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Research article

The prospects of clean hydrogen utilization in power generation industry

Daido Fujita*

Department of Advanced Environmental Science and Engineering, Faculty of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-city, Fukuoka 816-8580, Japan

* **Correspondence:** Email: fujita.daido.856@s.kyushu-u.ac.jp; Tel: +819065591600.

Abstract: Due to the commitment of carbon neutrality by 2050, all possible measures to be adopted to reduce greenhouse gas emissions. The purpose of power generation from clean hydrogen is towards achieving carbon-neutral ambitions and to hit the net zero target by 2050. Power generation from clean hydrogen is one of the solutions to substitute or minimize the use of natural gas and ensure energy security of the nation. This study mainly focuses on the quantitative and qualitative measures of potential renewable resources to produce the required hydrogen for power generation from combined cycle power plants, hydrogen storage, and material compatibility with hydrogen. PVsyst software is utilized to assess the potential of power generation from solar PV plants. Techno-economics assessments of co-generation (hydrogen 20% vol. + natural gas 80% vol.) with clean hydrogen produced from PEM electrolyzers are analyzed in this study. The novelty or highlight of this study is that it is feasible technically and economically to implement clean hydrogen utilization in power generation sectors to reduce green-house gas emission.

Keywords: PVsyst; renewable resources; clean hydrogen production; hydrogen storage; material compatibility with hydrogen; combined cycle power plant

1. Introduction

As an industrialized country, electricity consumption in Japan is extremely high at about 987 TWh in 2020 as shown in Figure 1. In 2019, the energy sector has emitted 1,066 million tonnes of carbon dioxide (Mt CO_2) where most of them are emitted from fuel combustion. The Japanese government introduced carbon pricing in October 2012 and increased the rate to JPY 289/tonne of CO_2 in 2016. The ambition of carbon-neutrality by 2050 requires Japan to accelerate the deployment of low-carbon technologies by 2030. It is also important to develop different decarbonization scenarios and to prepare for the possibility of low-carbon technologies. Hydrogen takes a vital role in reducing the reliance on fossil fuels. Power generation from clean hydrogen is one of the solutions to substitute or minimize the use of natural gas and ensure the energy security of the nation [1].

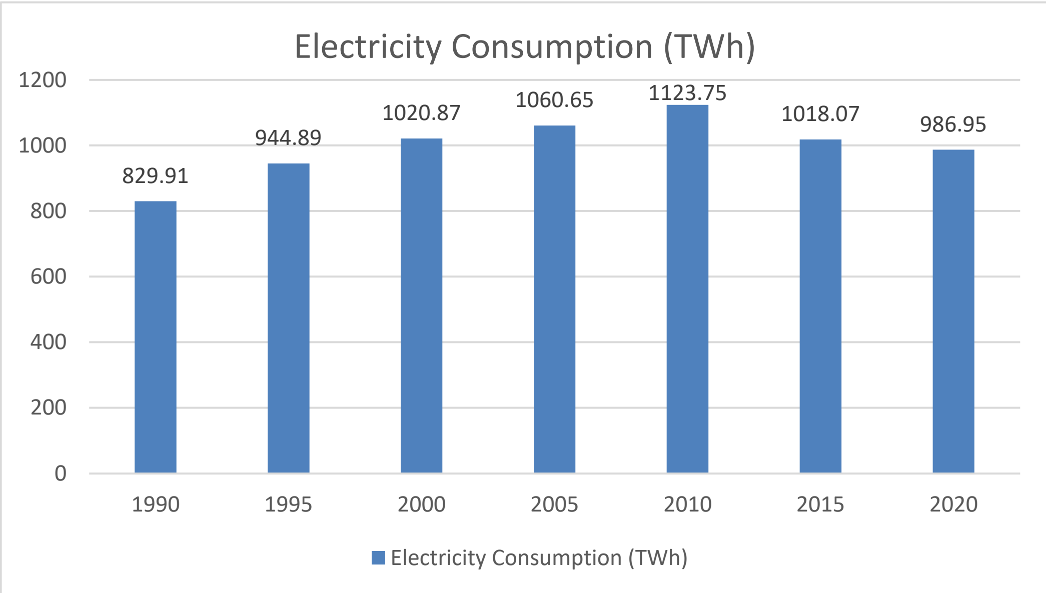

Figure 1. Electricity consumption profile in Japan adapted from IEA [1].

The use of hydrogen has a long-standing history where it is widely used in many energy sectors; refinery, metal treatment, fertilizer production, food processing spacecrafts and NASA even used liquid hydrogen as rocket fuel [2].

Hydrogen as a fuel feed for gas turbines is expected to increase. Several power plants in the USA, Netherland, and Japan have shown interest in using co-generation of natural gas and hydrogen in combustion gas turbines [2].

Currently, although the highest percentage of hydrogen generation is from grey hydrogen produced from fossil fuel as feedstock, it is gradually moving forward to utilize green hydrogen from 100% renewable energy since governments in many countries are encouraging the boosting of the hydrogen economy by supporting financial funding and developing strategies and infrastructure to achieve the net zero target by 2050 [3].

Hydrogen power generation is expected to replace a certain percentage of gas-fired power generation to reduce CO_2 emissions. Therefore, a massive amount of hydrogen will be consumed to generate electricity from hydrogen power plants. Hydrogen can be used by blending or mixing it with natural gas in a natural gas-fired power plant. The Japanese government is implementing measures to cut hydrogen-fueled power generation costs to 17 yen/kWh by 2030 and aims to further reduce the cost to 12 yen/kWh. This will enable costs competitive to liquified natural gas (LNG) power generation since the current unit LNG power generation cost is 12 yen/kWh based on a natural gas import price \$0.2/Kg that is converted based on the calorific value of hydrogen [4]. On the other hand, the import costs of LNG are drastically increasing due to the recent energy crisis and shortfall of energy supplies worldwide.

While aiming towards a carbon-neutral environment, it is essential that the source of feedstock also has to be carbon free. Hydrogen can be produced from various methods such as thermo-chemical processes, photo-electrochemical processes, and photo-chemical processes, using biomass as feedstock and water electrolysis [5].

PEM electrolyzers are the most suitable and viable to produce a large amount of hydrogen required for power generation, and it is also compatible to directly feed from renewable power supplies. The electrolyzers have less environmental impact compared to any other hydrogen production methods. The solar radiation from the sun supports life on Earth via photosynthesis and drives the Earth's climate and weather. The availability of sunshine on the surface of the Earth varies, and it is an intermittent resource as it will not be available at night and on cloudy days. Hydrogen production from solar energy is one of the promising technologies to overcome the intermittent nature [6].

This study analyzes the feasibility of clean hydrogen utilization in the power generation industry, especially hydrogen-fuel gas turbine power plants and combined cycle power plants. A 500 MW (installed capacity) solar PV power plant will be constructed at a mountain hill side located adjacent to the proposed combined cycle power plant. The electricity produced by this solar PV plant will power electrolyzers and produce hydrogen. The generated hydrogen will be directly fed to a gas turbine to minimize the cost of hydrogen storage. Only excess amounts of hydrogen will be stored in aboveground storage pressure vessels as reserve and will then be supplied to the gas turbine when any interruption in hydrogen production occurs. The reserved hydrogen storage will be 7 days storage capacity.

Based on the available power generated from the solar PV plant, it is expected to produce 20% of the hydrogen required for 557 MW gas turbine operations while the remaining 80% will be natural gas. Heat waste (exhaust heat) from the gas turbine will be captured by heat recovery steam generator and the HRSG will supply the required steam to a steam turbine to generate electricity.

2. Materials and methods

2.1. Combined cycle power generation

The combined cycle power generation uses two main cycles the Brayton cycle for the gas turbine and the Rankine cycle for the steam turbine with an overall plant efficiency of 60% to 65%, mainly using worldwide sources as the main source of power supplies. Natural gas is the main source of fuel for the gas turbine and waste heat or hot gases from the gas turbine exhaust are captured in a heat recovery steam generator which generates superheated steam at high temperatures to generate surplus electricity from the steam turbine. The gas turbine converts 40% of energy to electricity and the remaining 60% will be captured by the HRSG to drive the steam turbine, which generates another 20% to 25% of electricity [7]. The typical configuration and schematic diagram of the combined cycle power plant are presented in Figure 2.

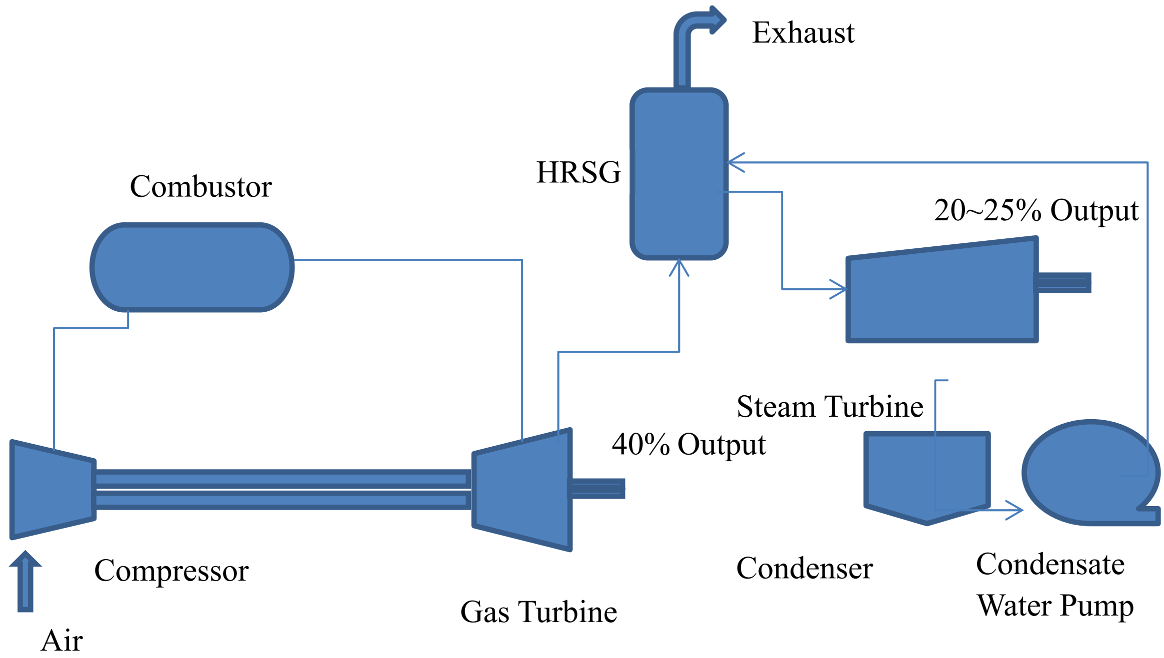

Figure 2. Schematic diagram of the combined cycle adapted from Boyce MP [7].

Apart from natural gas, there is a wide range of fuel that can be fired in the gas turbines, including liquefied natural gas after a gasification process and co-generation with hydrogen and natural gas. Gas turbine manufacturers set out the standard specification for each model with the allowable range in composition and contaminants to protect the gas turbine and ensure the effective burning of fuels. Allowable ranges are also defined with the modified Wobbe Index (MWI) and the temperature where MWI is usually calculated from the volumetric lower heating value (LHV) of the fuel gas, its specific gravity relative to air (SG) and its absolute temperature (T) by the equation (Eq 1) below.

$$MWI = LHV/\sqrt{((SG)(T))} \tag{1}$$

The above index is a relative measure of the energy entering the combustor for the pressure drop of the nozzle in which the typical allowable range is ±5%. When utilizing a fuel with lower heating value that is lower than the design value of gas turbine, the turbine compressor pressure ratio can increase due to the larger mass flowing through the turbine and can cause compressor surge, which may even damage the compressor. The possible solution for this cause is to limit the amount of air entering the engine by closing inlet guide vanes and extract air from the compressor discharge. Some modifications on the fuel delivery system may be required in order for the combustor to burn the fuel efficiently. Fuels with an LHV as low as 4 MJ/NM^3 are acceptable for modern gas turbines [8].

2.2. Power generation from hydrogen

Based on the combined cycle configuration, gas turbines are the largest power generation equipment after nuclear power plants, but the feedstock of a gas turbine is mainly natural gas. To meet the carbon neutral target by 2050, it is a necessity to drastically cut carbon emissions by switching fuel or using blended fuel as gas turbines able to accommodate several fuels and blended fuels. The use of hydrogen in gas turbines has become a popular way to shift towards de-carbonization. In recently manufactured gas turbines, the combustion features have been adapted to burn a blend of natural gas with a high percentage of hydrogen by utilizing a combustor that is capable of operating with syngas fuels and making minor upgrades to gas turbines, including the applicable auxiliary equipment [8].

With 100% H_2 as fuel feedstock for gas turbine combustion, we can foresee a significant amount of CO_2 reduction. Although the plant operation will still emit a very small amount of CO_2, approximately 0.04%, the emission from fuel can be eliminated. It is a very challenging task to burn hydrogen in a large-scale gas turbine with 100% hydrogen as a fuel feedstock. But the use of a small quantity of hydrogen as fuel to the primary operating zone with a mix of natural gas can greatly reduce unburned hydrocarbons and reduce carbon emissions [9].

Gas turbines operate at high speed and high temperature. The materials used in gas turbines have high strength capability and are durable at very high temperatures. It is not only that high-quality materials are required in the turbines, but the combustor liner also needs to withstand at extremely high temperatures [10].

Increasing turbine inlet temperature is a means of increasing efficiency. An increase in inlet temperature of 8 ℃ can lead to an increase in power output of 1.5 ~ 2.0% and an increase in efficiency of 0.3 ~ 0.6% [10].

Combustion in gas turbines can generate pollutants. Understanding how pollutant emission occurred in the combustion process will enable elimination at the source. With co-generation of 20% hydrogen with 80% natural gas, approximately 8% of CO_2 emissions can be saved compared to combustion of 100% natural gas. Although combustion of hydrogen does not emit CO_2, it can generate nitrogen oxide emissions that form in hotter areas of the combustor. By using premixed combustors, NOx emissions can be controlled or brought down to less than 25 ppm, which is lower than the acceptable range required by EPA regulation (30 ppm of NOx emission for gas turbine) [10].

However, the emission limits are tightening in some countries from 10 to 15 ppm for gas turbines and this requirement is harder to meet for large-scale turbines. In this case, the alternative post-combustion technology SCR (selective catalytic reduction), commonly used in advanced gas turbines, consists of injecting ammonia into the exhaust gas after it exits the gas turbines. In combined cycle power plants, a SCR unit is often placed within the heat-recovery steam generator [7].

Catalysts for SCR are normally metal oxides on a ceramic carrier. Various metals have been used, including vanadium, molybdenum, and platinum. The type of catalyst depends on the temperature of the exhaust gases. Metal oxides are more temperature resistant than others. In principle, an SCR-based nitrogen oxide reduction system can remove 95–99% of the nitrogen oxide from the exhaust gases. However, the system becomes more difficult to control when reduction levels exceed 80% as the reaction process does not proceed as smoothly, putting greater demands on the catalyst, often leading to higher levels of ammonia passing through the system and being released into the atmosphere.

The optimum solution is a balance between low nitrogen oxide burners and SCR so that both operate within the best efficiency range. With both SCR and a low nitrogen oxide burner, it is possible to reduce the NOx emissions level to below 10 ppm [7]. The typical configuration and schematic diagram of SCR is presented in Figure 3.

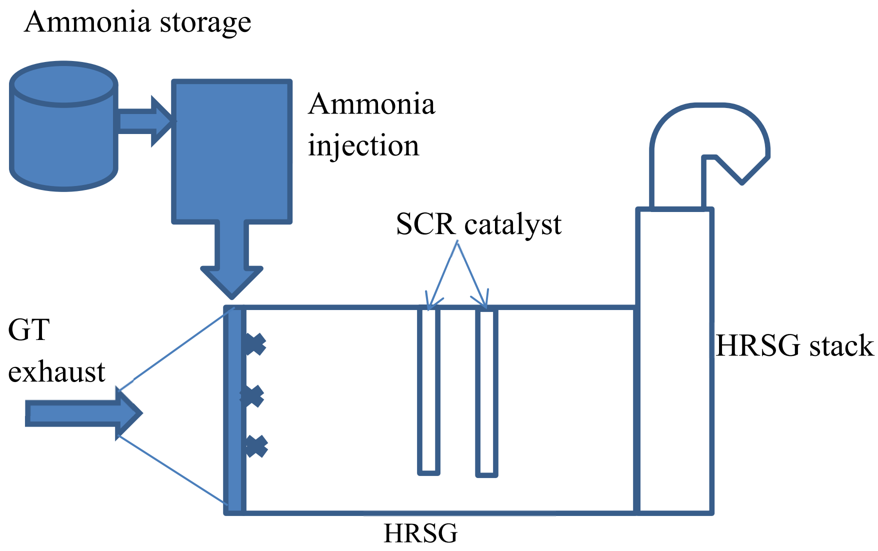

Figure 3. SCR reduction process in heat recovery steam generator adapted from Boyce MP [7].

Incomplete combustion of natural gas can generate carbon monoxide, and this carbon monoxide can be minimized using the same method for nitrogen oxide via a dry low emission combustor which is currently used in advanced gas turbines. The acceptable emission limit is similar to nitrogen oxide 10–25 ppm in operation. Low nitrogen oxide burners can sometimes cause higher carbon monoxide emissions. In this circumstance, an appropriate emission control system is needed. This is usually in the form of an oxidation catalyst that catalyzes the conversion of carbon monoxide into carbon dioxide. This may be a separate catalytic unit, but in combined cycle plants it is incorporated into the heat-recovery steam generator [10].

2.3. The cost of hydrogen-fuel gas turbines

Some existing advanced gas turbines can operate with a blend of natural gas and hydrogen, where a few of the gas turbine manufacturers have established 100% hydrogen fuel gas turbines for small scale turbines. This is due to flame speed and length, where flame speed from hydrogen combustion is faster than natural gas and flame length is also longer than natural gas. This causes the production of nitrogen oxide, and low dry NOx control combustion technology alone cannot control the emission limit. The capital cost of the natural gas-fired combined cycle power plant is estimated in Table 1.

Table 1. Capital cost for natural gas-fired combined cycle power plant [10,12].

Plant	Cost ($/kW)	Cost (Yen/kW)	Reference
Natural gas combined cycle power plant	1060 ~ 1150	127200 ~ 138000	[10]
Natural gas combined cycle power plant with carbon captured technology	1600 ~ 1900	192000 ~ 228000	[10]
Hydrogen-fired gas turbines	1320	158400	[12]

Therefore, it is necessary for SCR to be provided at HRSG in a combined cycle power plants and the capital cost of SCR ($320/kW) to be added in addition to the original cost of gas turbine ($1,000/kW) [11].

The cost information for combined cycle power plants is taken from Gas-Turbine Power Generation [10] and the cost for hydrogen-fired gas turbines is taken from [12].

2.4. PVsyst simulation

In this section, the potential of electricity generation from a solar PV plant will be analyzed. A photovoltaic (PV) system is comprised of a PV array and converter and no battery is required as the electricity produced from this solar PV plant will directly power electrolyzers via transformer rectifiers and produce hydrogen. PVsyst 7.2 software will be used to determine the possible energy output including hourly simulation of irradiation that provides many details. PVsyst gives access to many meteorological data sources available on the web and includes a tool to easily import the most popular ones [13].

The proposed solar photovoltaic plant is located in Okayama prefecture, Japan as presented in Table 2 and the manufacturer specifications of PV modules are shown in Figure 4.

Table 2. Geographical information.

Geographical site	Okayama, Japan
Latitude	34.69° N
Longitude	133.93° E

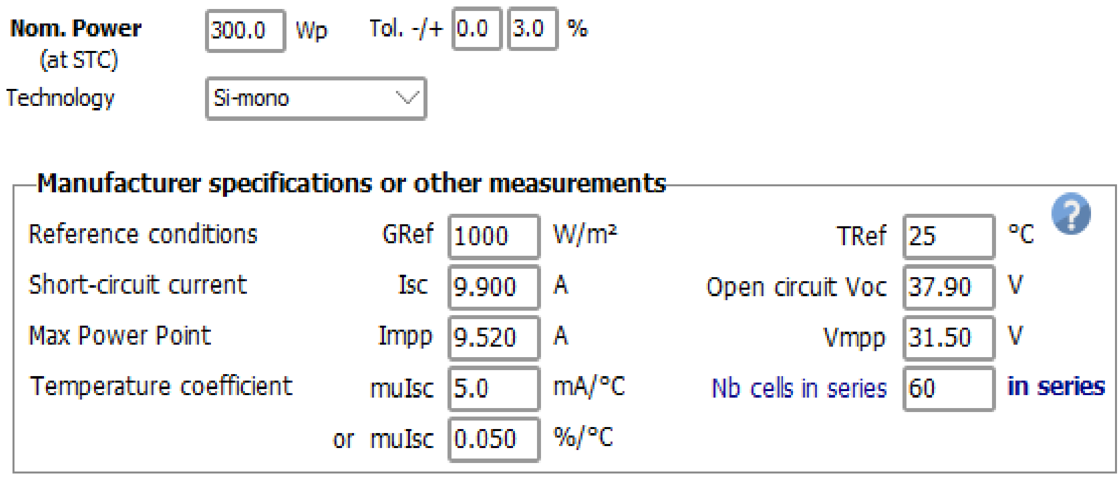

Figure 4. Specification of PV modules used in the proposed solar PV plant from PVsyst [14].

When designing for solar PV installation, it is important to design the correct inclination and orientation to optimize power output. The tilt angle of PV arrays should be equal to the location latitude in which the tilt angle is 35°. If the sun is at the north pole, the azimuth angle is 0° and the azimuth is 90° when the sun is at the equator [13]. Field parameters and orientation of PV arrays are presented in Figure 5.

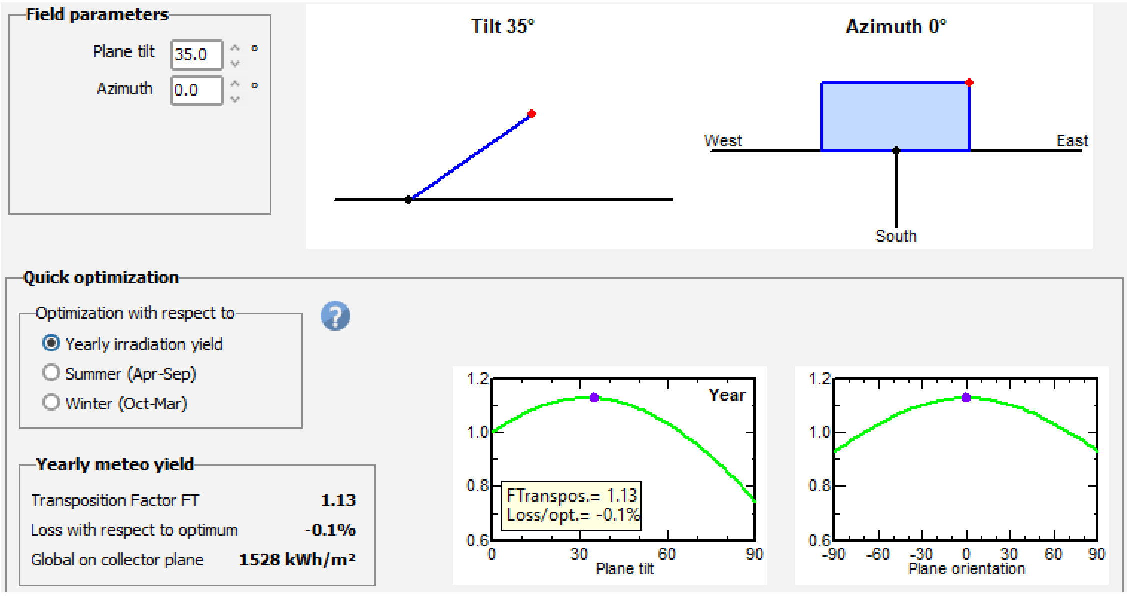

Figure 5. Field parameters and orientation of PV arrays from PVsyst [14].

It is very important to understand the sun path diagram to assess the performance of solar PV systems in which PVsyst enables the generation of a sun path diagram based on geographical location. Sun path (solar path) of the proposed solar PV plant is presented in Figure 6.

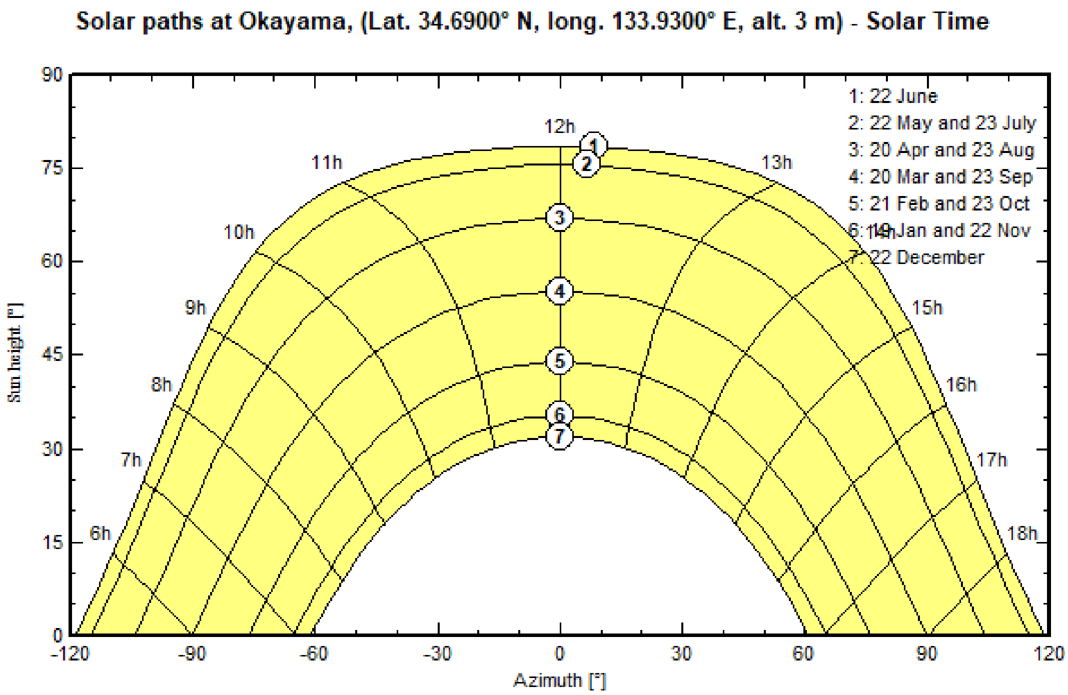

Figure 6. Solar path at the proposed solar PV plant from PVsyst [14].

Mono crystalline photovoltaic technology is used for this simulation as it is reasonably cheap and very efficient. In the system summary, the quantity of modules required for 500 MW solar PV plant is 1,666,665, the area required is 2,712 km² and 185 inverters are required as summarized in Table 3. Therefore, the land area to PV plant power scale is approximately 5.424 km²/MW installed capacity [14].

Table 3. Proposed solar PV plant system summary from PVsyst [14].

System summary	
No. of modules	1,666,665
Module area	2,711,464 m²
No. of inverters	185
Nominal PV power	500,000 kWp
Maximum PV power	496,941 kWDC
Nominal AC power	370,000 kWAC

The performance ratio is the ratio of the final PV system yield (Yʃ) and the reference yield (Yɤ).

$$PR = Y\int / Y\gamma \quad (2)$$

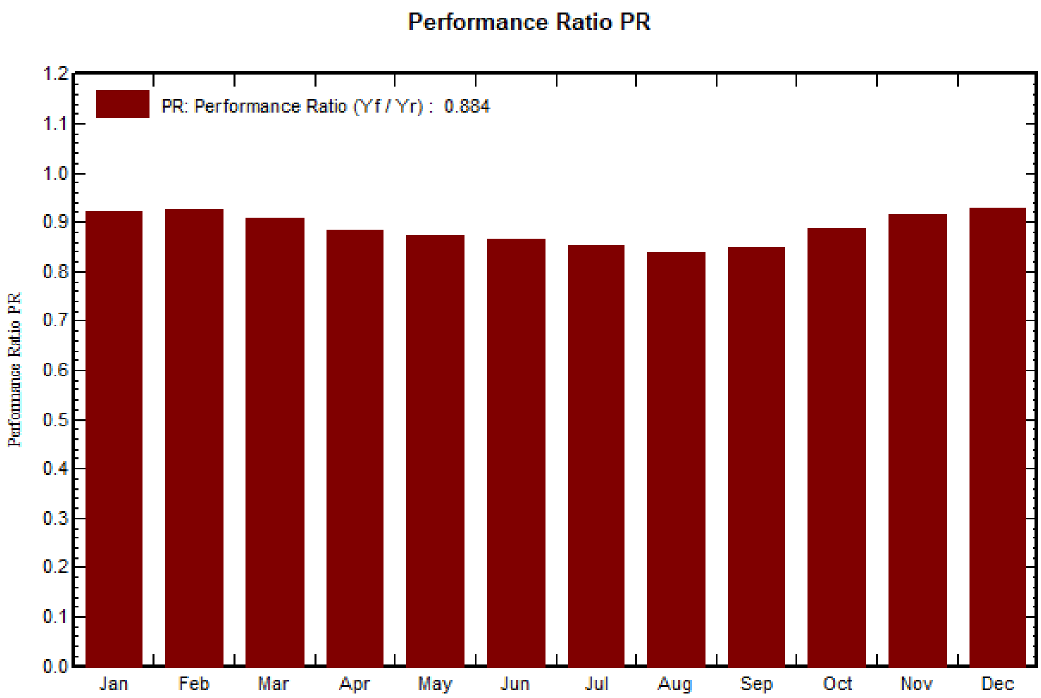

Figure 7. Performance ratio (PR) graph generated from PVsyst [14].

The performance ratio is very important for evaluating the efficiency of solar PV plants where it is the ratio of the actual output to the theoretical energy outputs as described in the above performance ratio formula. The PR ratio represents the energy injected to the grid; higher PR values close to 100% indicate better performance. Based on the simulation results shown in Figure 7, the annual performance ratio is 0.884 (88.4%), which is considered to be very good performance as higher than 80% is high performance [14].

Simulation
Meteo and incident energy

	GlobHor	DiffHor	T_Amb	WindVel	GlobInc	DifSInc	Alb_Inc	DifS_GI
	kWh/m^2	kWh/m^2	°C	m/s	kWh/m^2	kWh/m^2	kWh/m^2	ratio
January	71.6	32.60	3.43	2.4	108.4	23.13	1.294	0.000
February	80.2	51.10	4.67	2.2	98.6	35.41	1.449	0.000
March	114.9	63.30	8.91	2.3	132.5	39.73	2.075	0.000
April	138.8	80.90	14.96	2.2	140.4	50.28	2.508	0.000
May	155.3	84.30	20.51	2.0	145.4	48.97	2.807	0.000
June	139.8	93.10	24.09	1.8	124.8	59.06	2.526	0.000
July	146.2	95.60	28.54	1.9	133.1	59.70	2.643	0.000
August	151.8	85.40	29.27	2.0	148.9	52.23	2.743	0.000
September	114.6	63.50	24.02	1.9	125.4	41.89	2.071	0.000
October	101.3	56.90	18.03	1.6	126.8	37.28	1.830	0.000
November	74.2	35.90	11.45	1.6	109.5	24.45	1.341	0.000
December	67.4	32.40	5.71	2.2	104.8	22.91	1.217	0.000
Year	1356.1	775.00	16.20	2.0	1498.5	495.03	24.506	0.000

Figure 8. Simulation of meteo and incident energy from PVsyst [14].

The results shown in Figure 8 are the meteorological and incident energy of the PV system. Global horizontal irradiation is 1356 kW/m^2/year. Horizontal diffuse irradiation is 775 kWh/m^2/year, where the overall global incident energy on the collector plane is 1498.5 kWh/m^2/year.

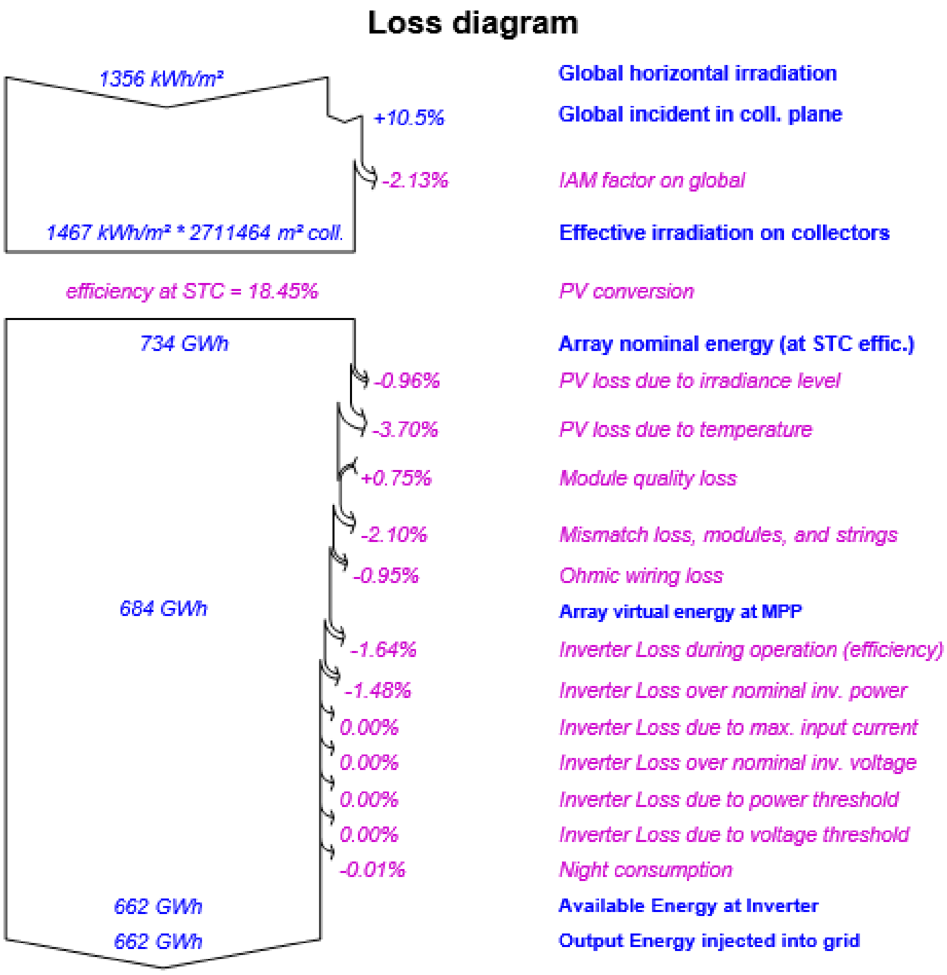

Figure 9. Loss diagram from PVsyst [14].

This diagram (Figure 9) shows the system loss diagram simulation result for the proposed PV plant. Global horizontal irradiation is 1356 kWh/ m². The effective irradiation on the collectors is 1467 kWh/m².

PV cells convert solar energy to electrical energy, and array nominal energy becomes 734 GWh after PV conversion. PV array efficiency is 18.45% as per standard test condition (STC).

Array virtual energy at maximum power point (MPP) is 684 GWh and the available energy at inverter output (after inverter loss) is 662.29 GWh, where such energy will be injected to the power supply of electrolyzers. “E-Grid” in the main simulation results represent the output of the solar PV plant.

Simulation
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	71.6	32.60	3.43	108.4	106.9	50777792	49914934	0.921
February	80.2	51.10	4.67	98.6	96.8	46443192	45668243	0.927
March	114.9	63.30	8.91	132.5	130.0	61054987	60052436	0.906
April	138.8	80.90	14.96	140.4	136.9	63045655	62019428	0.883
May	155.3	84.30	20.51	145.4	141.6	64604661	63517207	0.874
June	139.8	93.10	24.09	124.8	121.1	54987917	54039648	0.866
July	146.2	95.60	28.54	133.1	129.5	57581977	56584421	0.850
August	151.8	85.40	29.27	148.9	145.3	63444918	62384765	0.838
September	114.6	63.50	24.02	125.4	122.6	54096430	53160138	0.848
October	101.3	56.90	18.03	126.8	124.6	57048440	56133158	0.886
November	74.2	35.90	11.45	109.5	107.8	50917092	50077881	0.915
December	67.4	32.40	5.71	104.8	103.4	49587245	48738838	0.930
Year	1356.1	775.00	16.20	1498.5	1466.5	673590306	662291097	0.884

Figure 10. Balance and main results of PV Syst simulation from PVsyst [14].

Based on the simulation results shown in Figure 10, the highest energy output is in May with 63.52 GWh and the lowest energy output is in February with 45.67 GWh, where the total energy output is 662.29 GWh/annum.

The cost of the PV system is decreasing in market trends due to the development of technology, market opportunities and a wide range of competitive solar manufacturers. It is expected that costs are down by 23% compared to 2016 according to the report from International Technology Roadmap for Photovoltaic [15].

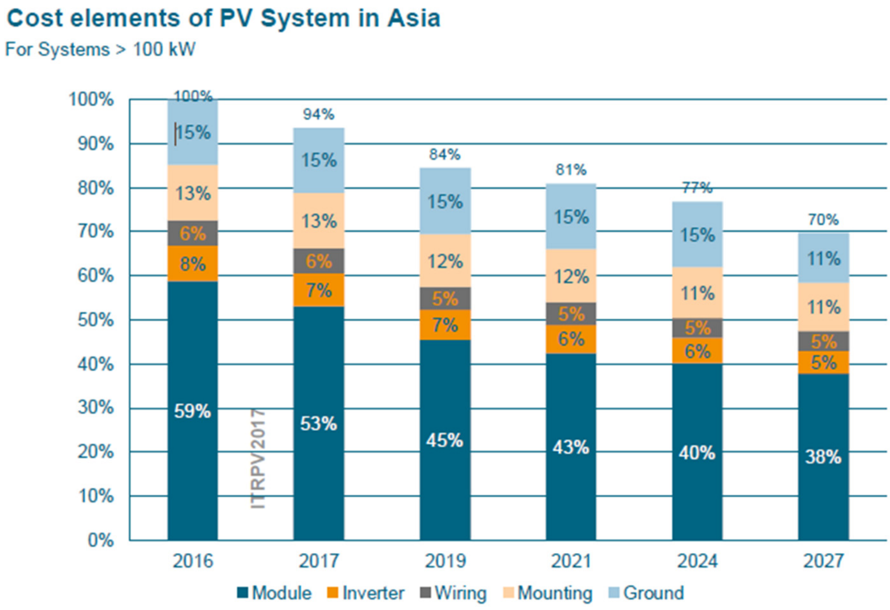

Figure 11. Cost of PV system in Asia adapted from ITRPV [15].

Figure 11 indicates the expected cost of PV systems in Asia. The cost is estimated based on statistics data from international organizations such as the National Renewable Energy Laboratory and Renewable Energy Institute, Japan [16–18].

Table 4. Cost of solar PV Plant [16–18].

Category	Cost data from NREL [17] (¥ per kW)	Cost data from REI [16] Japan (¥ per kW)	IRENA data [18] (¥ per kW)
Module price	40,800	30,000	
Inverter price	6,000	8,000	
Mounting system cost	10,800	15,000	
Cable connection cost	1,200	5,000	
EPC cost	84,000	80,000	
Total capital cost	142,800	138,000	138,000

Note: All currencies are in Japanese Yen converted from USD x 120.

Based on the above cost comparison shown in Table 4, the cost estimated by the Renewable Energy Institute, Japan is considered in this costing in which the total investment for a 500 MW solar PV plant is ¥ 69,000,000,000 equivalent to 575 million USD.

2.5. PVsyst hydrogen production, storage, and safety standards

Hydrogen can be produced from various energy resources, including renewable resources, and can also be stored. It has the potential to transform Japan towards decarbonization as Japan's energy sector is highly reliant on fossil fuels. Hydrogen will be generated using electrolysis technology, which involves splitting hydrogen from water utilizing electric current to flow and does not produce any by-products apart from hydrogen and oxygen.

Electric current is utilized to split water H_2 and O_2, as per the Eq 3 below.

$$H_2O \rightarrow 1/2\ O_2 + H_2 \quad (3)$$

In the anode portion, water is oxidized and produces O_2 and protons as per the Eq 4 below.

$$H_2O \rightarrow \frac{1}{2}O_2 + H + 2e \quad (4)$$

The produced protons wander to the cathode while electrons pass through the external circuit. On the cathode portion, the protons are reduced and form H_2 as per the Eq 5 below.

$$2H + 2e \rightarrow H_2 \quad (5)$$

In PEM electrolyzers, the membrane is a key component that provides many advantages. The thickness is between 100~175 µm, and is stable enough to maintain high conductivity of protons under high current densities greater than 2A/cm² [5]. Also, due to low gas permeability, H_2 purity can be 99.999 vol%. However, the selection of materials is limited, and the materials used may be expensive, such as titanium current collectors or noble metal catalysts. Although the investment is slightly more expensive than other technologies, water electrolysis with PEM has considerable advantages compared to water alkaline technology as explained in Table 5 [19].

Table 5. Comparison of PEM electrolyzer and Alkaline electrolyzer [19].

PEM electrolyzers	Alkaline electrolyzers
Tolerance in pressure differential due to strong and stable membrane.	Impossible to balance pressure.
No oxygen contamination in hydrogen.	Oxygen contamination in hydrogen is higher than PEM electrolyzers.
Possible contamination is water and nitrogen in produced hydrogen.	It required KOH to operate the system and it caused contamination.
No corrosion on equipment, long equipment lifetime with easy maintenance.	KOH need to fill regularly and difficult for maintenance.

The main characteristics of electrolyzer specification can be categorized via hydrogen production rate, electricity consumption, and feed water consumption. Based on currently available technology, large scale hydrogen production is now feasible, where 4920 Nm³/hr can be produced per each PEM electrolyzer skid. The detailed specification of Nel Hydrogen Electrolyzer, Model M5000 is summarized in Table 6 [20].

Table 6. Technical specification of nel hydrogen electrolyzer, Model-M5000 [20].

Currently available PEM electrolyzers technology	Large-scale on-site hydrogen generation and automatically can adjust input and output as per the required demand.
Electrolyte	Electrolyte is proton exchange membrane with caustic-free.
Hydrogen production	4920 Nm^3/hour 10,618 kg/day (24 hours)
Pressure	30 barg
Average power consumption at stack (kWh/Nm^3)	4.5 (22 MWh per skid)
Oxygen content in hydrogen	<1 ppmv
Water content in hydrogen	<5 ppmv
Feed water consumption (l/Nm^3)	0.9 (4428 l/Nm^3 per skid)

The efficiency of the electrolysis system can be calculated based on the ratio of heating value (HHV) hydrogen and electricity consumption.

$$Electrical\ efficiency\ (HHV) = \frac{HHV\ \ of\ hydrogen\ produced}{Electricity\ used} \quad (6)$$

The higher heating value (HHV) for hydrogen is 12,756.2 kJ/Nm^3 (141,829.6 kJ/kg). This is equivalent to 3.54 kWh/Nm^3 (39.39 kWh/kg) [22].

Based on the datasheet from NEL, average power consumption is 4.5 kWh/Nm^3. Therefore, the efficiency of the electrolyzer to be used is:

$$\text{Electrical efficiency (HHV)} = (3.54\ \text{kWh/Nm}^3) / (4.5\ \text{kWh/Nm}^3) \quad (7)$$

Therefore, the efficiency of the proposed electrolyzer is 78.7%.

The average power consumption per skid is 22 MW and the power produced from the PV plant is 364 MW. Therefore, 16 skids can be installed for a total hydrogen production of 16 x 4920 = 78,720 (Nm^3/hour) at ambient temperature (30 °C) and 30 barg (system output pressure).

Table 7 explained the cost of PEM electrolyzer in which the capital cost of PEM MW scale electrolyzer is 700~1400 USD/kW as per the data from IRENA [18] and 50,000 Yen/kW according to METI [4], Japan in which the total capital cost for a 352 MW electrolyzer plant is ¥ 17,600,000,000 (approximately 147 million USD) if the cost data from METI is considered [4].

Table 7. Costing of PEM Electrolyzer [4,18].

	Cost (Yen/kW) IRENA [18]	Cost (Yen/kW) METI [4]
Capital cost of PEM Electrolyzer	84,000 ~ 168,000	50,000
Total capital for 352 MW electrolyzer plant	29,568,000,000 ~ 59,136,000,000	17,600,000,000

The oxygen produced from the electrolysis process can be captured and stored in cylinders which can be utilized for other utilities within power plant area. Feed water will be used from a desalination plant which costs approximately $2 to $12 per 1000 gallons [22] depending on the location of power plant from the sea. In general, most power plants are located adjacent to the sea since large amounts of water are required to be utilized for power plant BOP (balance of plant) equipment including auxiliary boiler, utility water, service water, fire water and electro-chlorination systems.

The produced hydrogen will be fed to the gas turbine via the pipeline, and the excess hydrogen will be stored in pressure vessels. It is cost-effective to store hydrogen at medium pressures in tanks as PEM electrolyzers are capable of 30 bar output pressure and can directly store at storage tanks without the need for a compressor. Hydrogen storage options have attractive potential compared to battery storage as hydrogen can be stored in a storage tank for long period of time, season to season as needed, which is much longer than that of battery storage [23].

The required hydrogen safety precautions shall be taken care of in line with local and international standards. Currently, there is no specific law or code for the use of hydrogen, yet it falls under the High-Pressure Gas Safety Act. In order to construct hydrogen plants and storage facilities, permission is required from prefectural government authorities with specific requirements such as production capacity, storage capacity, etc. [24]. In the power generation industry, owner or end-user specifications usually call for NFPA standards in which NFPA 2 Hydrogen Technologies Code and NFPA 55, Compressed Gases and Cryogenic Fluids Code are to be confirmed if hydrogen generation and storage facilities will be constructed [25].

Hydrogen storage tanks will be installed outdoors with concrete plinths, and fences around storage tanks are necessary to limit access to authorized personnel only. Hydrogen generation equipment including electrolyzers, transformer rectifiers and control panels can be installed inside the building; otherwise, this equipment often comes with containers. For the hydrogen generation room or building, proper mechanical exhaust ventilation systems shall be provided to limit H_2 concentration at 2% per volume in air, which is 50% of the LEL (Lower Explosive Limit) since the LEL for H_2 is 4% per volume [25].

Hydrogen generation rooms, including open storage areas are classified as hazardous areas which are 4.6 m from any points of equipment or storage tanks in which any electrical devices/equipment to be installed inside hazardous area (within classified area) shall be explosion proof provisions [25]. The required spatial segregation from adjacent buildings, public streets, and line of property shall also be kept at a minimum of 7.62 m (25 ft) as required per NFPA 55 [26].

Table 8. Comparison of hydrogen storage methods [27].

Storage method	Advantages	Disadvantages
Compressed gas method	It is commonly used as a well-established method, reliable and suitable for long term storage.	Capital cost is high and possibility that container may rupture due to heat.
Liquid storage method	Provide high density at low pressure.	Capital cost is high and leakage can cause fire.
Metal hydride storage method	High volume efficiency, easy recovery, safe method	Expensive materials and heavy storage tanks.

Among the above storage methods explained in Table 8, compressed gas storage with large spherical pressure vessels will be applied which is commonly used for hydrogen storage. The capital cost of hydrogen storage is estimated in Table 9.

Table 9. Capital cost of hydrogen storage [28].

	Cost (Yen//kgH_2) [28]
Hydrogen storage for 24-hour operation	48,000 Yen ($400)
Cost for hydrogen storage (24 hrs)	8,154,624,000 Yen
Total capital for 7 days of storage tanks	57,082,368,000 Yen

Hydrogen plays a vital role in the transition of society towards decarbonization. However, due to its nature and characteristics, only high Ni materials such as SS316 L and aluminium alloy are permitted to be used in Japan due to their excellent resistance to hydrogen embrittlement and austenitic stainless steel like SS 304 are not allowed to be used or are not compatible with hydrogen. Most of the materials being used in turbine blades, bearings, rotor and the components for advanced gas turbines are SS 316 and they are compatible with hydrogen, but older turbines may not be compatible [29].

3. Results and discussion

Based on the electricity obtained from the solar PV pant, it can power 16 × 22 MW electrolyzer skids with a hydrogen production of 78,720 (Nm³/hour). This can supply 20% hydrogen fuel to the 557 MW output of GE gas turbine model-9HA.02 where it is required that the hydrogen flow rate 415,000 m³/hour. In the case of a combined cycle power plant, with the additional 20~25% power output from the steam turbine, a total of 700 MW of power output can be expected [21].

In the case of directly selling electricity generated from solar PV plants to the electric grid company, a total of 364 MW of output power can be sold without any complication. But, if every independent power provider simply sells the electricity produced from renewable power plants, it will have an impact on the reliability of the grid due to the variance and intermittent nature of renewable resources.

In the case of combined cycle power generation from clean hydrogen produced from PEM electrolyzers using the electricity from a solar PV plant, higher output (approximately 700 MW) can be obtained with the additional capital cost and operational cost investment in electrolysis equipment including the equipment used for the combined cycle plant. Due to the difference in the nature of the two different power generation plants, techno-economic assessment cannot be compared only looking at the cost. An energy mix is always recommended to secure the stability of the electricity supply rather than relying on a single source or renewable energy alone.

4. Conclusions

Based on this study, co-generation of 20% hydrogen and 80% natural gas solution is feasible without the need to upgrade gas turbine equipment and can save 8% of CO_2 emissions compared to the burning of natural gas fuel alone. This 20% hydrogen mix is generated as per the available power output received from in-house solar PV plant and on-site hydrogen generation plant. In fact, some reputable gas turbine manufacturers have already implemented 30% hydrogen co-generation with natural gas without major upgrades to existing generation facilities. The advantage of this configuration (PV + PEM + GT) is that it is a perfect approach for high electricity demand and megawatt scale plants as compared to other technologies such as PV with battery storage and PV with PEM + Fuel Cell, where those are suitable for small scales power plants.

In conclusion to this study, the innovation of 100% hydrogen-fuel gas turbines is certainly possible in the near future with the additional cost of SCR for NOx control including the material upgrade on combustor and applicable BOP equipment. On the other hand, hydrogen production and supply change should be well implemented to bring down the cost to compete with the import cost of natural gas.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declared that there is no conflict of interest in this research article.

Author contributions

Daido Fujita: Conceptualization, methodology, data analysis, software simulation, writing an original research paper.

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