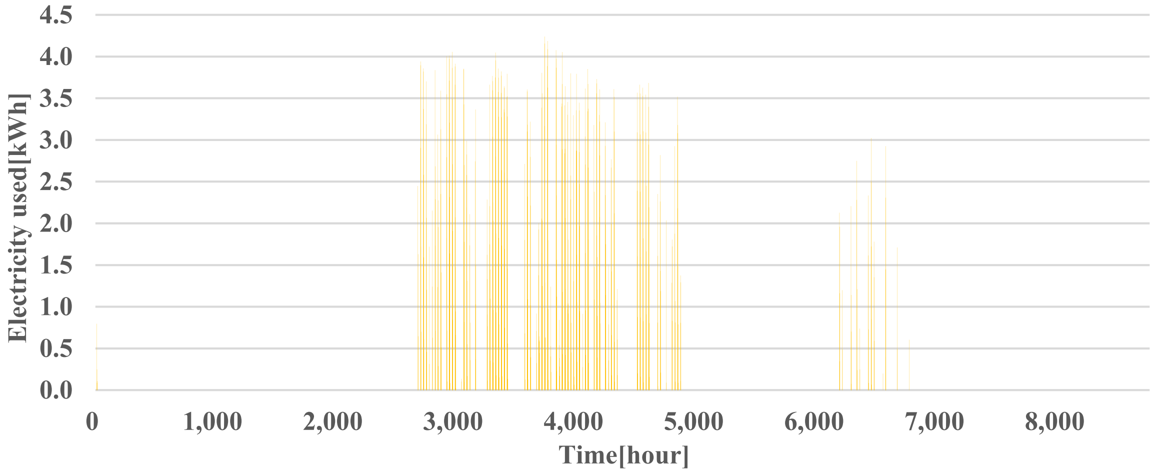
Demand (kWh)	
External Load	4373.16
Electrolyzer electricity consumption	3027.59
Supply (kWh)	
Solar PV	5391.20
Fuel Cell	2811.77
Balance	802.22 (Surplus electricity generated from the PV)



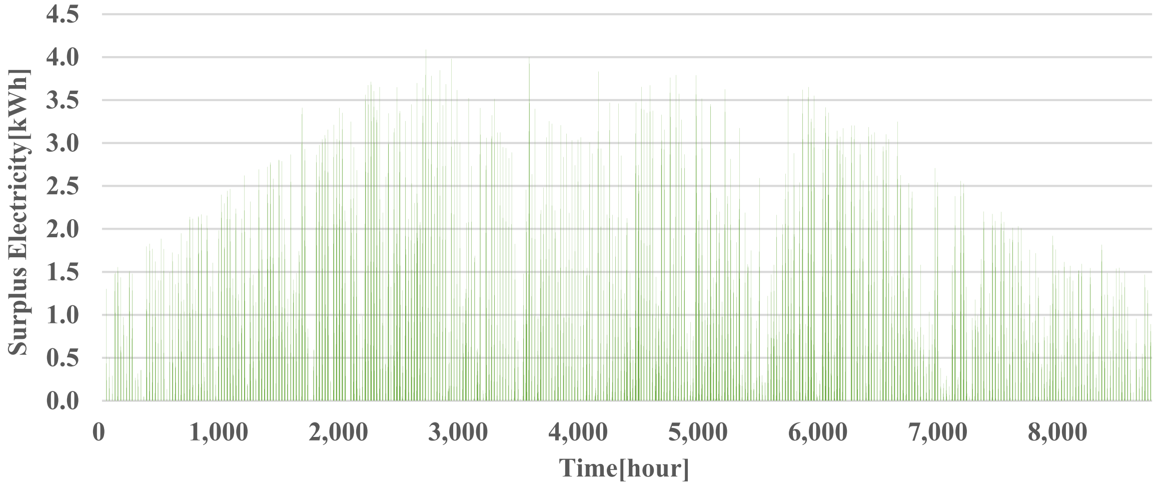
a) PV module electricity generation



b) Fuel cell electricity generation



c) Electricity used in electrolyzer



d) Surplus electricity from PV module

Fig. 32 Hourly electricity supply/demand scenario 1

Fig. 33 and Fig. 34 show the monthly average electricity generation and hydrogen production from the proposed HRES in 2018, respectively.

In winter season, the amount of the generated electricity from the fuel cell is higher than the other seasons. It is because that, the demand of electricity in winter-time is very high and the electricity generated from the PV module is not enough due to insufficient solar irradiation. Fig. 35 is the daily average hourly electricity generation from the proposed HRES within a period of three days in January (from Jan.1, 0:00 to Jan 3, 23:00) which indicates the maximum rate of hydrogen production from the SCWG in this period.

Fig. 36 shows the daily average hourly electricity generation from the HRES from Apr.1, 0:00 to Apr 3, 23:00. It can be observed from this figure that the amount of generated electricity from the PV module is enough to meet the demand of electricity during daytime. The annual wet biomass consumption of 1993.70[kg/year] would be needed to be used in the SCWG. Fig. 37 shows the electricity breakdown from PV module in each month.

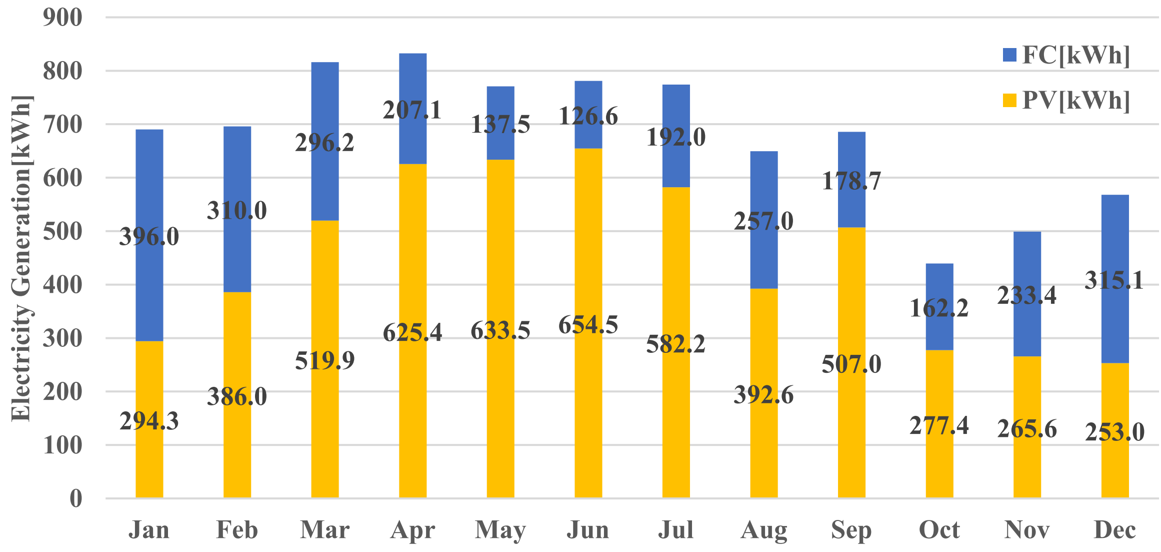


Fig. 33 Monthly average electricity generation in scenario 1

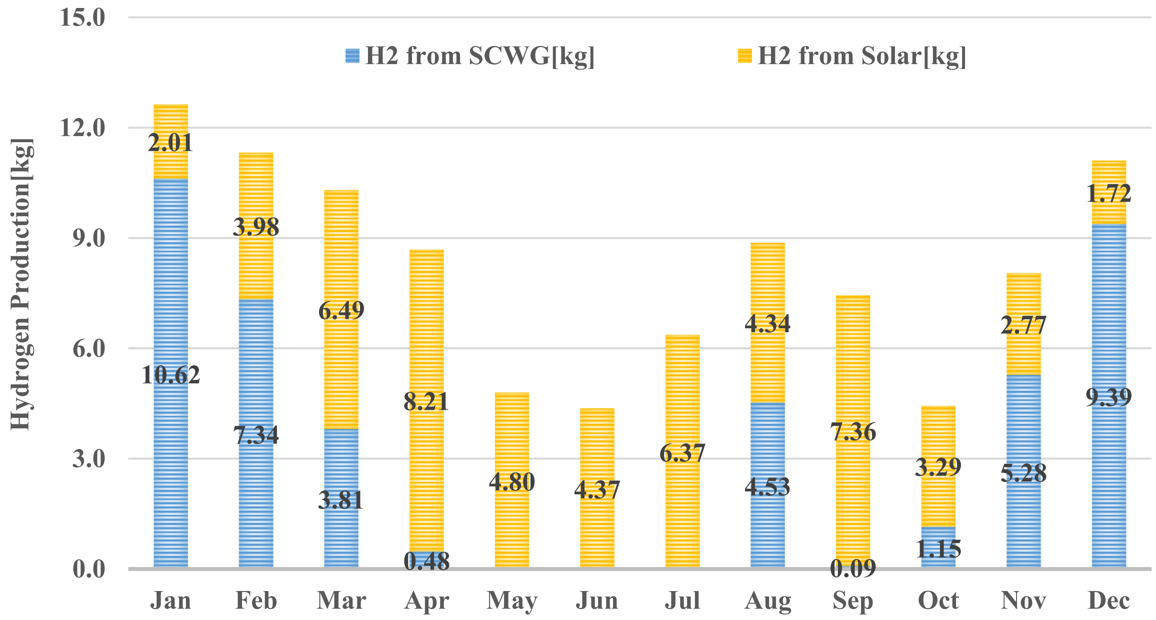


Fig. 34 Monthly Hydrogen production in Scenario 1

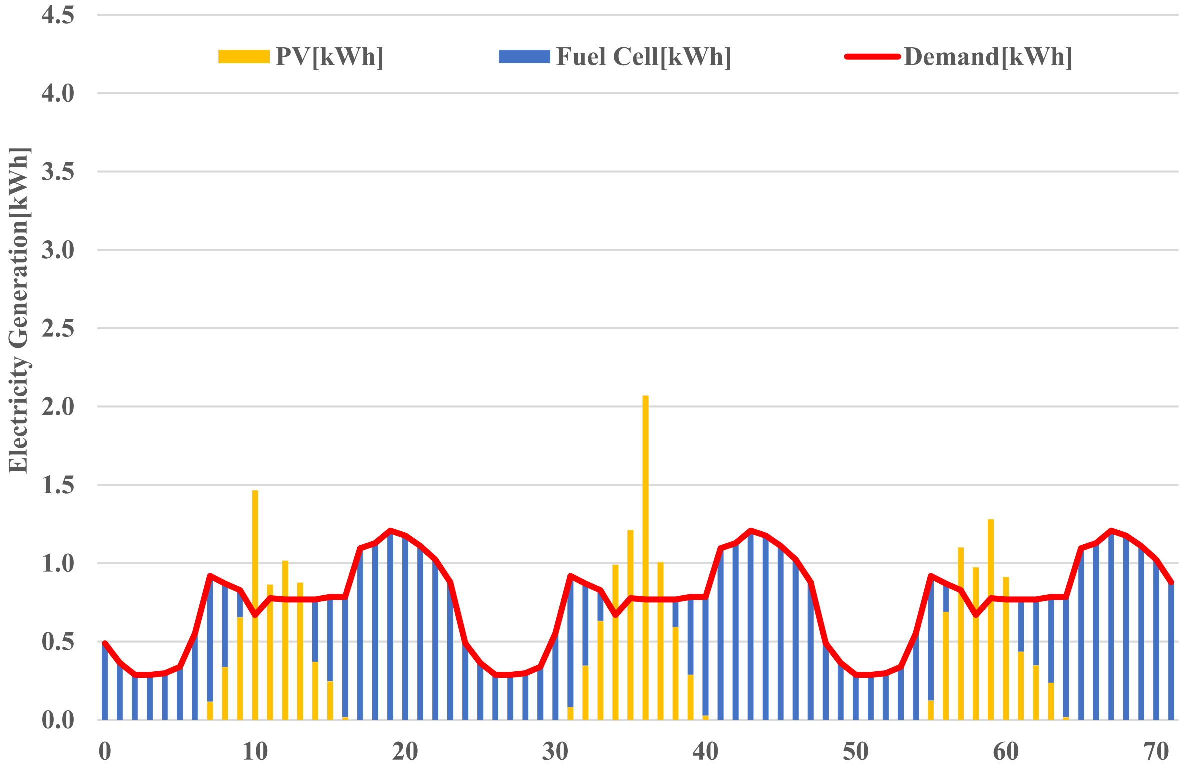


Fig. 35 Hourly electricity generation from Jan.1 - Jan.4 in Scenario 1

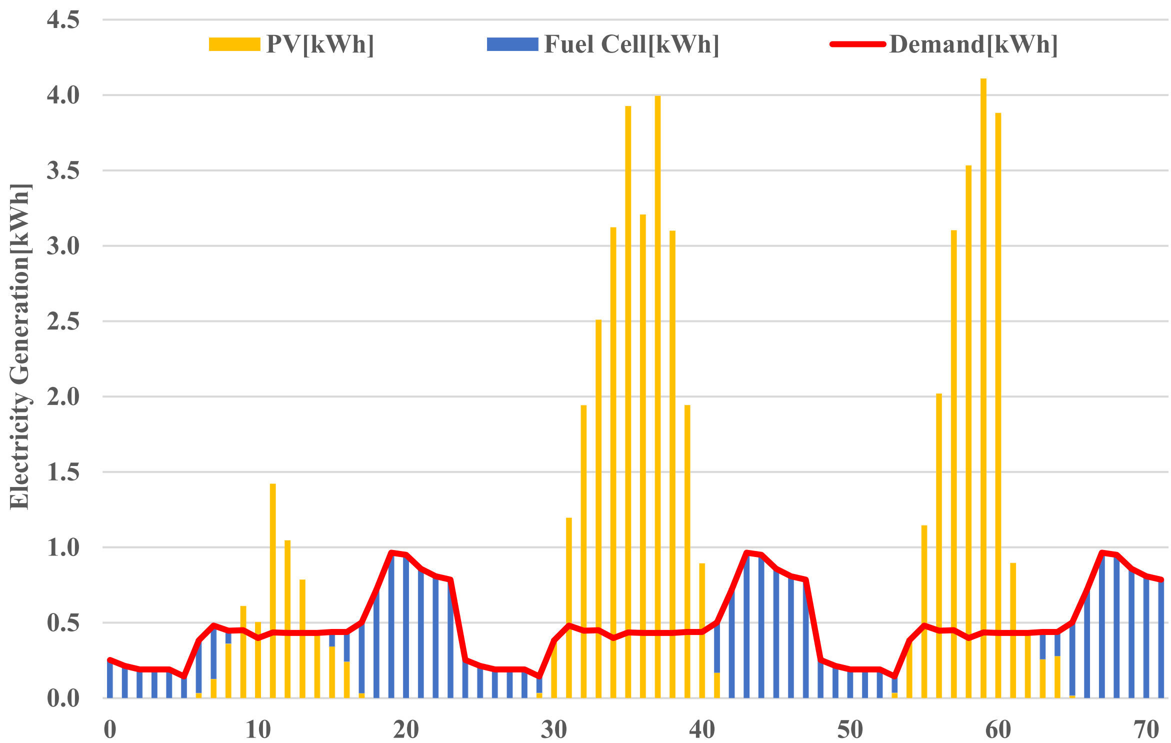


Fig. 36 Hourly electricity generation from April.1 - April.4 in Scenario I

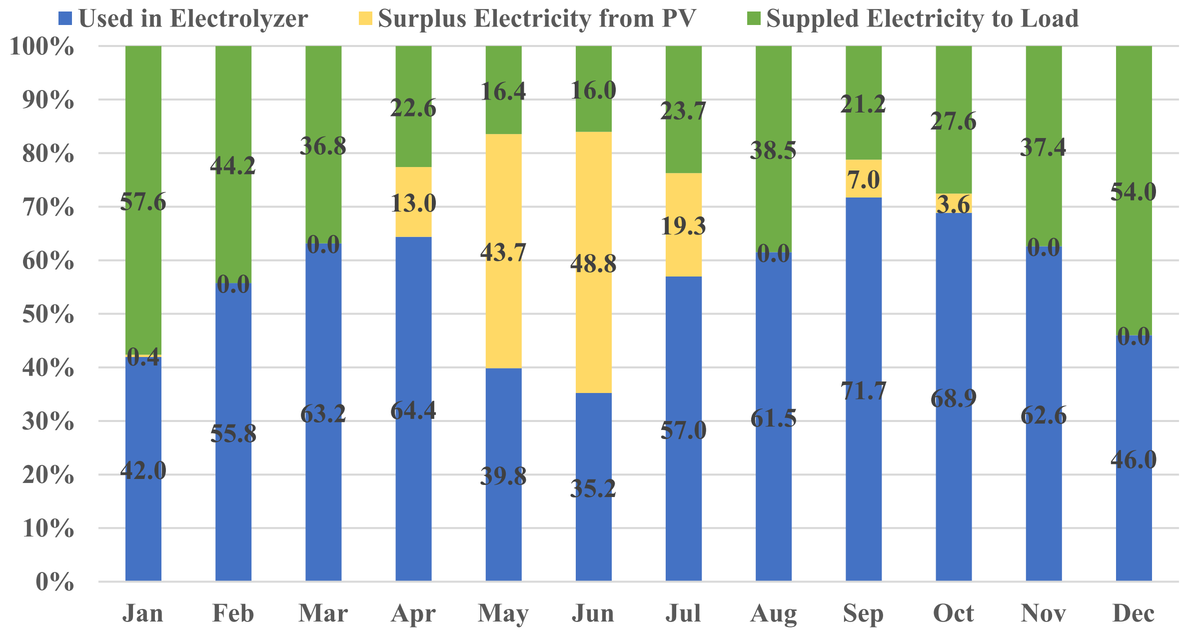


Fig. 37 PV monthly electricity generation in Scenario 1

The variation of the total cost of the system versus the number of iterations in the PSO model is represented in Fig. 38. By increasing the number of iterations, the probability of finding optimal solution increases. The optimal solution in this scenario is obtained at the discounted annual cost of 213,800[JPY/year] with a LCOE of 48.89[JPY/kWh] for the proposed HRES.

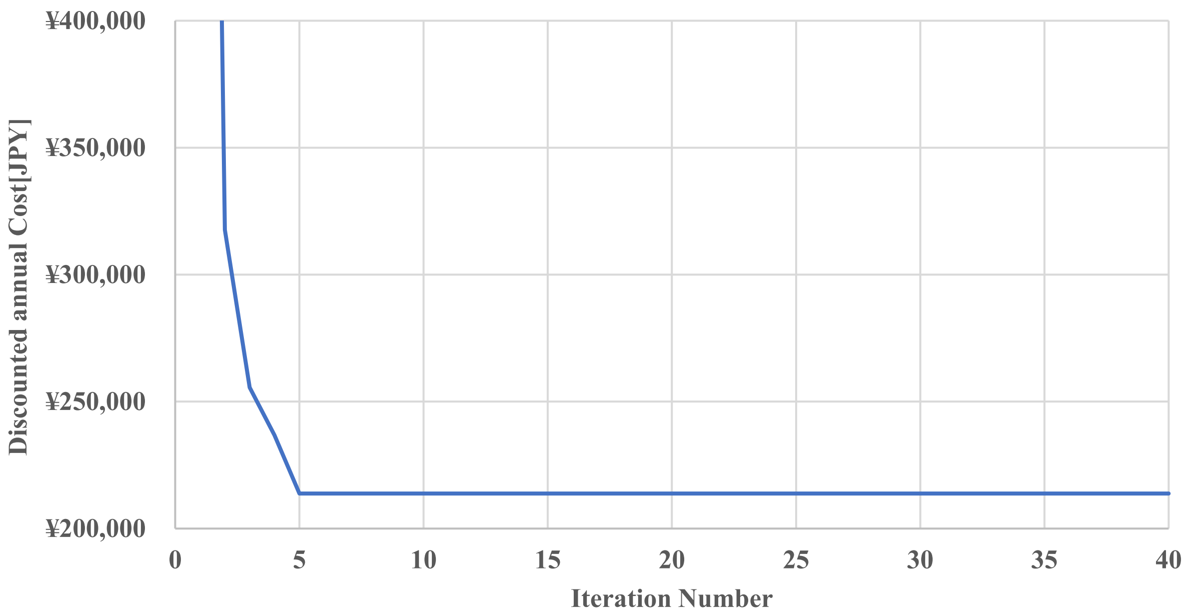


Fig. 38 Variation of the total cost of the system versus the number of iterations in Scenario 1

Fig. 39 and Fig. 40 show the PSO process through the swarms motion in different iterations from 0 to 20. It can be seen that particles (PV, Fuel cell, Hydrogen Tank, SCWG and Electrolyzer) fly from random initialization toward the particle best and global best so that all the particles converge to one point which is called Global best. Since the optimal combinations can be located in some far points from each other with the same fitness value and different configurations in the objective domain, designing such systems is a complex task. Nevertheless, the particles become very close to each other after 20 iterations and the best combination is identified.

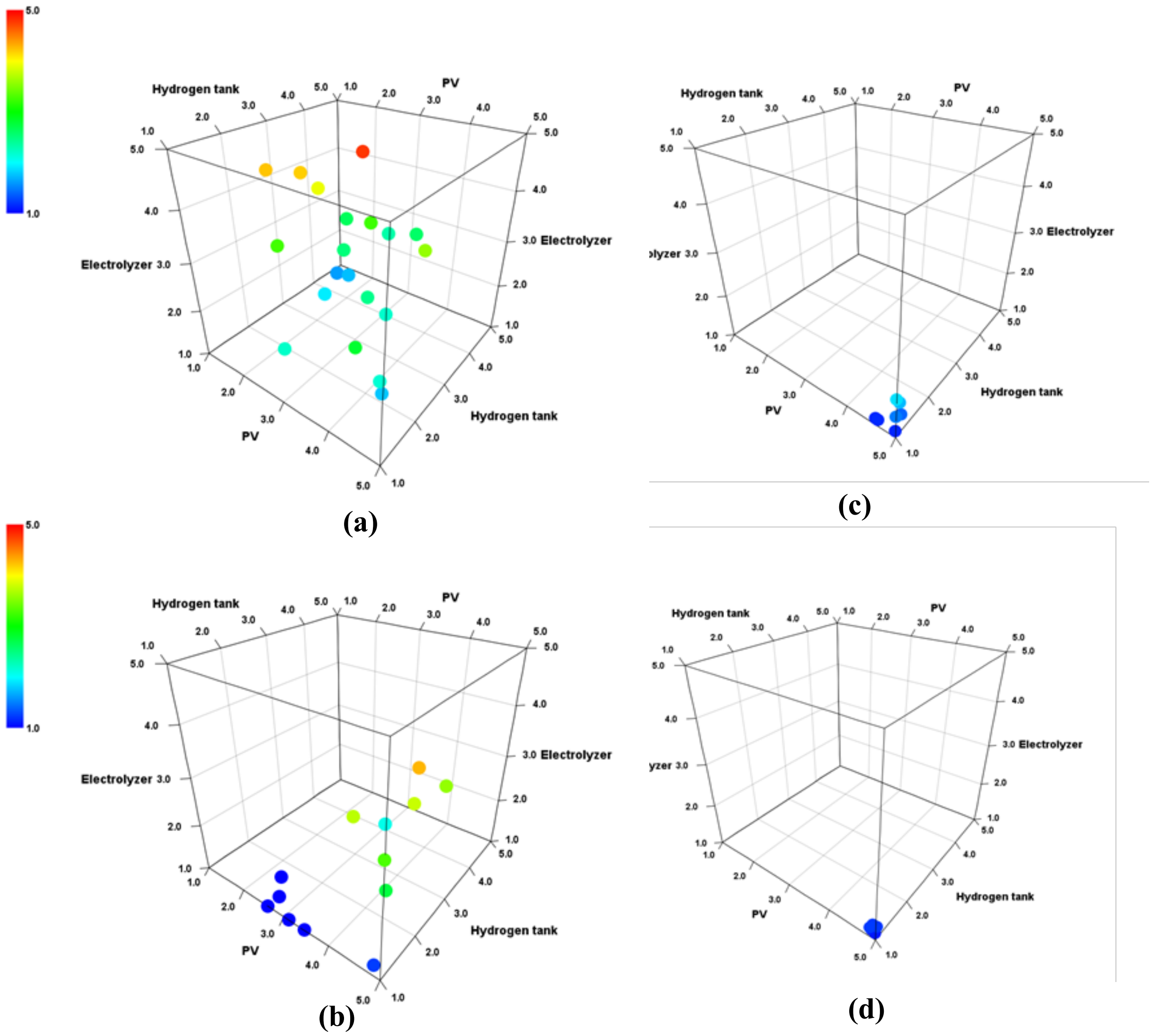


Fig. 39 Particle position (PV Vs. Hydrogen tank Vs. Electrolyzer) in each time step: a=0, b=3, c=9, d=20

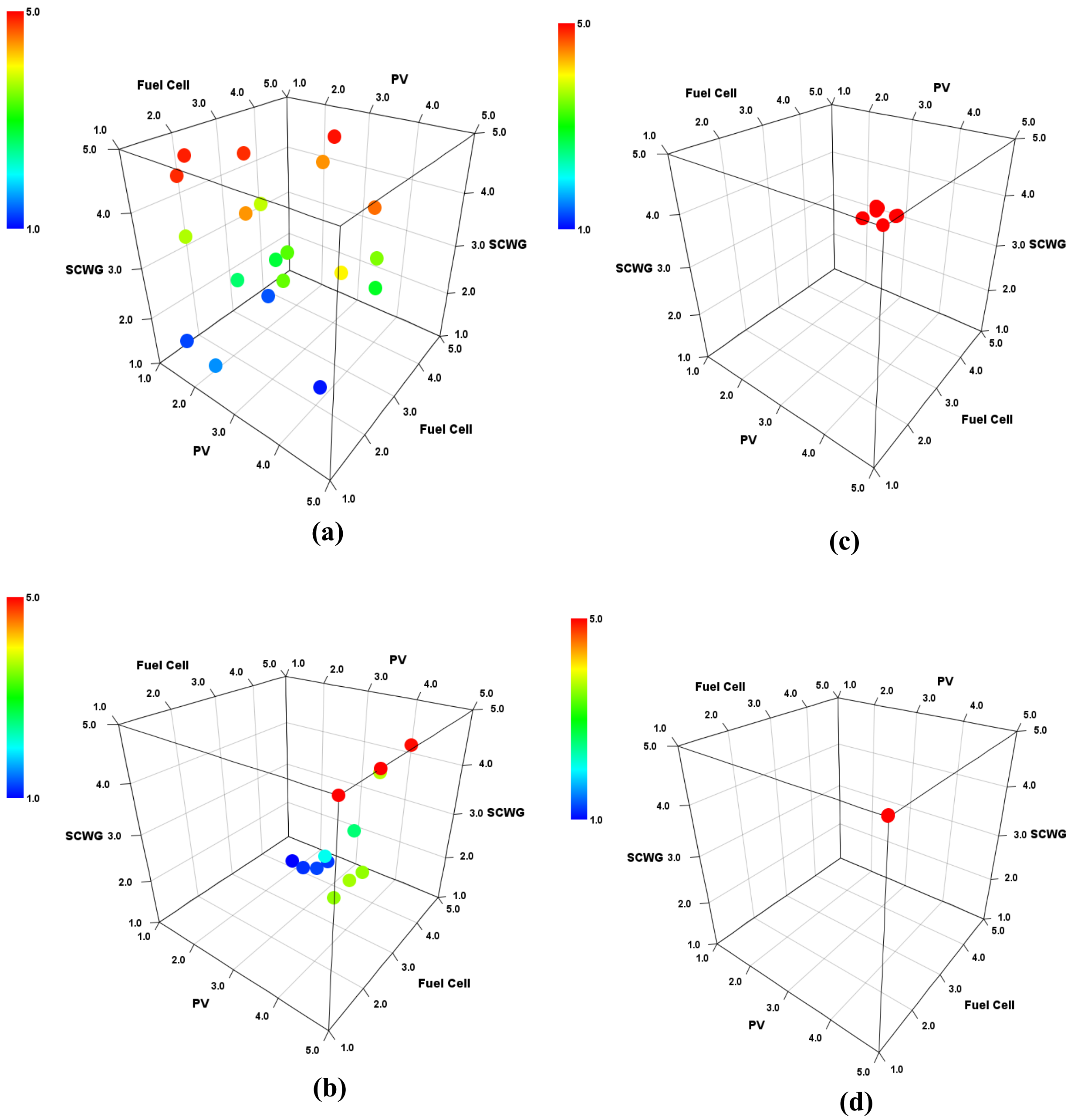


Fig. 40 Particle position (PV Vs. Fuel Cell Vs. SCWG) in each time step: a=0, b=3, c=9, d=20

4.3.2 Scenario 2: Total cost minimization with the limited biomass feedstock for SCWG

This scenario is based on the limited potential of waste biomass availability (including kitchen waste and organic material) which can be produced by each household in Japan. The total amount of annual food waste from the household sector in Japan is estimated about 8.32 million ton [50] . Considering Japan population in 2019 which was about 126.2 million, the total kitchen and food waste produced by each inhabitant can be calculated about 264.3[kg/year]. Take this assumption into consideration that 4 dwellers living in each household, the quantity of the annual food waste from one household is approximated at 262.4[kg/year] which can be fed to the SCWG.

The results of the optimization model for this scenario is shown in Tab. 6. According to the results of the model in this scenario, the PV module and fuel cell provide 39% and 61% of the total electricity demand, respectively.

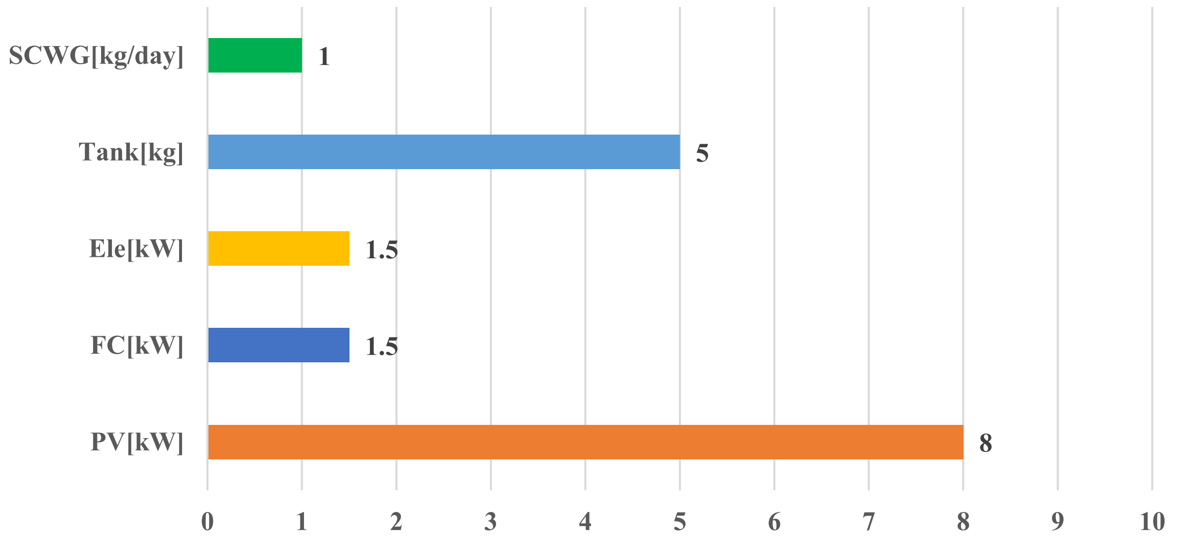
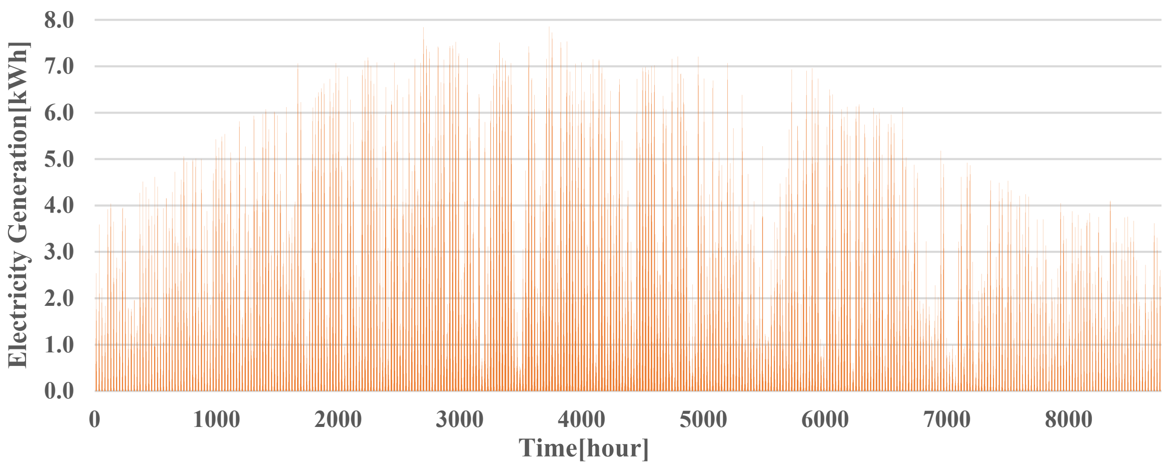


Fig. 41 Optimal configuration of the HRES in scenario 2

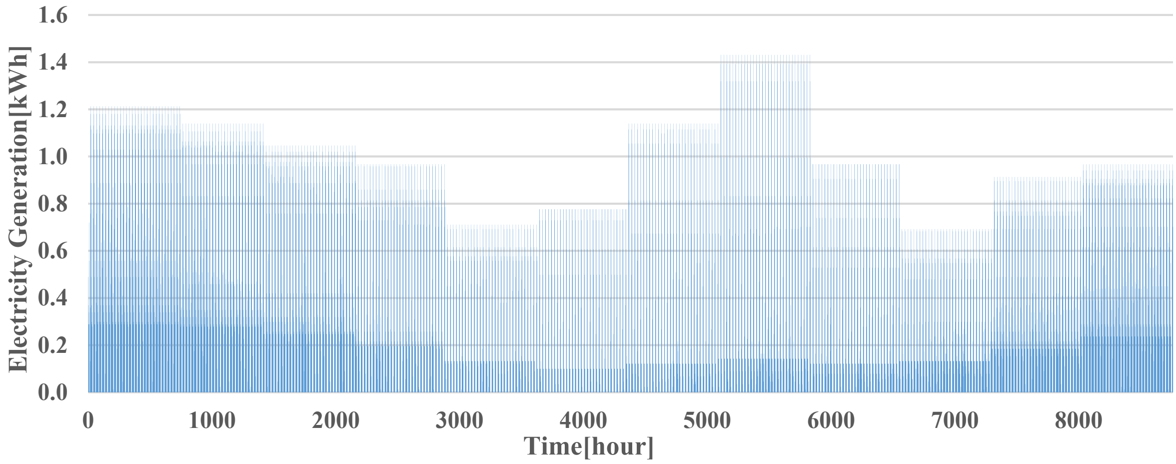
Tab. 6 Electricity supply-demand balance in scenario 2

Demand (kWh)	
External Load	4373.16
Electrolyzer electricity consumption	4017.88
Supply (kWh)	
Solar PV	9344.74
Fuel Cell	2675.74
Balance	3629.44 (Surplus electricity generated from the PV)

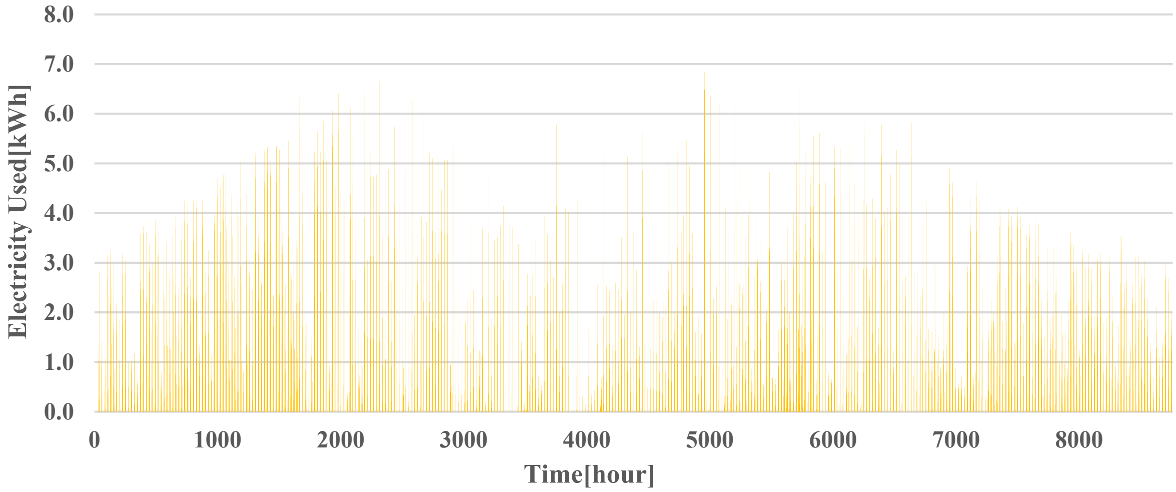
Since, the amount of annual biomass feedstock is limited in this scenario, therefore, the required hydrogen for feeding the fuel cell should be provided by the solar electrolyzer. During the cold seasons, the demand of hydrogen increases by the fuel cell and therefore, the SCWG has the pivotal role as the optional function for hydrogen generation which is basically due to lack of solar electricity generation during this period. Since, the amount of annual kitchen waste generated from one household is limited, therefore, additional sources of wet biomass such as sewage sludge from the nearby commercial buildings needs to be considered in this scenario.



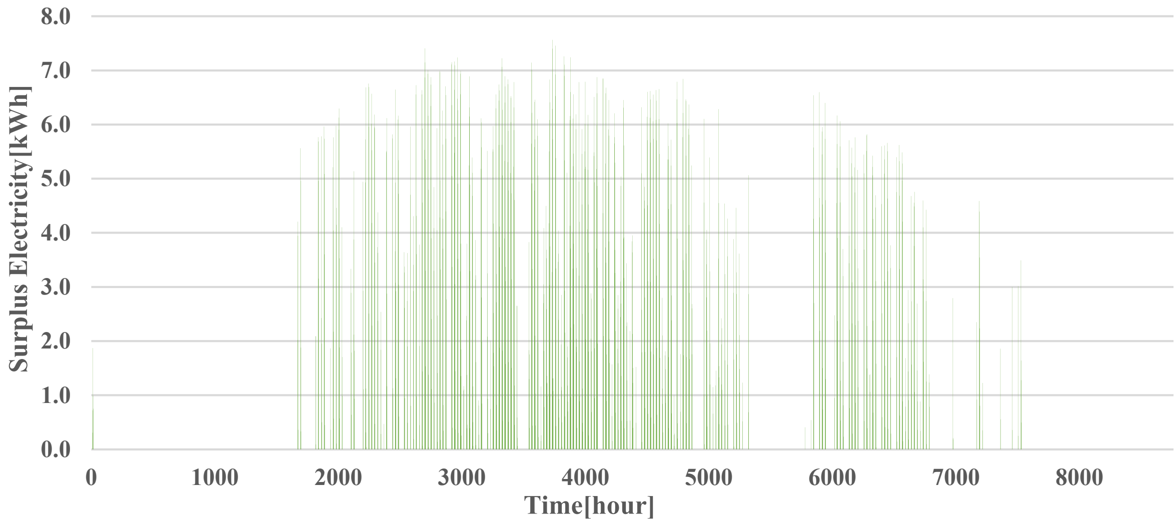
a) PV module electricity generation



b) Fuel cell output electricity generation



c) Electricity used in electrolyzer



d) Surplus electricity from PV module

Fig. 42 Hourly electricity supply/demand scenario 2

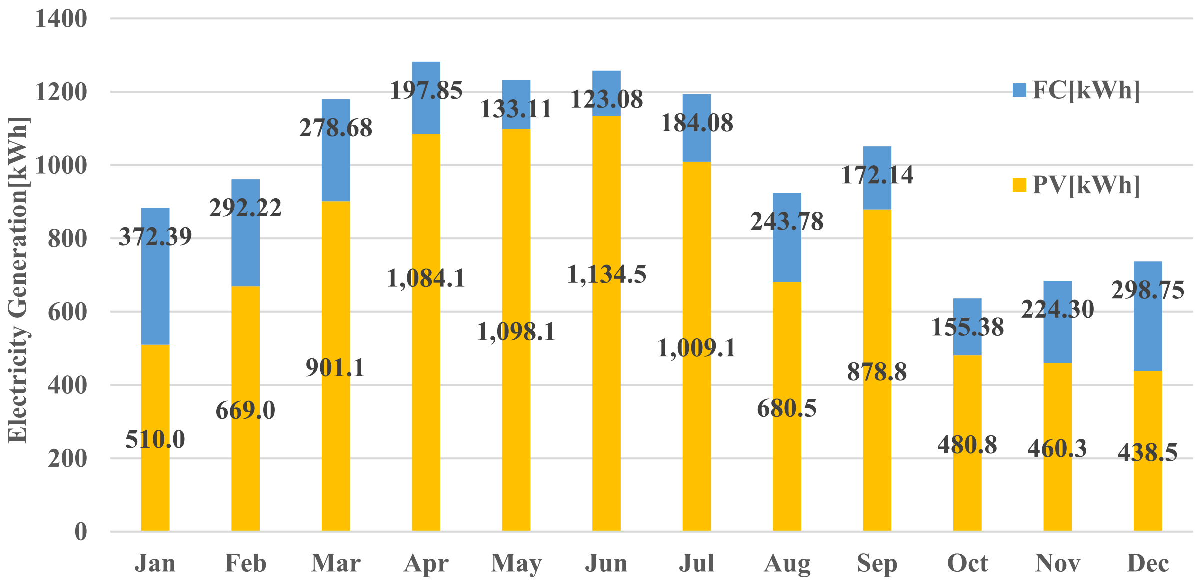


Fig. 43 Monthly average electricity generation in scenario 2

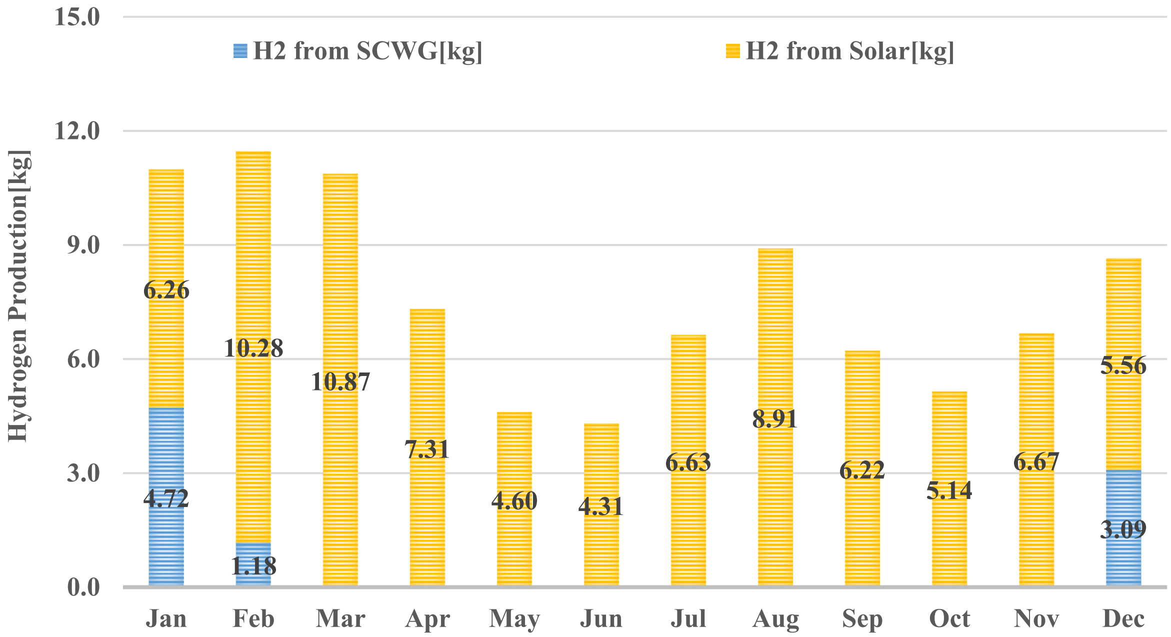


Fig. 44 Monthly average hydrogen production in Scenario 2

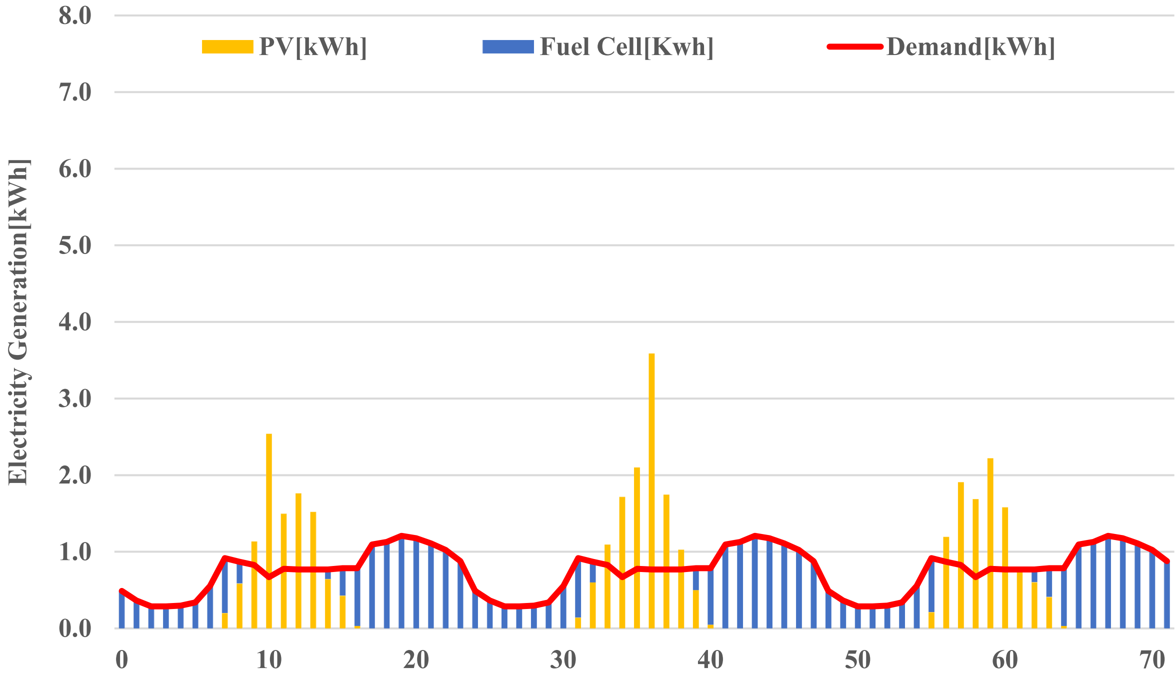


Fig. 45 Hourly electricity generation from Jan.1 - Jan.4 in Scenario 2

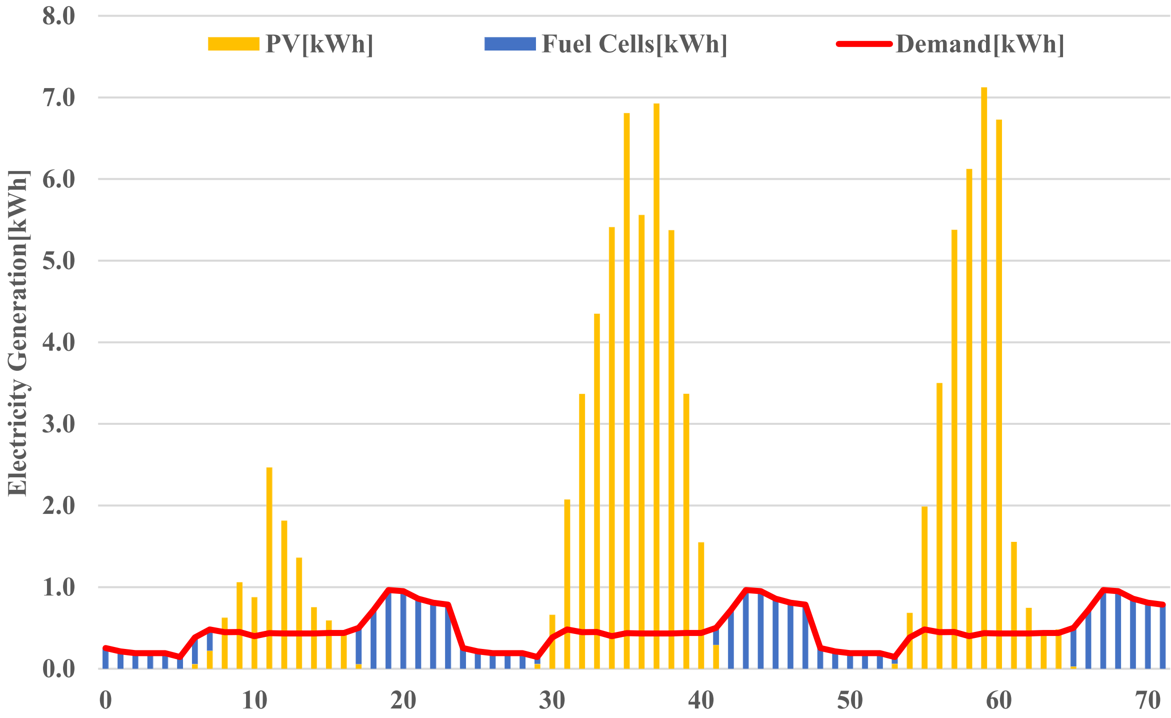


Fig. 46 Hourly electricity generation from April.1 - April.4 in Scenario Ⅱ

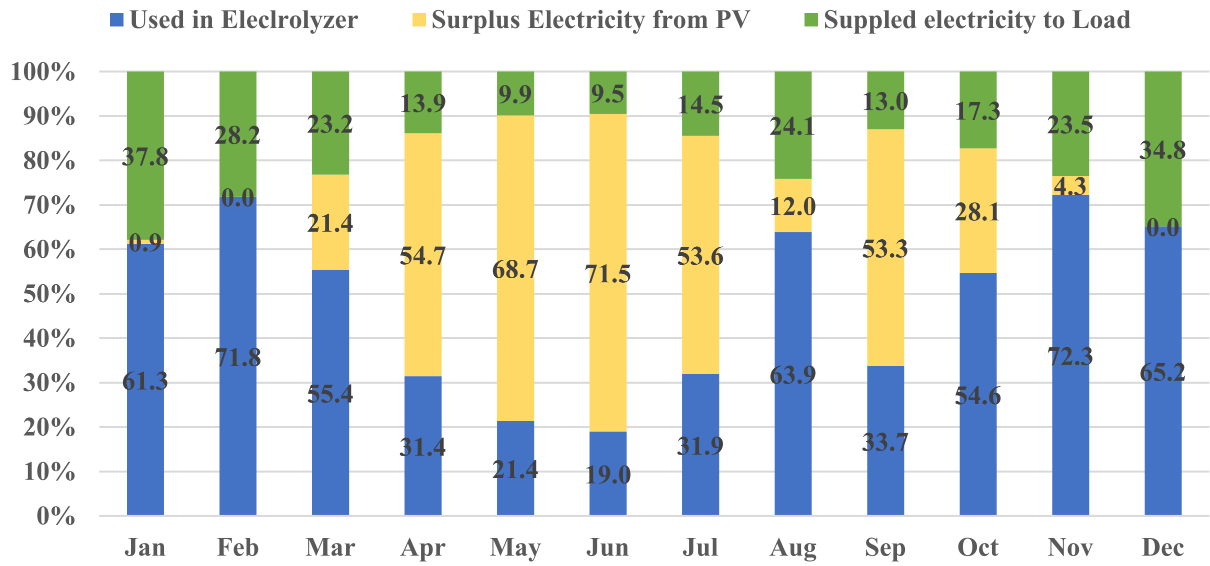


Fig. 47 PV monthly electricity generation in Scenario2

The optimal solution in this scenario is obtained at the discounted annual cost of 244,550[JPY/year]. The LCOE is estimated at 55.92[JPY/kWh] which is 12.5% higher than the Scenario I which is mainly due to deploying more installed capacity of the PV modules in this scenario. Comparison between scenario I and scenario II shows that the amount of power generated from the fuel cell remains unchanged, but the size of the solar electrolyzer extremely increases in order to provide sufficient amount of hydrogen for the fuel cell. Fig. 49 and Fig. 50 show the PSO process through the swarm's motion in this scenario.

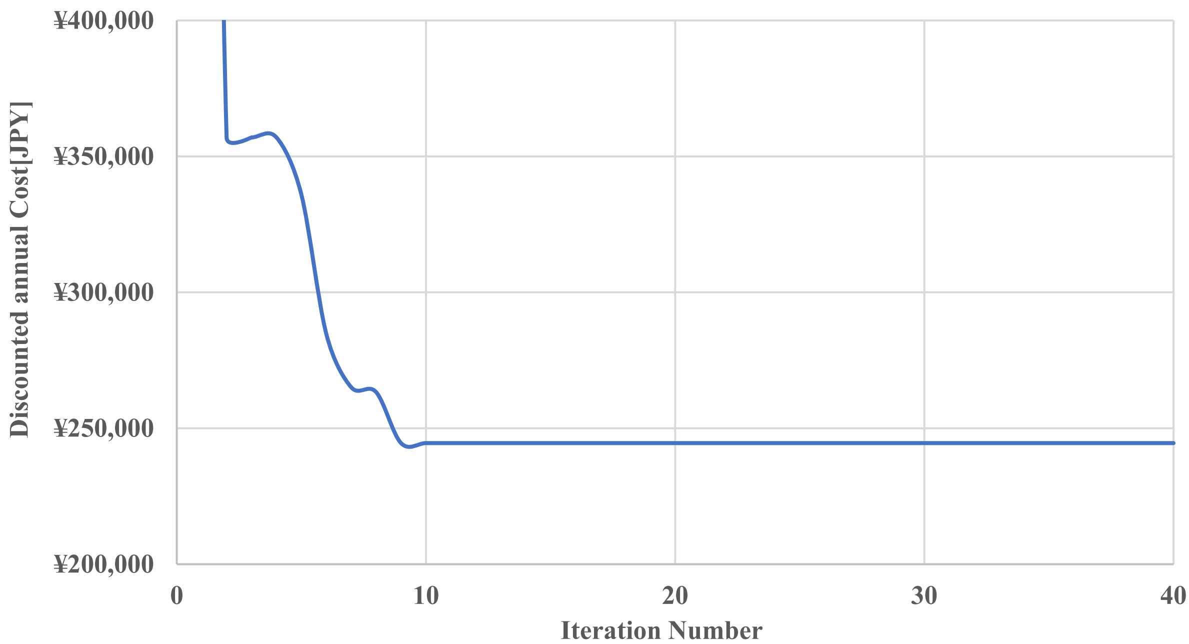


Fig. 48 Variation of the total cost of the system versus the number of iterations in Scenario 2

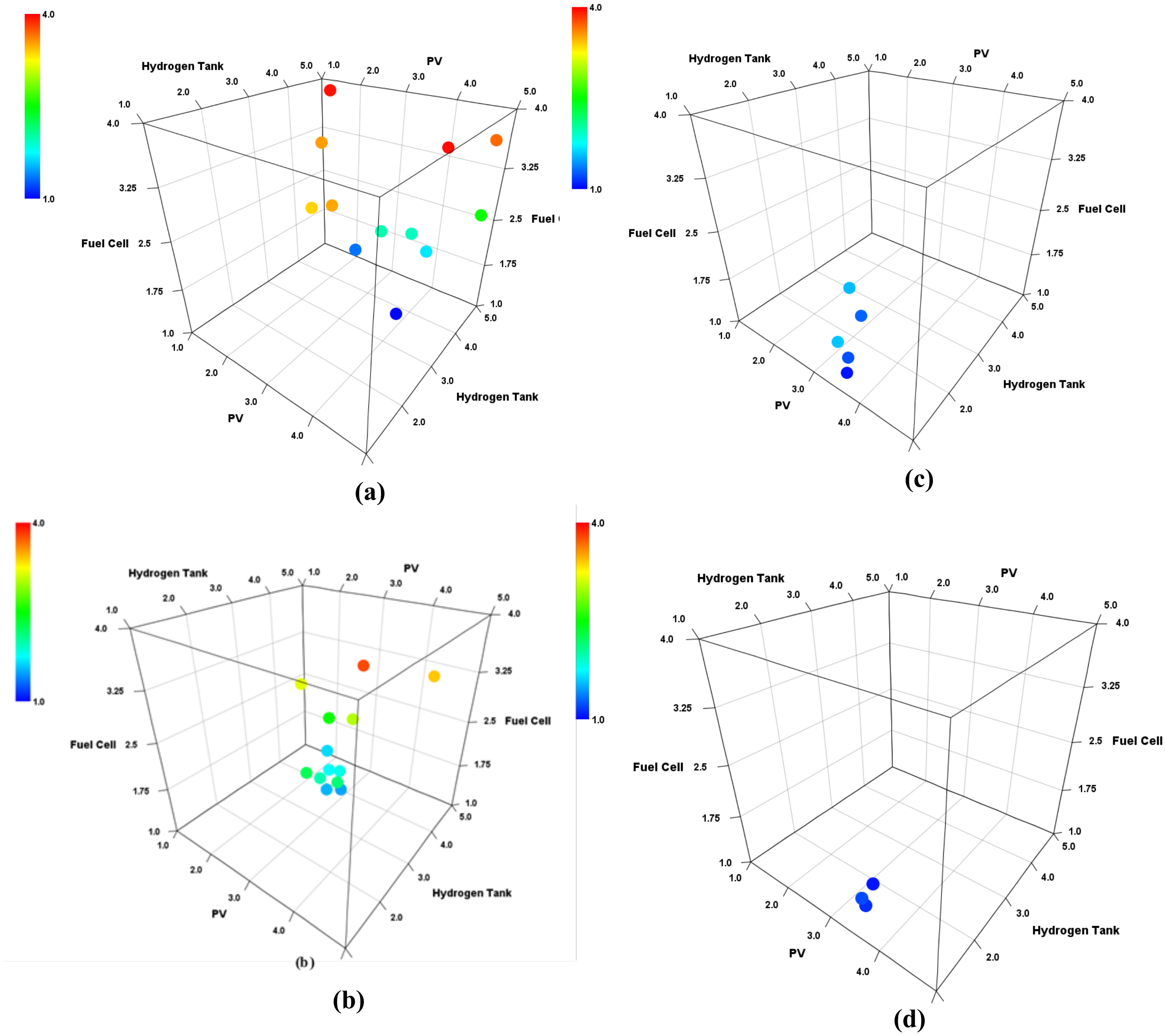


Fig. 49 Particle position (PV Vs. Fuel Cell Vs. Hydrogen Tank) in each time step: a=0, b=3, c=9, d=20

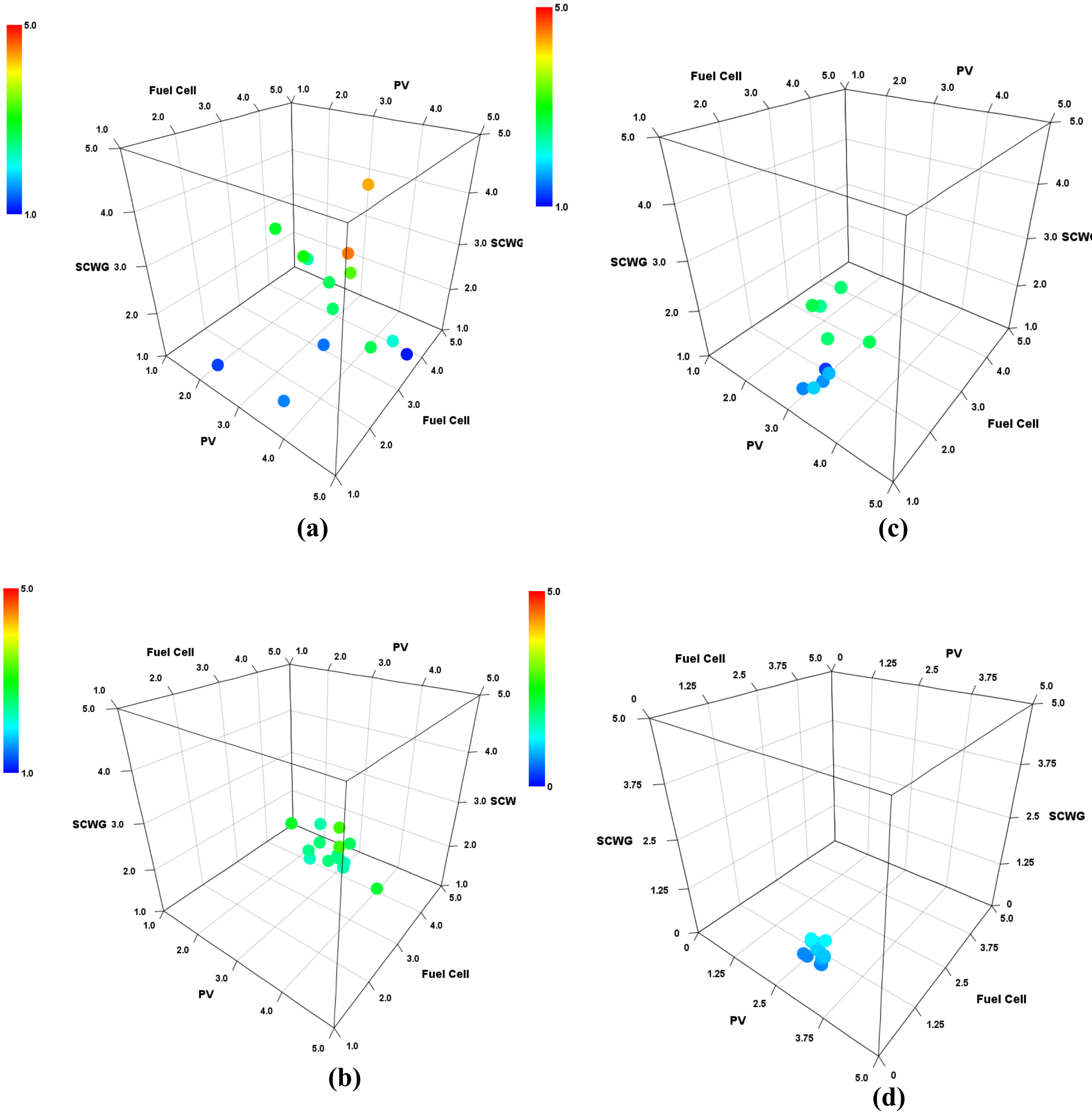


Fig. 50 Particle position (PV Vs. Fuel Cell Vs. Hydrogen Tank) in each time step: a=0, b=3, c=9, d=20

4.3.3 Scenario 3: Profit maximization together with Feed-In-Tariff scheme

As explained in chapter 2, the profit maximization problem is defined to quantify the net profit obtained from selling generated electricity by the proposed HRES to the grid in the selected residential area. Based on this scenario, the total revenue from deploying the proposed HRES can be derived from two ways: 1) replacing purchased electricity which is needed to meet the load requirement with the electricity generated by the HRES and 2) Selling back the surplus electricity generated by the PV module to the grid, considering the FIT scheme. In this study, the average electricity tariff and FIT are considered at 25 JPY/kWh and 28 JPY/kWh, respectively.The optimal configuration and the electricity balance of the HRES in this scenario are reported in Tab. 7. The model estimates the annualized total cost of the system at 262,100[JPY/year]. The LCOE is calculated about 59.93[JPY/kWh], which can guarantee a net profit of 15,140[JPY/year] for the system.

Fig. 53 and Fig. 54 show the annual electricity generation and hydrogen production from the Proposed HRES in this scenario. According to the results, in order to provide the sufficient amount of hydrogen for the fuel cell, both the capacity and the size of the SCWG reactor and PV module will increase. To obtain the maximum profit, the first priority is given to the SCWG to provide enough hydrogen and fill the hydrogen tank. Therefore, the surplus solar electricity would be available for selling back to the grid which will result in increasing the total revenue from electricity generation by the HRES. Based on an official restriction on size of PV panel for the residential applications, the maximum size of the PV module was limited to 10[kW] in this scenario.

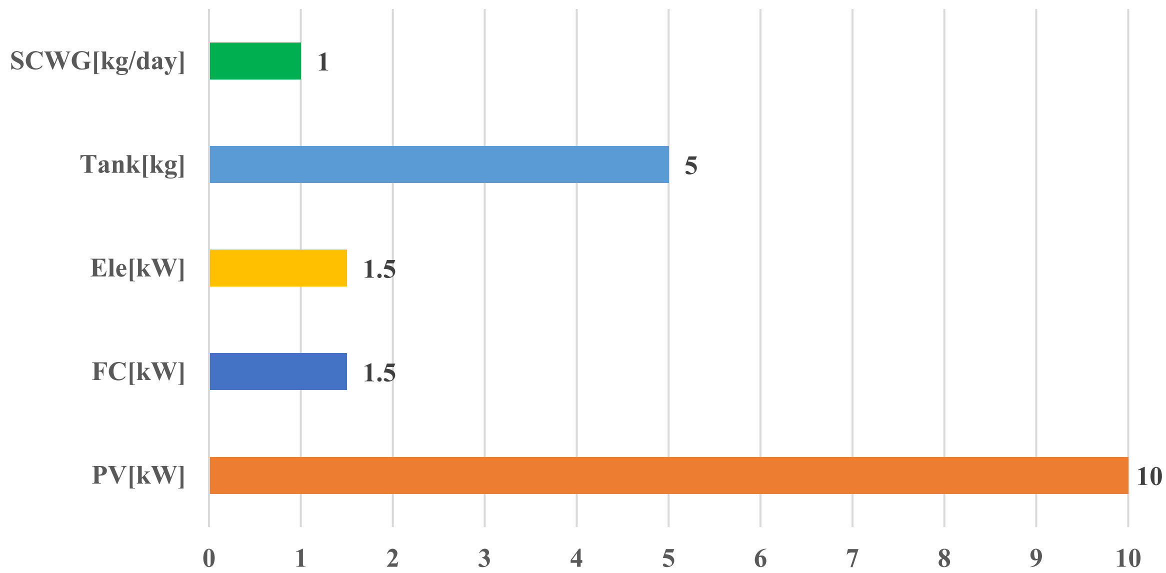
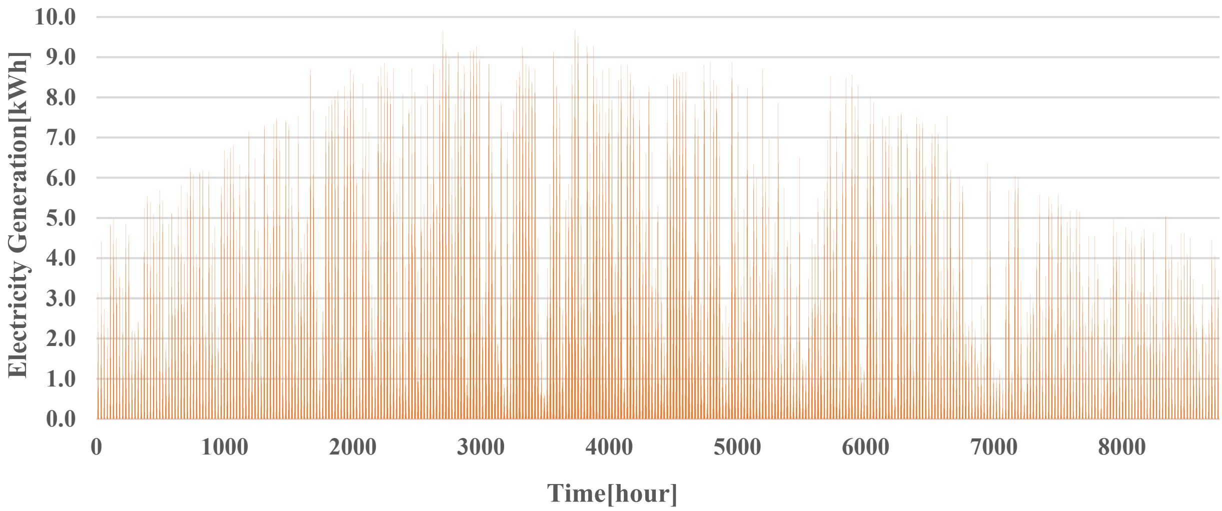


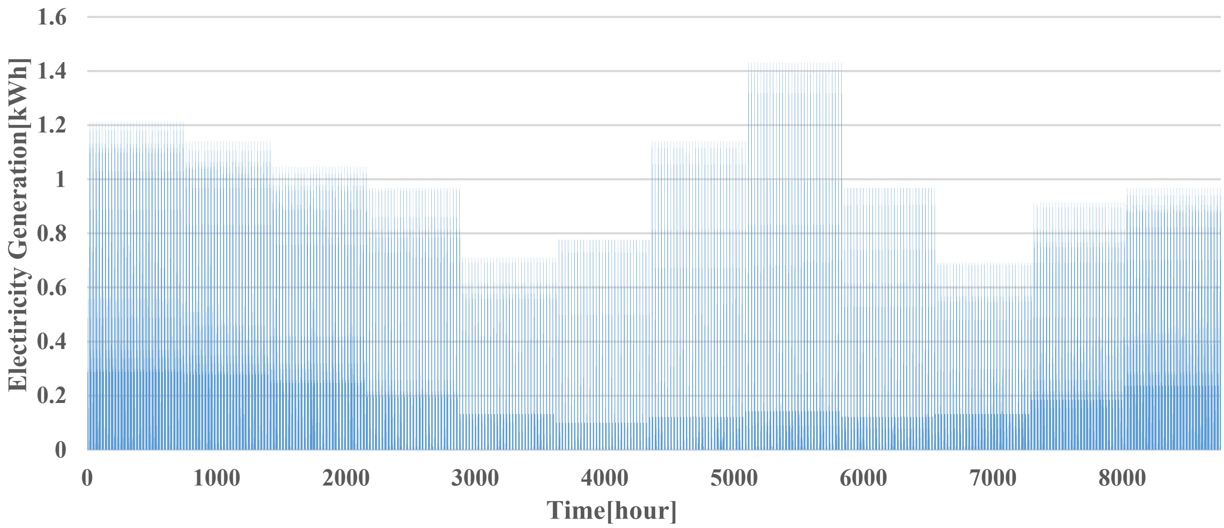
Fig. 51 Optimal configuration of the HRES in scenario 3

Tab. 7 Electricity supply-demand balance in scenario 3

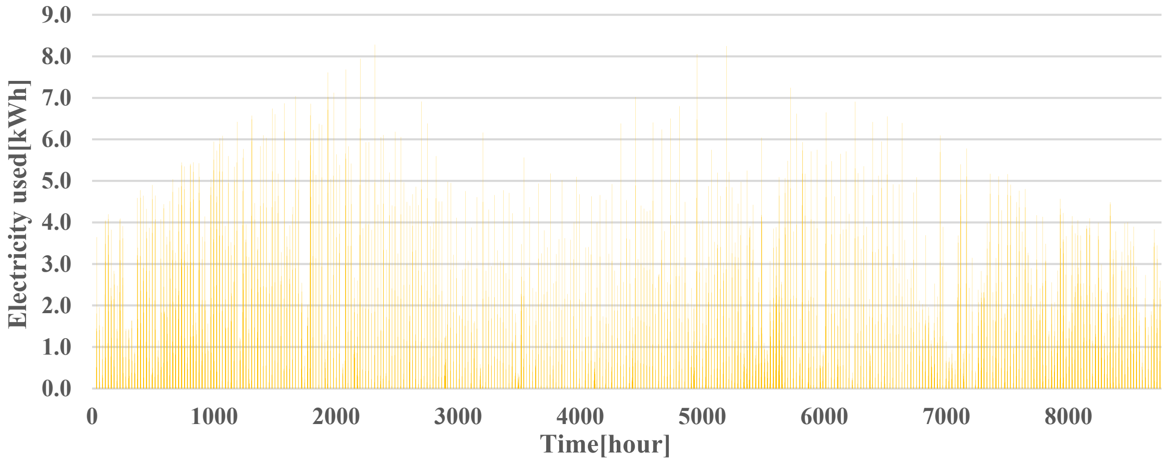
Demand (kWh)	
External Load	4373.16
Electrolyzer electricity consumption	4159.94
Supply (kWh)	
Solar PV	11501.22
Fuel Cell	2647.12
Balance	5615.24 (Surplus electricity generated from the PV)



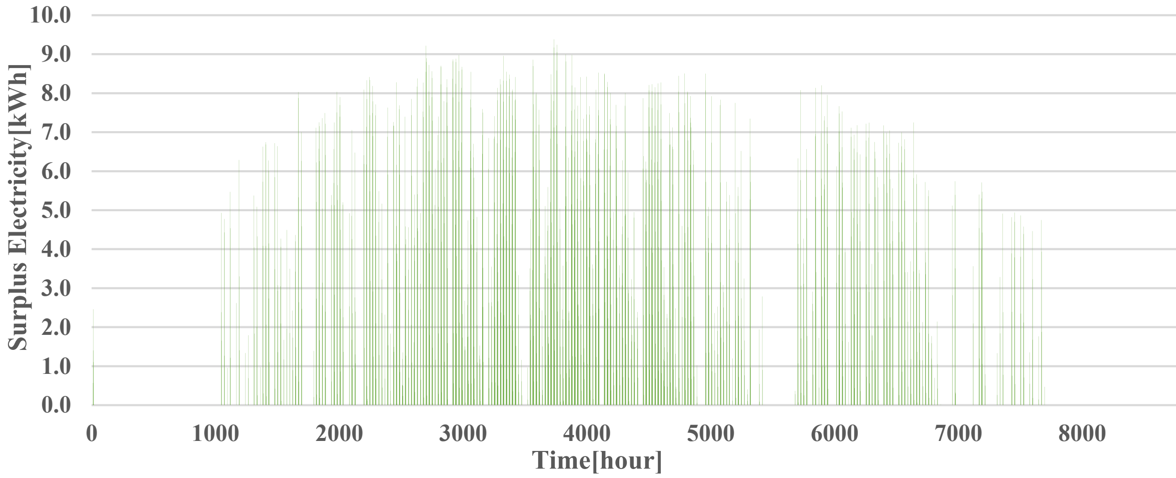
a) PV module electricity generation



b) Fuel cell output electricity generation



c) Electricity used in electrolyzer



d) Surplus electricity from PV module

Fig. 52 Output power transition in each timesteps of scenario 3

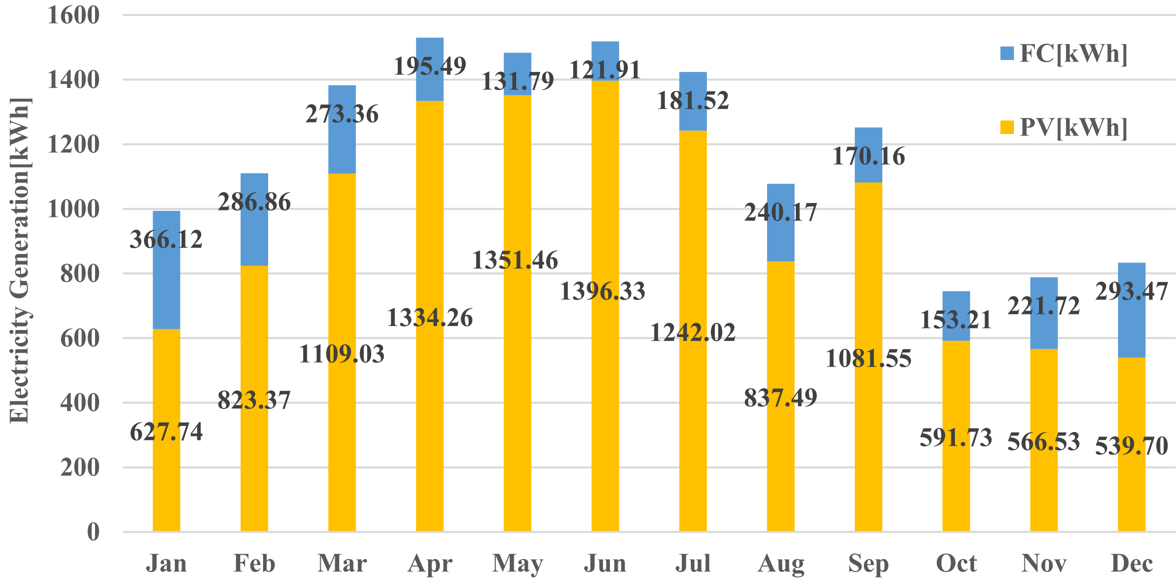


Fig. 53 Monthly average electricity generation in scenario 3

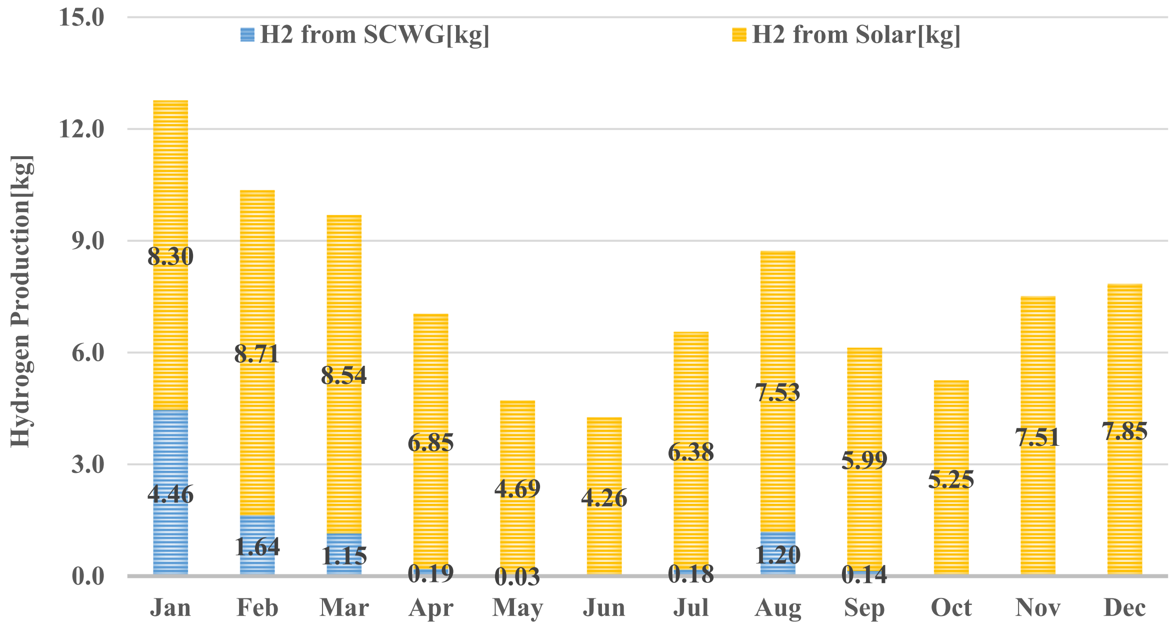


Fig. 54 Monthly average Hydrogen production in Scenario 3

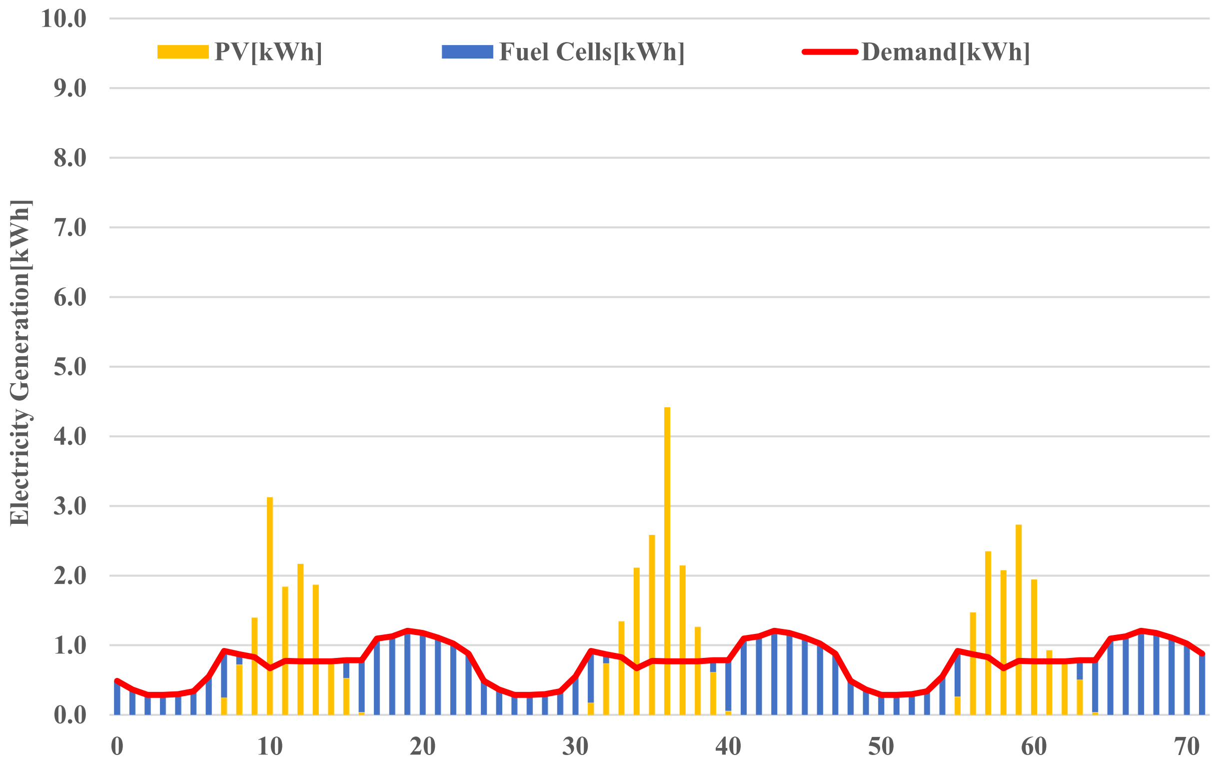


Fig. 55 Hourly electricity generation from Jan.1 - Jan.4 in Scenario 3

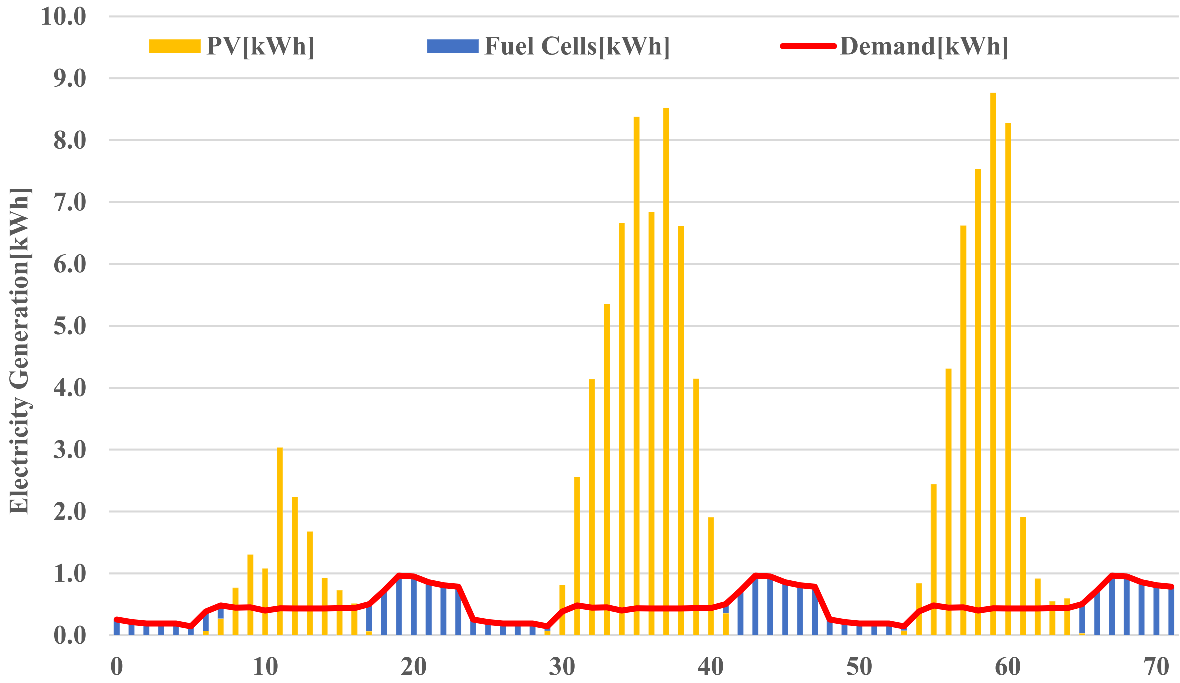


Fig. 56 Hourly electricity generation from April.1 - April.4 in Scenario 3

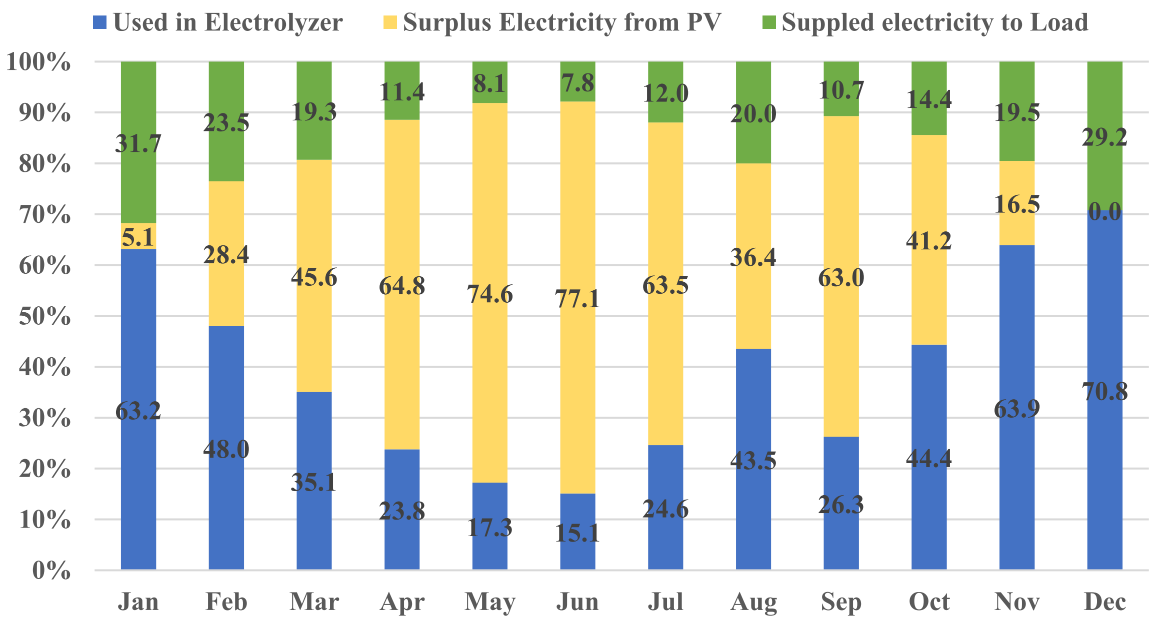


Fig. 57 PV monthly electricity generation in scenario 3

During winter season, the share of surplus electricity is around 0-1% which is negligible due to the severe weather conditions and higher demand of electricity in the selected residential area. In summer and spring, the demand electricity decreases, therefore the HRES will be able to supply more surplus electricity to the grid.

4.4 Model Validation

Although there exist a very few studies on combined solar hydrogen and biomass supercritical water gasification, but none of these studies present a detailed balance of plant configuration and therefore it would be difficult to compare the results obtained here with these studies. To this aim, the model validation was carried out through comparing the results obtained from the PV module and the SCWG with other similar studies. The check the validity of whole system, the model results was compared with the results of the HOMER software which was developed by NREL.

Fig. 58 shows the comparison between the amount of power generated from the PV module in this study and the NEDO[1] database [51] which indicates good agreement between the model and NEDO results.

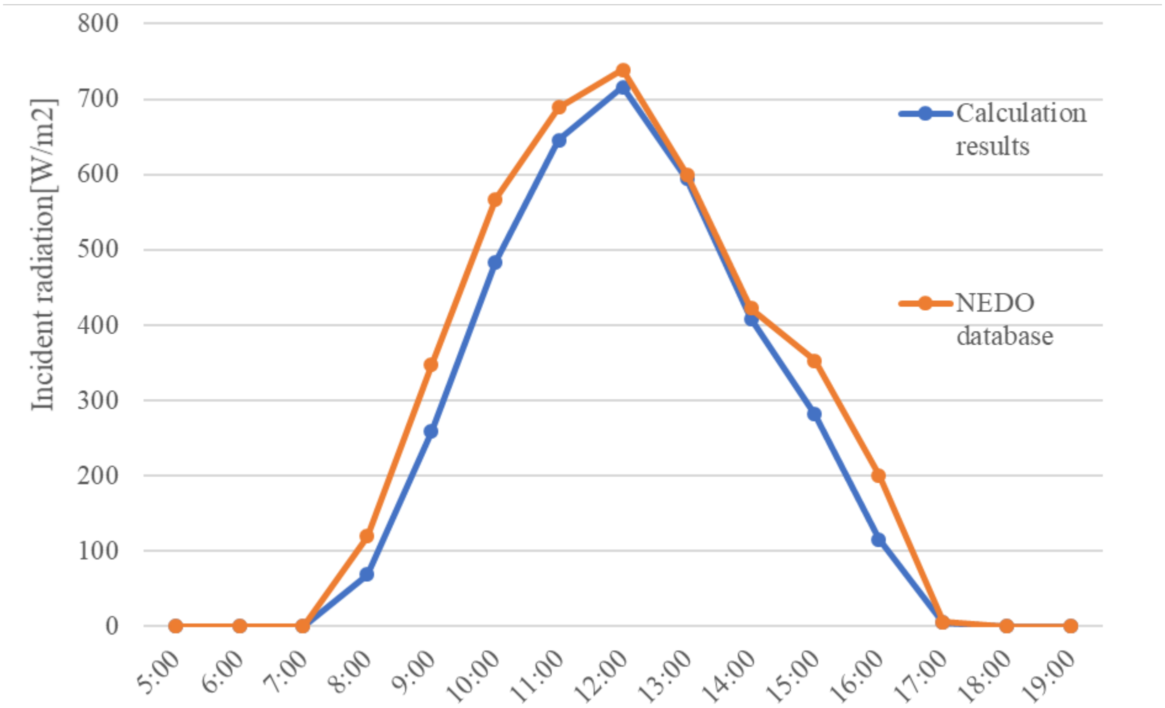


Fig. 58 Comparison between calculation PV module results and NEDO system

Comparison between the SCWG model developed here with experimental data is validated in Tab. 8, in terms of hydrogen yields. The biomass feedstock is glucose for all cases. Different operating temperature and pressure are reported in the experiments. As can be seen the model captures the experimental data well at the operating temperature of 650 ^{0}C.

Tab. 8 Comparison between the SCWG model and various experiments

	Process conditions		Hydrogen Yield* (%)
	Temp (^0C)	P (bar)	
Farzaneh [9]	650	230	50.1
Antal [52]	745	280	46.0
Kruse [53]	600	250	57.2
Holgate [54]	600	246	61.3
Yu [55]	600	345	61.6
GA [56]	650	230	50.0
This research	600	230	52.9

*Mole fraction of Hydrogen in the product gas

Fig. 59 shows the schematic view of the proposed HRES which was developed in HOMER software. The comparison between the model results and the HOMER software results are given in Fig. 61 and Tab. 9 Comparison of the LCOE between PSO calculation and HOMER software Tab. 9, based on Scenario 2.

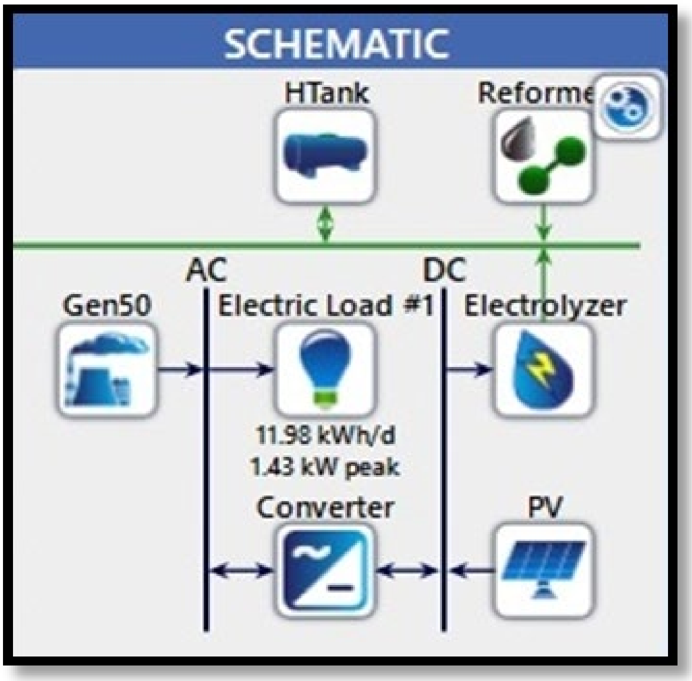


Fig. 59 HOMER software schematic view

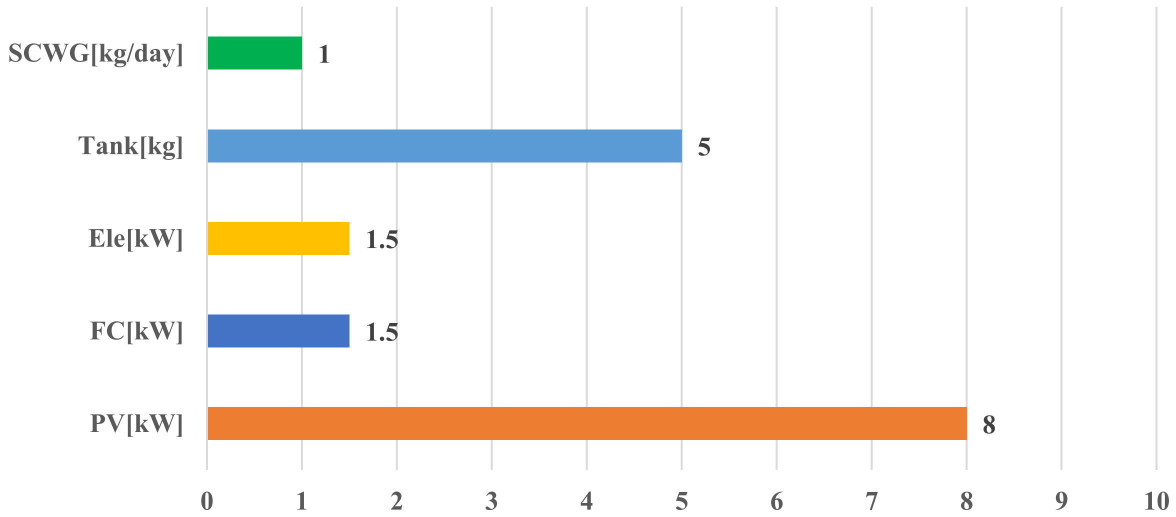


Fig. 60 Optimal configuration of PSO calculation

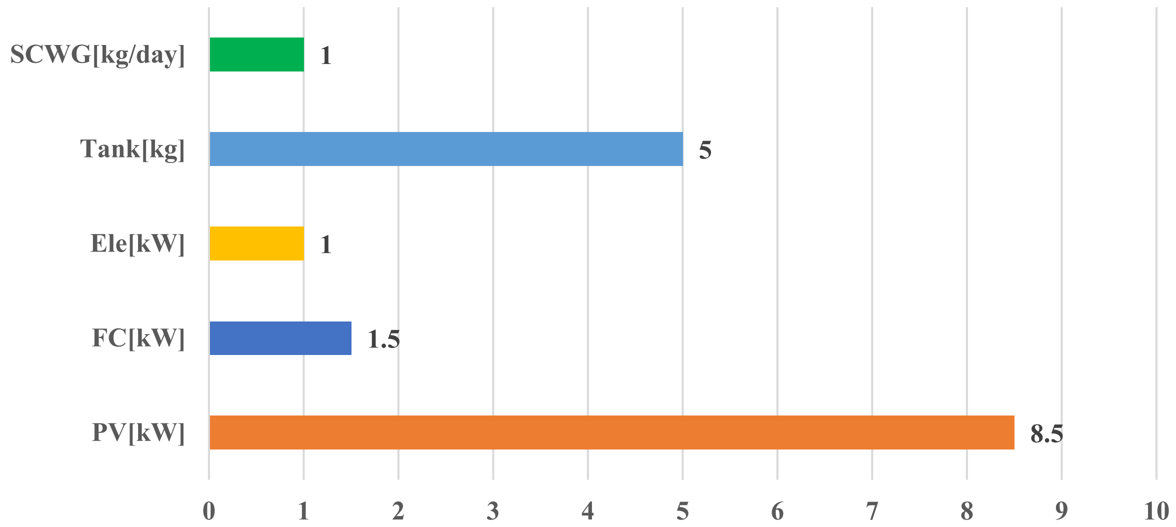


Fig. 61 Optimal configuration of HOMER calculation in this research

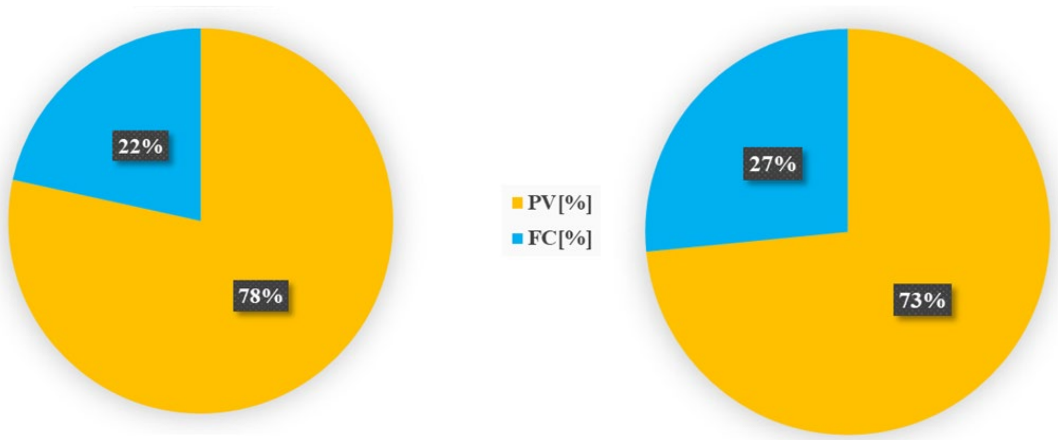


Fig. 62 Electricity generation based on the Model results and HOMER (Left: Model calculation Right: HOMER software)

Tab. 9 Comparison of the LCOE between PSO calculation and HOMER software in Scenario 2

	PSO	HOMER
Annual Supplied Electricity to Load[kWh]	4373.2	4373.2
LCOE[JPY/kWh]	55.9	60.6

Chapter 5

Conclusions

Chapter 5: Conclusions

The main aim of this work in this thesis was to carry out a techno-economic analysis for a proposed HRES which consists of PV modules, Fuel Cell and SCWG reactor in Shinchi-machi, Fukushima prefecture. To this aim, the main objective was set by the following tasks:

1. A comprehensive literature survey on different types of the HRES was carried out. In the case of the utilization of biomass resources, the conventional methods to convert to the energy are combustion and gasification system. As an alternative to the conventional gasification, the supercritical water gasification (SCWG)process uses water over 22 MPa and 374 (critical point) as the gasifying agent to decompose the wet biomass feedstock, allowing to achieve a much higher ratio of gasification and hydrogen generation. Although the high cost of the feedstock is a challenging issue in utilizing the SCWG, low-cost feedstocks like sewage sludges are widely available to be used as a heavily moisture-laden feedstock in this process. The thermochemical conversion process of these feedstocks generates clean products with less NOx and SOx emissions in the SCWG
2. An innovative HRES was introduced with specific emphasis on the integration of renewable generation into the power grid. The proposed HRES was based on the combination of hydrogen generation from two sources: (1) SCWG process of the residential kitchen waste and organic wastewater and (2) solar water electrolysis process which uses the surplus electric power generated by the solar cells. The fuel cell converts hydrogen into electrical power, which can be used during the periods when the sunlight is not available. So, the proposed HRES forms a composite energy system capable of all-weather conditions.
3. In order to evaluate the technical and economic feasibility of HRES two optimization criterions of: 1) Cost minimization 2) Profit Maximization was considered in this research. First, the cost minimization model evaluates the total cost of HRES such as capital investment, operation, maintenances and fuel cost. The profit maximization includes the total cost of HRES and revenue from selling surplus solar electricity under FIT scheme. An optimization algorithm was developed, using the PSO method in order to find the optimal configuration of the proposed HRES in the selected study area, a residential area which is located in Shinchi-machi, Fukushima prefecture.
4. The summary results of the optimization model for three scenarios are reported in Tab. 10 and Tab. 11.

Tab. 10 Optimal configuration based on each scenario

Scenarios	Component capacity				
	PV [kW]	Fuel Cells [kW]	Hydrogen Tank[kg]	Electrolyzer [kW]	SCWG [kg/hour]
1: Cost minimization with unlimited biomass feedstock	4.5	1.5	5	1	2.5
2: Cost minimization with limited biomass feedstock	8	1.5	5	1.5	1
3: Profit maximization with limited biomass feed	10	1.5	5	1.5	1

Tab. 11 Techno-economic analysis results for the different scenarios

Scenarios	Power mix [%]		Annual Hydrogen Production mix [%]		Annual Biomass Consumption [kg]	Total cost [JPY/year]	LCOE [JPY/kWh]	LCOE-including the annual profit [JPY/year]
	PV	FC	PV	SCWG				
1: Cost minimization with unbound biomass feed	66	34	45	55	1933.7	¥213,800	¥48.89	-
2：Cost minimization with limited biomass feed	78	22	90	10	264.3	¥244,550	¥55.92	-
3: Profit maximization with limited biomass feed	81	19	90	10	264.3	¥262,100	¥59.93	¥56.47

Comparison between scenario 1 and scenario 2 showed that the capacity of electrolyzer and PV module with limited biomass feedstock increases. The highest demand of solar hydrogen in scenario 2 has resulted in increasing the share of the PV panels from 45% to 90% in electricity generation mix and decreasing the share of the fuel cell from 55% to 10%. The major part of the solar power was consumed in the electrolyzer to support the required level of hydrogen consumption in the fuel cell.

Comparison between scenario 2 and scenario 3 revealed the role of PV module in increasing the profit through selling back the surplus electricity to the grid, using the FIT mechanism. The model was employed to perform sensitivity analyses of the LCOE with respect to the size of solar-powered hydrogen generation system (Solar PV + electrolyzer). The result of the sensitivity analysis showed that the substitution of biomass hydrogen with solar hydrogen can significantly influence the LCOE of the system. By increasing the amount of hydrogen produced by the electrolyzer, the total cost of the system increases. Therefore, the reduction of the cost of the solar hydrogen system turns out to be by far the most important cost driver. However, under the profit maximization scenario with limited biomass feedstock, the capacity of the solar electricity increases when the FIT system is enforced.

There are future works which should be considered:

- The detail design and cost of the post-treatment equipment in the proposed HRES including the hydrogen separation unit such as the pressure swing adsorption (PSA) which removes its contaminants from the SCWG syngas should be taken into consideration.
- The necessity of thermal load calculation in the energy balance should be taken into account. In the proposed SCWG, the recovered heat from the flue gas of the fuel cell can be used to preheat the feedstock. In addition, the off-gas produced by the system can be used in a fired heater to bring the feedstock to the required reactor inlet temperature. It is also necessary to estimate the possibility of cogeneration using exhaust heat in the fuel cells. The benefits from surplus thermal energy from the system which is available for export or other in-plant uses, such as hot utilities (hot water or steam) can be added to the cost-benefit analysis of the system.

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Appendix

Appendix.1 - The source cord of schematic model in this thesis

```
Sub Main()
    Dim Ppv(5), Ph2(5), Pel(5), Pfc(4), Pscwg(5), cost, c1, c2,
inertia, dcomp As Double
    Dim i, j, k, l, n, p, flag, iteration, comp As Integer
    Dim Particle() As Variant

    n = 5 'Demension number
    p = 20 'Particle number
    iteration = 40
    'Iteration number

    '----------------Component Size Definition---------------------
-----
    'definition pv
    For i = 1 To 5
        Ppv(i) = 6500 + i * 500
    Next i

    'definition H2tank
    For i = 1 To 5
        Ph2(i) = 5000 + i * 2500
    Next i

    'definition electrolyzer
    For i = 1 To 5
        Pel(i) = i * 1000
    Next i

    'definition fc
    For i = 1 To 4
        Pfc(i) = 1000 + i * 500
    Next i

    'definition scwg
    For i = 1 To 5
        Pscwg(i) = 500 + i * 500
    Next i
    '-----------------Component Size Definition end----------------
------


    '---------------------------------------------initialization--
-----------------------------------
    ReDim Particle(1 To p, 1 To n + 1) 'p = number of particles
                               'p,1:particle nuber, 2:Ppv, 3:Ph2,
4:Pel, 5:Pfc
    ReDim v(1 To p, 1 To n) As Double
    ReDim x(1 To p, 1 To n) As Double


    'initialization of particles & x arrays
    For i = 1 To p
        Particle(i, 1) = i
```

```
        For j = 2 To n + 1
            Randomize
            If (j = 5) Then
                x(i, j - 1) = (3 * Rnd) + 1
            Else
                x(i, j - 1) = (4 * Rnd) + 1
            End If
            comp = Format(x(i, j - 1), "0")

            Select Case j
                Case 2
                    Particle(i, j) = Ppv(comp)
                Case 3
                    Particle(i, j) = Ph2(comp)
                Case 4
                    Particle(i, j) = Pel(comp)
                Case 5
                    Particle(i, j) = Pfc(comp)
                Case 6
                    Particle(i, j) = Pscwg(comp)
            End Select
        Next j
    Next i

    'initialization of v arrays
    For i = 1 To p
        For j = 1 To n
            Randomize
            dcomp = 1 * (Rnd - 0.5)
            v(i, j) = dcomp
        Next j
    Next i

    ReDim Output(1 To (n * 2) + 2) As Double 'iteration, cost, x4,
v4
    ReDim pbest(1 To p, 1 To (n * 2) + 2) As Double 'iteration
cost,x4,v4
    ReDim gbest(1 To (n * 2 + 3)) As Double  'iteration cost, x4,v4


    ReDim Output(1 To n * 2 + 2) As Double 'iteration, cost, x4, v4
    ReDim pbest(1 To p, 1 To (n * 2) + 2) As Double 'iteration
cost,x4,v4
    ReDim gbest(1 To (n * 2 + 3)) As Double  'iteration cost, x4,v4

    'definition of sheets
    ReDim WS(1 To p) As Worksheet
    For i = 1 To p
        Select Case i
            Case 1
                Set WS(i) = Worksheets("Particle1")
            Case 2
                Set WS(i) = Worksheets("Particle2")
            Case 3
                Set WS(i) = Worksheets("Particle3")
            Case 4
                Set WS(i) = Worksheets("Particle4")
```

```
            Case 5
                Set WS(i) = Worksheets("Particle5")
            Case 6
                Set WS(i) = Worksh
eets("Particle6")
            Case 7
                Set WS(i) = Worksheets("Particle7")
            Case 8
                Set WS(i) = Worksheets("Particle8")
            Case 9
                Set WS(i) = Worksheets("Particle9")
            Case 10
                Set WS(i) = Worksheets("Particle10")
            Case 11
                Set WS(i) = Worksheets("Particle11")
            Case 12
                Set WS(i) = Worksheets("Particle12")
            Case 13
                Set WS(i) = Worksheets("Particle13")
            Case 14
                Set WS(i) = Worksheets("Particle14")
            Case 15
                Set WS(i) = Worksheets("Particle15")
            Case 16
                Set WS(i) = Worksheets("Particle16")
            Case 17
                Set WS(i) = Worksheets("Particle17")
            Case 18
                Set WS(i) = Worksheets("Particle18")
            Case 19
                Set WS(i) = Worksheets("Particle19")
            Case 20
                Set WS(i) = Worksheets("Particle20")
        End Select
    Next i

    inertia = 0.7
    c1 = 1
    c2 = 0.5

    For j = 1 To p
        WS(j).Select
        Output(1) = 0
        Output(2) = 0
        For k = 1 To n
            Output(k + 2) = x(j, k)
            Output(n + k + 2) = v(j, k)
        Next k
        '**
        Range("A5:L5") = Output
    Next j



    '----------------------------------------------initialization
end------------------------------------
```

```
    '-----------------------------------iteration start------------
-----------------------------------------------
    'For i = 1 To iteration
    For i = 1 To iteration
    '---------particle axis---------------
        For j = 1 To p
            WS(j).Select

                If (i = 1) Then
                    pbest(j, 2) = 1000000
                    gbest(2) = 10000000
                    For k = 1 To n
                        pbest(j, k + 2) = x(j, k)
                        pbest(j, k + n + 2) = v(j, k)
                    Next k
                    If (j = 1) Then
                        For k = 1 To n
                            gbest(k + 2) = x(j, k)
                            gbest(k + n + 2) = v(j, k)
                        Next k
                        gbest(2 * n + 3) = j
                    End If
                End If

                 'position and vector calculation-------------------
---------------------------------
                For k = 1 To n
                    v(j, k) = v(j, k) * inertia + c1 * (pbest(j, k +
2) - x(j, k)) + c2 * (gbest(k + 2) - x(j, k))
                    If (Abs(v(j, k)) > 5) Then
                        v(j, k) = v(j, k) / 2
                    End If
                    x(j, k) = x(j, k) + v(j, k)
                    comp = Format(x(j, k), "0")
                    If (comp < 1) Then
                        comp = 1
                        x(j, k) = 1
                        v(j, k) = 0.5
                    ElseIf (comp > 5) Then
                        comp = 5
                        x(j, k) = 5
                        v(j, k) = -0.6
                    End If

                    If (comp > 4 And k = 4) Then
                        comp = 4
                        x(j, k) = 4
                        v(j, k) = -0.6
                    End If

                    Select Case k
                        Case 1
                            Particle(j, k + 1) = Ppv(comp)
                        Case 2
                            Particle(j, k + 1) = Ph2(comp)
```

```
                Case 3
                    Particle(j, k + 1) = Pel(comp)
                Case 4
                    Particle(j, k + 1) = Pfc(comp)
                Case 5
                    Particle(j, k + 1) = Pscwg(comp)
            End Select
        Next k

        For k = 1 To (2 * n + 2)
            Cells(2, k + 1) = pbest(j, k)
        Next k

        For k = 1 To (2 * n + 3)
            Cells(3, k + 1) = gbest(k)
        Next k


        '---------------checking hydrogen balance and
electricity----------------------------------------
        flag = Total_cal(CDbl(Particle(j, 2)),
CDbl(Particle(j, 3)), CDbl(Particle(j, 4)), CDbl(Particle(j, 5)),
CDbl(Particle(j, 6)))

        If (flag = 1) Then
            cost = 1000000
        Else
            cost = Cost_calculation(Particle(j, 2),
Particle(j, 3), Particle(j, 4), CDbl(Particle(j, 5)),
CDbl(Particle(j, 6)))
        End If
        '===============checking hydrogen balance and
electricity==========================================

        '---------------output to sheets-------------------
        Output(1) = i
        Output(2) = cost
        For k = 1 To n
            Output(k + 2) = x(j, k)
            Output(n + k + 2) = v(j, k)
        Next k

        For k = 1 To (n * 2 + 2)
            Cells(5 + i, k) = Output(k)
        Next k
        '---------------output to sheets-------------------


        'updating best parameters------------------------
        '=comparison to personal best
        If (cost < pbest(j, 2)) Then
            pbest(j, 1) = i
            pbest(j, 2) = cost
            For k = 1 To n
                pbest(j, k + 2) = x(j, k)
                pbest(j, n + k + 2) = v(j, k)
            Next k
```

```
                End If

                If (cost < gbest(2)) Then
                    gbest(1) = i
                    gbest(2) = cost
                    For k = 1 To n
                        gbest(k + 2) = x(j, k)
                        gbest(n + k + 2) = v(j, k)
                    Next k
                    gbest(n * 2 + 3) = j
                End If
                'updating best parameters-------------------------

        Next j
    '---------particle axis---------------
    Next i

    MsgBox ("done")

End Sub
Function Total_cal(Ppv, Ph2, Pel, Pfc, Pscwg As Double) As Integer
    'ループ変数設定
    Dim i, j, k, flag, daynumber, l, Counter, judge, x As Integer
    Dim start As String
    Dim PV, Wind, SCWG, Demand, FC, defference, q, P_FC,
Production_H, Sum_PV, Sum_Wind, delta_H, feed, alpha, sumfeed As
Double
    Dim lcoe_PV, lcoe_Wind, rated_H As Double


    '日付変数の設定
    Dim iDays(1 To 12) As Integer
    iDays(1) = 31
    iDays(2) = 28
    iDays(3) = 31
    iDays(4) = 30
    iDays(5) = 31
    iDays(6) = 30
    iDays(7) = 31
    iDays(8) = 31
    iDays(9) = 30
    iDays(10) = 31
    iDays(11) = 30
    iDays(12) = 31

    Dim name_month(1 To 12) As String
    name_month(1) = "Jan"
    name_month(2) = "Feb"
    name_month(3) = "Mar"
    name_month(4) = "Apr"
    name_month(5) = "May"
    name_month(6) = "Jun"
    name_month(7) = "Jul"
    name_month(8) = "Aug"
    name_month(9) = "Sep"
    name_month(10) = "Oct"
    name_month(11) = "Nov"
```

```
    name_month(12) = "Dec"


    judge = 0
    Counter = 4
    hydrogen = Ph2
    rated_H = 0
    flag = 0
    alpha = 0.034
    sumfeed = 0
    limitfeed = 262400
    For i = 1 To 12
        For j = 1 To iDays(i)
            daynumber = daynumber + 1
            '______________________________ここからループ(時間ループ)________
____________________
            For k = 0 To 23
                With Sheets("Total Output")
                    '時間表示
                    .Cells(Counter, "A") = Counter - 3 'ループ数の表示
                    .Cells(Counter, "B") = name_month(i) '月の表示
                    .Cells(Counter, "C") = j '日付の表示
                    .Cells(Counter, "D") = k / 24 '時間の表示

                    '太陽光一表示
                    solar = PVmodule(CDbl(Ppv), daynumber, Counter,
CInt(k))
                    .Cells(Counter, "F") = solar


                    Sum_PV = Sum_PV + solar / 1000

                    'supply and demand comparison
                    defference = solar - (1000 * .Cells(Counter,
"E"))
                    .Cells(Counter, "H") = defference

                '------------hydrogen control--------------------
                    '-------------------fuel cells------------------
                    If (defference < 0) Then
                        If (hydrogen > (Ph2 * 0.05)) Then
                            '-----Fuel Cell Calculation Start------
                            With Sheets("FuelCell")
                                Select Case Pfc ' この値が
                                    Case 1000
                                        .Cells(2, "F") = 35
                                        .Cells(5, "F") = 30
                                    Case 1500
                                        .Cells(2, "F") = 33
                                        .Cells(5, "F") = 48
                                    Case 2000
                                        .Cells(2, "F") = 70
                                        .Cells(5, "F") = 30
                                    Case 2500
                                        .Cells(2, "F") = 60
                                        .Cells(5, "F") = 45
                                    Case 2500
```

```
                                    .Cells(2, "F") = 65
                                    .Cells(5, "F") = 50
                            End Select
                            For l = 11 To 440
                                If .Cells(l, "M") > (-defference)
Then
                                    q = .Cells(l, "A")
                                    P_FC = .Cells(l, "L")
                                    Exit For
                                End If
                            Next l
                        End With
                        hydrogen = hydrogen - q * 3600
                        .Cells(Counter, "J") = P_FC
                        .Cells(Counter, "K") = q * 3600
                        .Cells(Counter, "M") = solar + P_FC
                        .Cells(Counter, "N") = solar
                        '=====Fuel Cell Calculation End======
                    Else
                        'MsgBox ("lack of hydrogen")
                        flag = 1
                    End If


                '----------------hydrogen Production------------
------
                Else

                    .Cells(Counter, "M") = solar - defference

                    '-----------------SCWG----------------------
-
                    If (hydrogen < (0.7 * Ph2)) Then
                        If (sumfeed < limitfeed) Then
                            delta_H = Ph2 * 0.7 - hydrogen
                            feed = delta_H / alpha
                            If (feed > Pscwg) Then
                                feed = Pscwg
                            End If
                            hydrogen = hydrogen + feed * alpha
                            .Cells(Counter, "P") = feed * alpha
                            sumfeed = sumfeed + feed
                            .Cells(Counter, "R") = feed
                        End If
                    End If
                    If (hydrogen < (0.95 * Ph2)) Then
                        defference = defference / 1000 ' Convert
from [W] to [kW]
                        Production_H =
electrolyzer(CDbl(defference), CDbl(Pel))
                        .Cells(Counter, "L") = Production_H
                        hydrogen = hydrogen + Production_H

                        .Cells(Counter, "N") = solar - defference
* 1000
                        .Cells(Counter, "O") = defference * 1000
                    Else
```

```
                            Production_H = 0
                            .Cells(Counter, "L") = Production_H
                            hydrogen = hydrogen + Production_H

                            .Cells(Counter, "N") = solar - defference
                            .Cells(Counter, "O") = defference
                            .Cells(Counter, "Q") = defference
                        End If
                    End If


                    'Output amount of hydrogen
                    .Cells(Counter, "I") = hydrogen

                    '================hydrogen
control==================

                    Counter = Counter + 1
                    End With

                    'Exception handling(例外処理)------------------
                    If flag = 1 Then Exit For
                    'Exception handling(例外処理)==================

                Next k
                  '==============ここまでループ(時間ルー
プ)=================

                'Exception handling(例外処理)------------------
                If flag = 1 Then Exit For
                'Exception handling(例外処理)==================
            Next j

            'Exception handling(例外処理)------------------
            If flag = 1 Then Exit For
            'Exception handling(例外処理)==================
        Next i

        Total_cal = flag

End Function
Function Cost_calculation(Ppv, Ph2, Pel, Pfc, Pscwg As Double) As
Double

    Dim totalcost As Double
    Dim unit(5), om(5), LT(5) As Double

    unit(1) = 230000 'pv
    unit(2) = 150000 'h2
    unit(3) = 170000 'akaline water electrolysis
    unit(4) = 700000 'fc
    unit(5) = 42000

    om(1) = unit(1) * Ppv / 1000 * 0.005 'pv
    om(2) = 9000
    om(3) = Pel / 1000 * 3000
    om(4) = unit(4) * Pfc / 1000 * 0.01 'fc
```

```
    om(5) = 0

    LT(1) = 20
    LT(2) = 20
    LT(3) = 20
    LT(4) = 20
    LT(5) = 20

    Dim i As Integer
    totalcost = 0

    For i = 1 To 5
        Select Case i
            Case 1
                totalcost = totalcost + unit(i) * Ppv / 1000 / LT(i)
+ om(i)
            Case 2
                totalcost = totalcost + unit(i) * Ph2 / 1000 / LT(i)
+ om(i)
            Case 3
                totalcost = totalcost + unit(i) * Pel / 1000 / LT(i)
+ om(i)
            Case 4
                totalcost = totalcost + unit(i) * Pfc / 1000 / LT(i)
+ om(i)
            Case 5
                totalcost = totalcost + unit(i) * Pscwg / 1000 /
LT(i) + om(i)
        End Select
    Next i

    Cost_calculation = totalcost


End Function
Function electrolyzer(p, Rated_power As Double) As Double
    Dim A, B, c2, QH2, Qrated As Double


    Qrated = 0.656 / 39.4 * (Rated_power / 1000) ' To calcurate
rated flowrate
    A = 20
    B = 40
    QH2 = (p - A * Qrated) / B

    If (QH2 > 0) Then
        electrolyzer = QH2 * 1000
    Else
        electrolyzer = 0
    End If

End Function
Function FuelCell(hydrogen As Double) As Double
    'pre 計算に関する変数宣言
    Dim Tafel_slope, Temp, C_F, A_reaction, Thickness_membrane,
PH2O, Psat, Ratio_P, m, n, MH2, No_cell, Ramda, C_ohmic, Stoichi,
q As Double
```

```
    'Gibbs Energy 計算
    Dim G, A, B As Double
    A = 0.05264 'slope
    B = -244.2766

    'Power 計算の変数宣言
    Dim i, i_density, E_ideal, E_real, Vr, Vo, Vd, p As Double

    '物理定数
    C_F = 96485.3329 '[s A/mol]

    '変数
    Temp = 353.15  '[K]
    A_reaction = 1000  '[cm2]
    Thickness_membrane = 125 '[μm]
    PH2O = 1 '[atm]
    n = 8 '[cm2/A]
    MH2 = 2.02 '[cm2/A]
    No_cell = 82
    q = 0.01 '[g/s]
    Stoichi = 1

    '________________________変数の計算__________________
    Tafel_slope = Tafel(C_F, Temp)
    Psat = Sat_P(Temp) '飽和水蒸気圧の計算
    Ratio_P = PH2O / Psat '水蒸気分圧／飽和水蒸気圧
    m = Diffusion(Temp) '拡散係数の計算
    Ramda = Water_content(Ratio_P) '膜中水分含有量計算
    MsgBox Tafel_slope

    'current flow[A/cell]計算
    i = 2 * C_F * q / (No_cell * Stoichi * MH2)

    'current Density[A/cm2]計算
    i_density = i / A_reaction

    'gibbs energy 計算
    G = A * Temp + B
    E_ideal = -G * 1000 / (2 * C_F)

    'loss[V]計算
    Vr = Tafel_slope * (Log(i_density) + 3)
    Vo = i_density * Thickness_membrane * 0.0001 * (181.6 * ((1 +
0.03 * i_density) + 0.062 * (Temp / 303) ^ 2 * i_density ^ 2.5)) /
((Ramda - 0.634 - 3 * i_density) * Exp(4.18 * (Temp - 303) / 303))
    Vd = m * Exp(n * i_density)
    'E_real[V]計算
    E_real = E_ideal - Vr - Vo - Vd

    'P[W]計算
    p = E_real * No_cell * i


End Function
Function Tafel(C, T As Variant) As Double
    Tafel = 0.5 * 2 * C / (8314 * T)
```

```
End Function
'飽和水蒸気圧の計算
Function Sat_P(T As Variant) As Double
    Sat_P = 10 ^ (-2.1794 + 0.02953 * (T - 273.15) - 9.1837 * 10 ^
-5 * (T - 273.15) ^ 2 + 1.445 * 10 ^ -7 * (T - 273.15) ^ 3)
End Function
'拡散係数の計算
Function Diffusion(T As Variant) As Double
    If (T > 312.5) Then
        Diffusion = 1.1 * 10 ^ -4 - 1.2 * 10 ^ -6 * (T - 273.15)
    Else
        Diffusion = 3.3 * 10 ^ -3 - 8.2 * 10 ^ -5 * (T - 273.15)
    End If
End Function
'膜中の水分含有量計算
Function Water_content(r As Variant) As Double
    If (r < 1) Then
        Water_content = 0.043 + 17.81 * r - 39.85 * r ^ 2 + 36 * r
^ 3
    ElseIf (r < 3) Then
        Water_content = 14 + 1.4 * (r - 1)
    Else
        Water_content = 22
    End If
End Function
'電流計算
Function Current_flow(q, No_cell As Variant) As Double
    Dim C, Stoichi, MH2 As Double
    C = 96485.3329 '[s A/mol]
    Stoichi = 1 '[-]
    MH2 = 2.02 '[g/mol]
    Current_flow = 2 * C * q / (No_cell * Stoichi * MH2)
End Function
Function PVmodule(Prated As Double, day, Counter, time As Integer)
As Double
      '基本変数
      pi = 4 * Atn(1)
      Dim judge As Integer

      'Radiation 変数の設定
      Dim latitude, longitude, setupangle, zeta_deg, phi, zeta,
GMT, C, reflectioness, I_nedo, I_global, I_t, st As Double

      '角度
      Dim delta, alpha, xi, chi, cos_theta As Double


      'ループ変数の設定
      Dim dayofyear, y, i, j, k, m, daynumber As Integer


      'データベース初期設定
      longitude = 140.9189  '任意
      latitude = 37.7973  '任意
      'I_nedo = 145 '[0.01MJ/m2]
      'I_global = I_nedo * 10 ^ 4 / 3600 '取得(W/m2)
```

```
      setupangle = 30  '任意
      zeta_deg = -5  '任意

      reflectioness = 0.5  '固定
      C = 0.8  '固定

      'Rad 変換
      phi = Rad(CDbl(setupangle))
      zeta = Rad(CDbl(zeta_deg))

      '日付型の設定
      Dim d1, d2 As Date
      d1 = "1/1/2017"  '自動
      d2 = "1:0:0"  '自動

      'Power 変数の設定
      Dim Tworking, Tambient, Ct, Eff_cell, Pmax, Tc_noct, Ta_noct,
GT_noct, C_temp, c2, G_stc, Tc_stc, A_cell, Power As Double
      Dim No_module As Integer

      Tambient = 9.7
      c2 = 0.9
      Tc_stc = 25
      G_stc = 1000
      DF = 0.8


      'カタログデータ
      Pmax = 325 '[W/モジュール当たり]
      Eff_cell = 0.2176 '[%] 基本効率
      Tc_noct = 44 'テストセル温度
      Ta_noct = 20 'テスト外部温度
      GT_noct = 0.8
      C_temp = -0.258
      A_cell = 1.25 '面積


      No_module = Prated / Pmax + 1


      daynumber = day

      With Sheets("output-PV")
         st = solartime(daynumber, longitude, time / 24) 'solar
time

         delta = sun_declination(CDbl(daynumber)) 'sun declination
         alpha = solar_angle(st) 'solar angle
         xi = solar_azumith(alpha, latitude, CDbl(delta)) 'solar
azumith
         chi = solar_zenith(delta, latitude, CDbl(alpha)) 'solar
zenith
         cos_theta = all_angle(phi, chi, xi, CDbl(zeta)) 'cosθ

         '日射量計算
```

```
        It = .Cells(Counter, "B") * (cos_theta + C * ((Cos(phi / 2)) ^ 2 + reflectioness * (Cos(chi) + C) * (Sin(phi / 2)) ^ 2))
'solar radiation
        .Cells(Counter, "H") = It

        '出力計算
        It = It * 10 ^ 6 / 3600
        Tworking = .Cells(Counter, "A") + It / 1000 * (Tc_noct - Ta_noct) / GT_noct * (1 - Eff_cell / c2)
        Power = Pmax / A_cell * DF * (It / G_stc) * (1 / 1.114 + C_temp * 0.01 * (Tworking - Tc_stc))
        .Cells(Counter, "I") = Power
        .Cells(Counter, "J") = Power * No_module
        PVmodule = Power * No_module
      End With

End Function
'うるう年の判断
Function judging_leap_year(y As Integer) As Integer

    If (y Mod 4 = 0) Then
        If (y Mod 100 = 0) Then
            If (y Mod 400 = 0) Then
                judging_leap_year = 1
            Else
                judging_leap_year = 0
            End If
        Else
            judging_leap_year = 0
        End If

    Else
        judging_leap_year = 0
    End If
End Function
'solartime 計算
Function solartime(dn, lo, d As Double) As Double
    Dim EOT, B, R_B, Llocal, LST, GMT As Double

    B = 360 * (dn - 81) / 364
    R_B = Rad(CDbl(B))
    EOT = -(9.87 * Sin(2 * R_B) - 7.53 * Cos(R_B) - 1.5 * Sin(R_B)) / 1440
    Llocal = lo / 1440
    GMT = lo / 15
    LST = d

    solartime = LST + EOT - 4 * Llocal + 60 * GMT / 1440
End Function
'Sun declination(δ)
Function sun_declination(dn As Double)
    sun_declination = Rad(-23.45 * Cos(360 / 365 * (dn + 10) * pi / 180))
End Function
'solar_angle(α)
Function solar_angle(st As Double) As Double
    solar_angle = Rad(360 / 24 * (st * 24 - 12))
```

```
End Function
'solar_azumith(ξ)
Function solar_azumith(A, la, d As Double) As Double
    Dim tan_x, lat As Double
    lat = CDbl(la)

    tan_xi = Sin(A) / (Sin(Rad(lat)) * Cos(A) - Cos(Rad(lat)) *
tan(d))
    solar_azumith = Atn(tan_xi)
End Function
'solar_zenith(χ)
Function solar_zenith(d, la, A As Double) As Double
    Dim lat, cos_chi As Double
    lat = Rad(CDbl(la))
    cos_chi = Sin(d) * Sin(lat) + Cos(d) * Cos(lat) * Cos(A)
    solar_zenith = ACN(CDbl(cos_chi))
End Function
'Cosθ
Function all_angle(p, C, x, z As Double) As Double
    all_angle = Cos(p) * Cos(C) + Sin(p) * Sin(C) * Cos(x - z)
End Function
'Sin 逆関数
Function ASN(x As Double) As Double
    Select Case x
        Case Is = -1
            ASN = -pi / 2
        Case Is = 1
            ASN = pi / 2
        Case Else
            ASN = Atn(x / Sqr(1 - x ^ 2))
    End Select

End Function
'Cos 逆関数
Function ACN(x As Double) As Double
    Select Case x
        Case Is = -1
            ACN = pi
        Case Is = 1
            ACN = 0
        Case Else
            ACN = pi / 2 - Atn(x / Sqr(1 - x ^ 2))
    End Select
End Function
'Deg→Rad 変換
Function Rad(x As Double) As Double
    Rad = x * pi / 180
End Function
'test
Sub testPSO()
    Dim gbest, gbestscore, score As Double

    Dim i, j, n, iteration As Integer

    iteration = 40
    n = 10 'number of particles
```

```
    ReDim pbest(1 To n) As Double
    ReDim pbestscore(1 To n) As Double
    ReDim x(1 To n) As Double
    ReDim v(1 To n) As Double

    For i = 1 To n
        Randomize
        x(i) = (Rnd - 2) * 20
        v(i) = (Rnd - 0.5) * 4
        pbestscore(i) = obj(x(i))
    Next i

    Dim inertia, c1, c2 As Double
    inertia = 0.7
    c1 = 0.75
    c2 = 1.0
    gbestscore = 5

    For i = 1 To iteration
        For j = 1 To n
            v(j) = inertia * v(j) + c1 * (pbest(j) - x(j)) + c2 *
(gbest - x(j))
            x(j) = x(j) + v(j)
            score = obj(x(j))
            If (score < gbestscore) Then
                gbest = x(j)
                gbestscore = score
            End If
            If (score < pbestscore(j)) Then
                pbest(j) = x(j)
                pbestscore(j) = score
            End If
        Next j
    Next i

    With Sheets("test")
        .Range("A10:J10") = pbest
        .Range("A11:J11") = pbestscore
    End With

    MsgBox (gbest)

End Sub
Function obj(x1) As Double
    obj = x1 ^ 4 + 4 * x1 ^ 3 + 4 * x1 ^ 2 - 1
End Function
'Initialize worksheets
Sub IniParticle()
    Dim n, p As Integer

    n = 5 'Demension number
    p = 8 'Particle number

    ReDim v(1 To n) As Double
    ReDim x(1 To n) As Double
```

```
    ReDim Output(1 To (n * 2) + 2) As Double 'iteration, cost, x4,
v4
    ReDim pbest(1 To (n * 2) + 2) As Double  'iteration cost,x4,v4
    ReDim gbest(1 To (n * 2 + 3)) As Double  'iteration cost, x4,v4


    'definition of label
    ReDim header(1 To (n * 2 + 1)) As String
    header(1) = "cost"
    header(2) = "Xpv"
    header(3) = "Xh2"
    header(4) = "Xel"
    header(5) = "Xfc"
    header(6) = "Xscwg"
    header(7) = "Vpv"
    header(8) = "Vh2"
    header(9) = "Vel"
    header(10) = "Vfc"
    header(11) = "Vscwg"

    'definition of sheets
    ReDim WS(1 To p) As Worksheet
    Set WS(1) = Worksheets("Particle1")
    Set WS(2) = Worksheets("Particle2")
    Set WS(3) = Worksheets("Particle3")
    Set WS(4) = Worksheets("Particle4")
    Set WS(5) = Worksheets("Particle5")
    Set WS(6) = Worksheets("Particle6")
    Set WS(7) = Worksheets("Particle7")
    Set WS(8) = Worksheets("Particle8")

    'shows personal best score information
    Dim i As Integer

    For i = 1 To p
        WS(i).Select
            Cells(1, 2) = "Iteration No"
            Range("C1:M1") = header
            Cells(1, "N") = "Particle No"

            'personal best
            Cells(2, 1) = "Personal Best"
            Range("B2:K2") = pbest

            'global best
            Cells(3, 1) = "Global Best"
            Range("B3:N3") = gbest

            'header and transition of each particles
            Cells(4, 1) = "Iteration"
            Range("B4:L4") = header
    Next i

End Sub
Sub test()
    Dim j(2) As Double
```

```
    j(1) = Rnd
    j(2) = Rnd

    With Sheets("test")
        .Range("A13:B13") = j
    End With


    '-------------------output----------------------
    With Sheets("Test")
        For i = 1 To p
            For j = 1 To 5
                .Cells(i + 1, j) = Particle(i, j)
            Next j
        Next i
    End With
    '----------------------------------------------

End Sub
Sub output1()
    Dim csvFile As String
    Dim i, p, n As Integer
    Dim WStemp As Worksheet
    Dim Filename As String
    Dim startpoint As Integer


    p = 20
    n = 6
    iteration = 40

    ReDim WS(1 To p) As Worksheet
    For i = 1 To p
        Select Case i
            Case 1
                Set WS(i) = Worksheets("Particle1")
            Case 2
                Set WS(i) = Worksheets("Particle2")
            Case 3
                Set WS(i) = Worksheets("Particle3")
            Case 4
                Set WS(i) = Worksheets("Particle4")
            Case 5
                Set WS(i) = Worksheets("Particle5")
            Case 6
                Set WS(i) = Worksheets("Particle6")
            Case 7
                Set WS(i) = Worksheets("Particle7")
            Case 8
                Set WS(i) = Worksheets("Particle8")
            Case 9
                Set WS(i) = Worksheets("Particle9")
            Case 10
                Set WS(i) = Worksheets("Particle10")
            Case 11
                Set WS(i) = Worksheets("Particle11")
```

```
            Case 12
                Set WS(i) = Worksheets("Particle12")
            Case 13
                Set WS(i) = Worksheets("Particle13")
            Case 14
                Set WS(i) = Worksheets("Particle14")
            Case 15
                Set WS(i) = Worksheets("Particle15")
            Case 16
                Set WS(i) = Worksheets("Particle16")
            Case 17
                Set WS(i) = Worksheets("Particle17")
            Case 18
                Set WS(i) = Worksheets("Particle18")
            Case 19
                Set WS(i) = Worksheets("Particle19")
            Case 20
                Set WS(i) = Worksheets("Particle20")
        End Select
    Next i

    Dim j, k As Long
    startpoint = 4

    ReDim best(1 To iteration) As Long

    For i = 1 To iteration
        best(i) = 10000000
    Next i

    For k = 1 To iteration
        Filename = "¥data¥data" & Str(k) & ".csv"
        csvFile = ActiveWorkbook.Path & Filename
        Open csvFile For Output As #1

        For i = 1 To p
            Set WStemp = WS(i)
            'For j = 3 To 4
            'Print #1, Format(WStemp.Cells(startpoint + k,
3).Value, "0") & ",";
            'Print #1, Format(WStemp.Cells(startpoint + k,
4).Value, "0") & ",";
            Print #1, WStemp.Cells(startpoint + k, 3).Value & ",";
            Print #1, WStemp.Cells(startpoint + k, 6).Value & ",";
            'Next j
            Print #1, WStemp.Cells(startpoint + k, 7).Value & vbCr;
            If (WStemp.Cells(startpoint + k, 2).Value < best(k))
Then
                best(k) = WStemp.Cells(startpoint + k, 2).Value
            End If
Continue:
        Next i
        Close #1
    Next k

    Filename = "¥gbest.csv"
    csvFile = ActiveWorkbook.Path & Filename
```

```
    Open csvFile For Output As #2

    For k = 1 To iteration
        Print #2, best(k) & vbCr;
    Next k
    Close #2

End Sub
```