Techno-economic Analysis of Renewable Power to Hydrogen Applications Considering Grid Flexibility Requirement

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1. Introduction

After the Great East Japan Earthquake in 2011, Japan government almost shut down all the nuclear power plant considering the security. In response to the decline in energy self-sufficiency ratio, the government made continuous efforts in energy independency of the country, including energy efficiency measures and electricity market reform. Feed-in tariff scheme launched in 2012 accelerated the integration of renewable production. Meanwhile, Japan has outlined ambitious goals to cut greenhouse gas emissions by 26% by 2030 compared with 2013 level. Renewable integration phased out the contribution of conventional thermal plant and reduced the marginal cost of electricity, spot market prices reaching a minimum of 0.01/kWh for 4 hours between 11AM and 3PM Kyushu Electric Power Company firstly implemented curtailment of PV production on October 13, 2018 based on Japan Electric Power Exchange data (Zissler, 2019). However, output of renewable source varies significantly depending on the condition of weather, the grid operator mainly adjust the capacity factor of thermal plant to respond to the fluctuation of renewable energy. Recently, Japanese electric companies had announced the capacity limits of variable renewable energy that could be connected to their grids based on history power consumption and production. Kyushu Electric Power Company firstly implemented curtailment of PV production on October 13, 2018. Integration of different energy carriers including power, heat and gas networks was expected to increase overall energy system flexibility, meanwhile, help decarbonize social energy system.

2. Literature review

Continuous rising penetration level of intermittent renewable generation poses significant techno-economic challenges operator of public grid. Kawajiri et al. (2019) proposed a model to clarified the flexibility under different operating condition and estimated the capacity limits of VRE in Japan, benefits of VRE can be increased by incorporating measures to restrict their output fluctuation and reduce the curtailment due to technical limitation. Optimal combination of different energy sectors was expected to provide flexibility resources and facilitate transition towards future low carbon energy system (Klyapovsky et al. 2019). Due to the stochastic characteristics of output, market value of wind and solar power tends to drop with increasing market share (Hirth, 2013; Hirth et al. 2015; Hirth, 2016). Furtwängler and Weber (2019) proposed model to investigate effects of reserve flexibility from CHP, and focusing on deriving cost optimal combination of heat demand and spot marketing opportunities in German electricity market. Dujardin et al. (2017) stated the effectiveness of hydropower in dealing with intermittent energy resource, how the 'required import' and 'required export' of electricity change as a function of ratio between solar and wind power generation, strategy for balancing supply and demand as a function of PV-wind mixing ratio. In order to meet increased variability of integrated renewable generation, power to heat (P2H) in demand side was proposed as an incentive to shave renewable production, results indicated that thermal storage increased the flexibility provided by P2H, cooperative electricity market is essential to control P2H production (Åberg et al., 2019). Zhang et al. (2019) quantified the building to grid demand response flexibility from heat pump aggregations, the energy payback following the P2H demand response event could be reduced significantly. Eggimann et al. (2019) simulated the potential to reduce national peak electricity load with managed heat pump in UK, built a high-resolution simulation modeling framework to explore the diffusion of large-scale heat pump and highlight importance of demand side management considering supply-demand matching and load shifting. Cao et al. (2018) evaluated the economic performance of wind powered thermal energy system that help decarbonize power and heating systems, it presented as an economic competitive technology for space heat supply. Yilmaz et al. (2018) pointed out that large P2H technologies could contribute to system balancing and ancillary services considering the intermittent characteristics of renewable energy, small scale P2H technologies were not yet economically viable and hard to participate in European balancing market.

In the context of power to gas (P2G) conceptions, existing study emphasize the potential analysis and assessment of technological feasibility. Li et al. (2019) quantified the potential of renewable production to hydrogen considering grid flexibility requirement and made sensitivity analysis of P2G under different renewable share ratios and implemented capacities of electrolysis. Gas switching reforming combined cycle plant was suggested to hydrogen production with integrated CO_2 capture, it presented a higher annualized investment return compared with natural gas combined cycle (Szima et al. 2019). Braff et al. (2016) stated that economic feasibility of storage system highly depends on storage power and duration period, and the energy related costs, further improvement is needed in wind and solar generation costs and storage costs. Gholizadeh et al. (2019) presented the positive impact of wind power to gas among energy hub, it can help decrease security cost due to the role of P2G in enhancing thermal demand by providing their input gas carrier during gas lines contingencies. Taking advantage of fluctuations in electricity prices and intermittent renewable output, Glenk and Reichelstein(2019) found that renewable hydrogen was already cost competitive in niche application and was projected to become competitive with industrial-scale supply within a decade in Germany and Texas. Lee et al. (2018) pointed that polymer electrolyte membrane water electrolysis was found to be economically profitable, increased capacity factor resulted in positive net present values and shorten discounted payback period in Korea.

We will investigate the potential of hydrogen production as seasonal storage to increase the value of renewable energy generation. And analyze the invest optimal capacity of electrolysis to convert surplus renewable generation.

3. Data and method

3.1 Data source

Kyushu is seen as a successful example of implementing renewable integration, features with large integrated PV capacity. Fig.1 illustrated the scenario of power contribution by sources of Kyushu power companies. FIT refers to the integrated renewable energy under feed-in tariff scheme, other presents the electricity from other companies. We clearly observe that conventional power plants including coal, LNG and oil were still the dominant energy resource, renewable typical was mainly composed of FIT and not FIT types experienced a rapid development over recent year, especially after shutdown of nuclear plant due to the big east earthquake in 2011. Higher renewable penetrations lead to larger and more frequency ramps, it was worth noting that Kyushu power company had to curtail the excess PV production during midseason period due to the grid flexible limitation (METI, 2019). Future power supply system enters the next phase of transition, focused on how to allow higher shares of RES and ensure the grid reliability.

The optimal mix structure of power sources highly depends on the generating cost of power generators, all have a well-defined variable cost and fixed cost. Ministry of Economy, Trade and Industry has estimated the future generation cost of each type of power technology in Japan, Fig.2 presented the assumed scenario in 2030 (METI, 2015).

Fig.1 Power supply of power company by sources, Kyuden (K.E.P. Company, 2019)

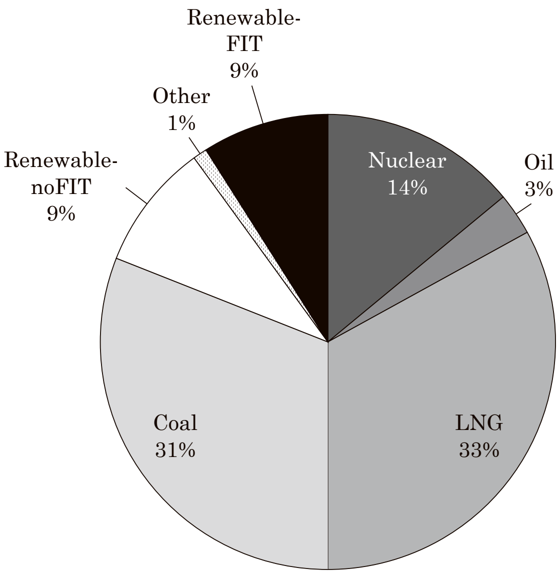
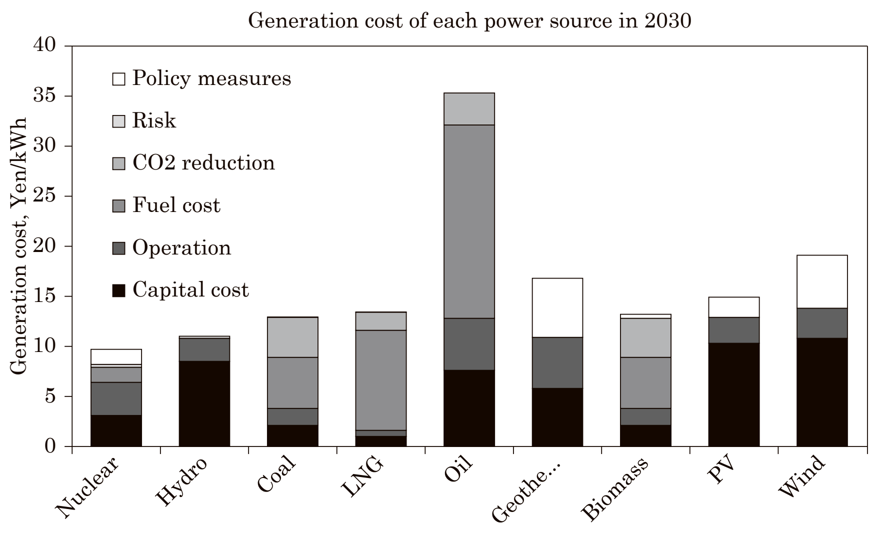


Fig.2 Power generation cost of each power source



Feed-in tariff scheme permit the renewable resource integrated into the grid, capacity of integrated PV system experienced a sharp rising period over recent years, as illustrated in Fig.3.

Fig.4 shows the scenario of system operator how to adjust electricity production to match both variable demand and variable supply in real time. It can clearly observe that nuclear power plants serve as baseload plant with stable output throughout the day.

Fig.3 Increasing trend of cumulative integrated PV capacity in Kyushu

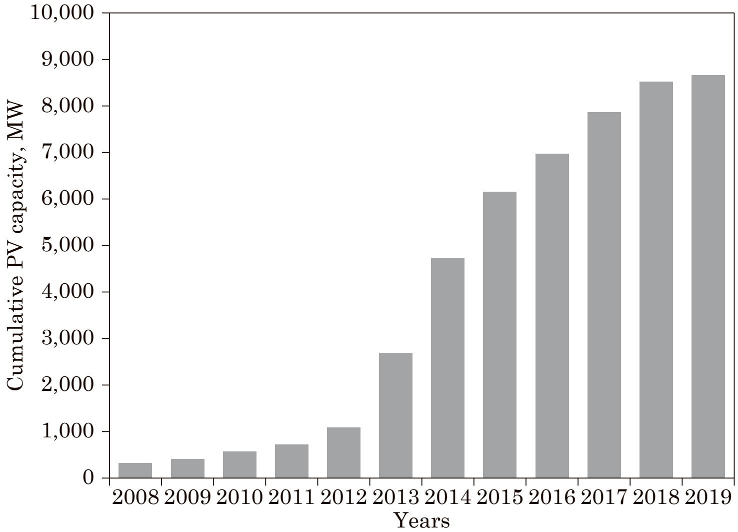
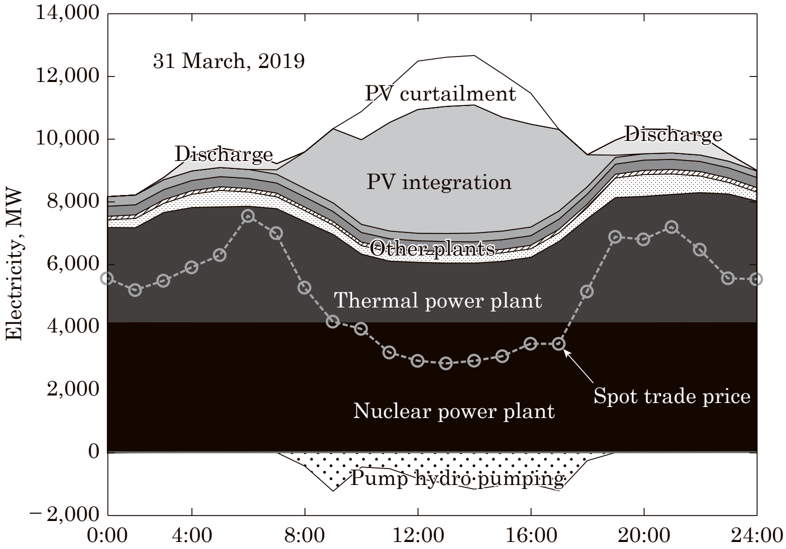


Fig.4 Actual daily balance between supply and demand in Kyushu



Fossil-fired power plants (coal, oil, and gas) as well as pumped hydro start to provide flexible sources by ramping down output and charging reservoirs of the pump hydro system in the morning. Then the upward direction occurred to meet rising load, the discharging occurred when the production of PV system drops. The output of flexible plants has reached its minimum value during daytime, part of PV production has to be curtailed due to grid flexible limitation, resulted the oversupply period. The cycle of pump

Fig.5 Color-scale distribution of residual grid load 2017 (left) 2018 (right)

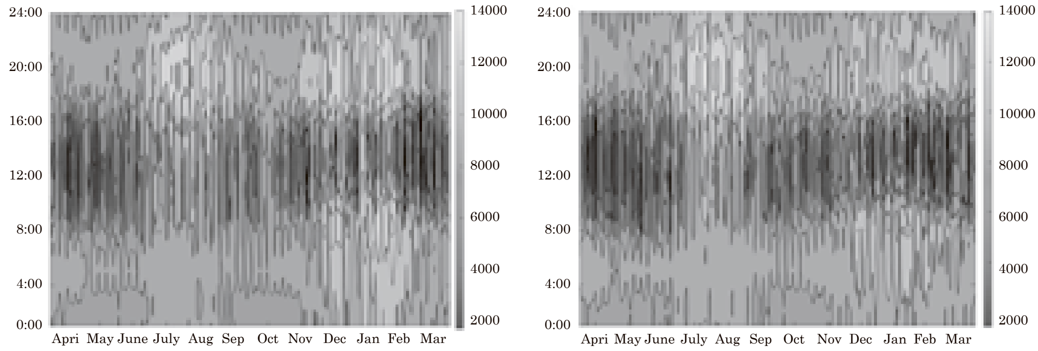
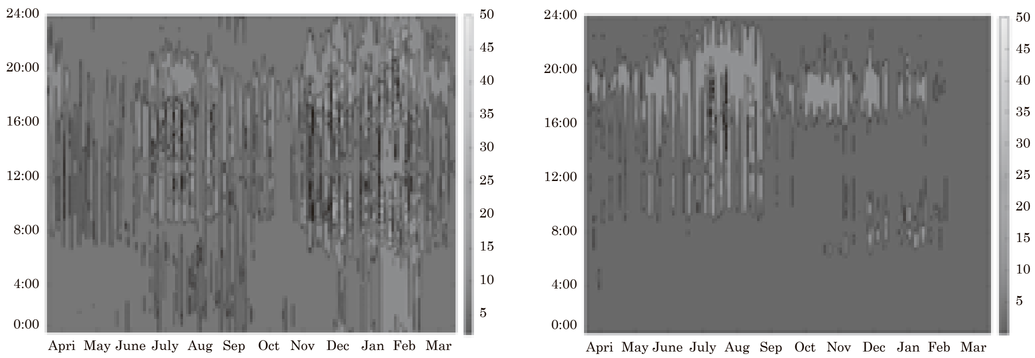


Fig.6 Color-scale distribution of the spot market trading 2017 (left) 2018 (right)



hydro storage system helps mitigate the PV overproduction, however, the expansion potential of pumped hydro storage is limited due to the lack of favorable geographic site. The curtailment has occurred because conventional power system will be unable to accommodate the ramp rate and large pumping capacity of pump storage system is needed. Meanwhile, the PV contribution has shaped the net grid load into a duck curve, the spot trading curve presented similar pattern described as the red dot line in Fig.4.

The rapid growth of variable solar generation also has led to significant impacts on wholesale electricity price, the trend can be obviously observed in recent spot market trading price. Fig.5 presented the color scale distribution of residual load obtained by subtracting PV production, the duck curve is obvious during the mid-season because during sunny day when demand is low and solar generation is high. The wholesale prices can be very low, it indicated potential economic benefits from conversion of renewable power to heat or fuel (Sternberg and Bardow, 2015). Fig.6 illustrated the annual variation of power spot market trading in 2017 and 2018, the peak price showed similar pattern with the residual load, higher spot price occurred at peak load period.

3.2 Method

The renewable generation has a very low marginal cost, it will always be dispatched for the full amount of its production. The conventional plant will service the rest of the load, all the generators have a well-defined fixed and variable cost. the cost screen curve is usually used to determine the optimal mix of thermal power plants, the fixed capacity of baseload plant (nuclear and coal based) will dominate the main cost, it will show an economic advantage with longer operational period compared with peak plant (LNG or oil based) features with high fuel cost. The intersections of curves illustrated in Fig.7 can determine the type of power plant technology that can supply optimal levels of grid load for a given annual number of hours at the minimum overall cost.

Fig.8 presents the relationship between PV production to grid load ratio and spot market trade pricing. Emission free solar production has zero fuel cost, it has price reduction effects on wholesale market prices, the spot market trading price is less expensive when the renewable dominated the grid load supply, the trading price even drop from 50 Yen/kWh to 5 Yen/kWh with rising penetration level of solar production.

RES production is variable and uncertain. To maintain the security and reliability of the power system, the flexible plant is necessary to absorb the mismatch between simultaneous generation and grid load. Considering structure of the current power supply system and technical constraints, the constant base-load plant and residential grid load are given as:

$$C = \gamma L_{grid}^{\max} \tag{1}$$

$$Net = L_{grid} - C \tag{2}$$

Here, γ refers to the ratio of constant output to annual peak value of the grid load L_{grid}. Net represents the net grid load by subtracting the constant output from must-run plants.

Considering flexible requirements, available renewable energy and the supply-demand balancing process, real-time direct PV integration can be calculated as:

$$RE_{i,j}^{\text{int}} = \min\left(RE_{i,j}, \max\left(0, Net_{i,j} - \delta Net_{i,j}^{\max}\right)\right) \tag{3}$$

where $RE_{i,j}^{\text{int}}$ denotes direct PV integration without any storage device. Flexible plants can range their rational output to balance the residual load at real time. The minimum output of a dispatchable plant is supposed to be a ratio δ of maximum net residual load in each day $Net_{i,j}^{\max}$.

Fig.7 Determining optimal capacity of generator using screening curve

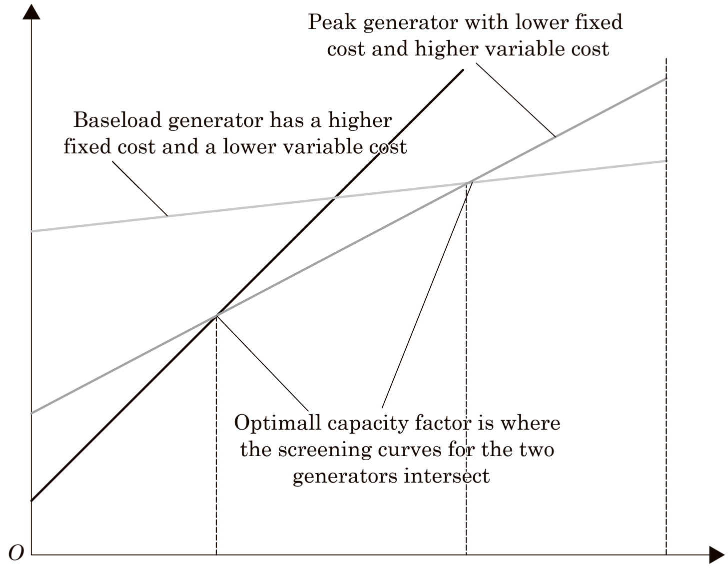
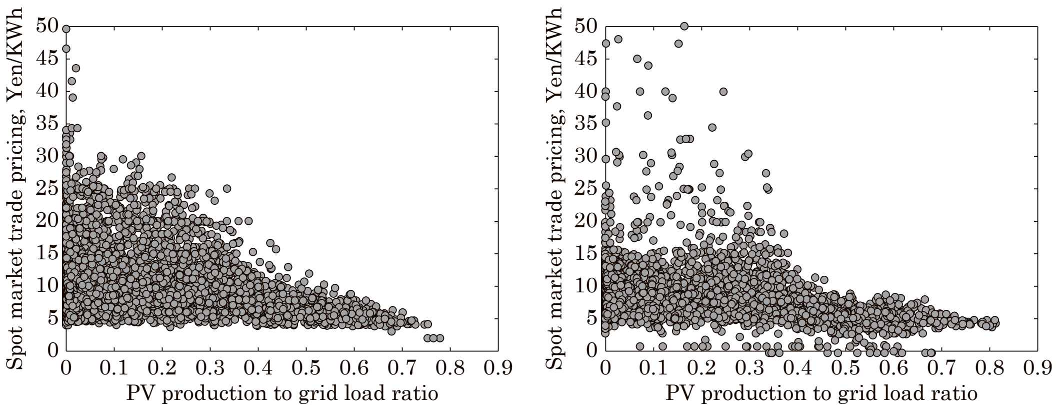


Fig.8 Relationship between PV production to grid load ratio and spot market trade pricing



4. Result and analysis

Limited to the constant-output plant ($\gamma = 0.3$) and minimum output ($\delta = 0.3$) of a flexible plant, Fig.9 presented the simulated scenario of renewable integration including direct integration and curtailment without storage dispatch, curtailment is larger during mid-season due to the grid flexible limitation. Fig.10 presented the sorted surplus PV production curved corresponding different gross share ratios of solar production to grid load. We can combine the maximum rectangle method (MRM) could be used to determine

Fig.9 Integration & curtailment of PV production with 30% solar penetration level

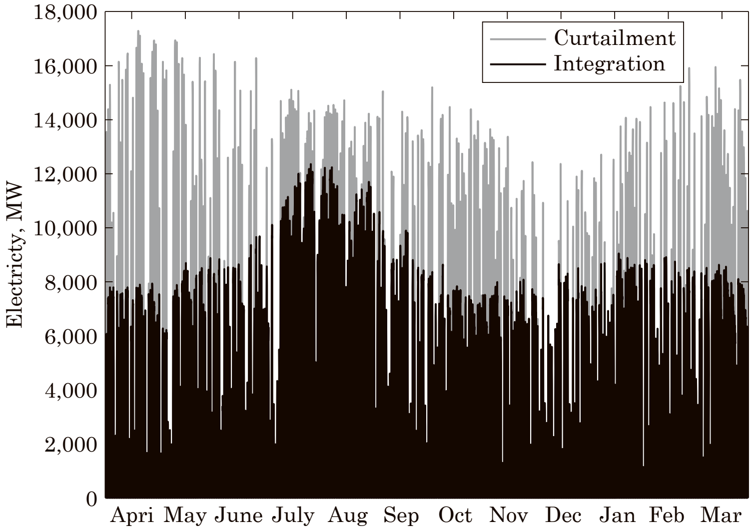


Fig.10 Annual surplus PV production in descending order and their corresponding rectangles in the MRM

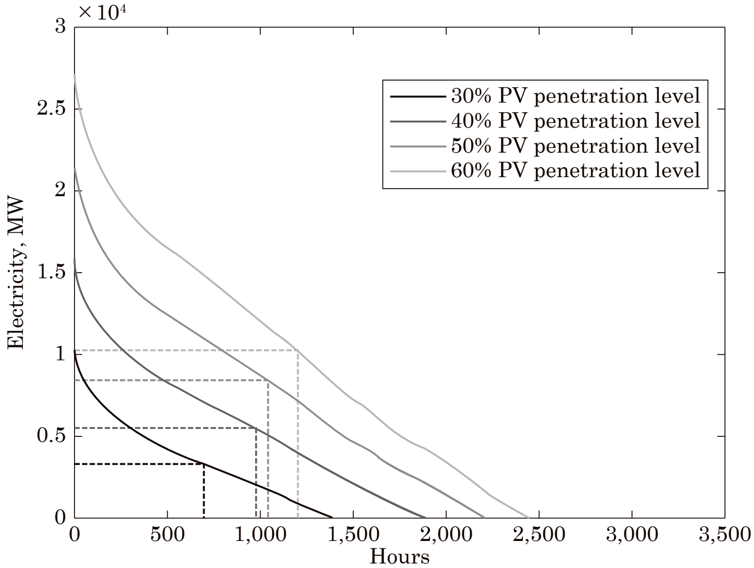
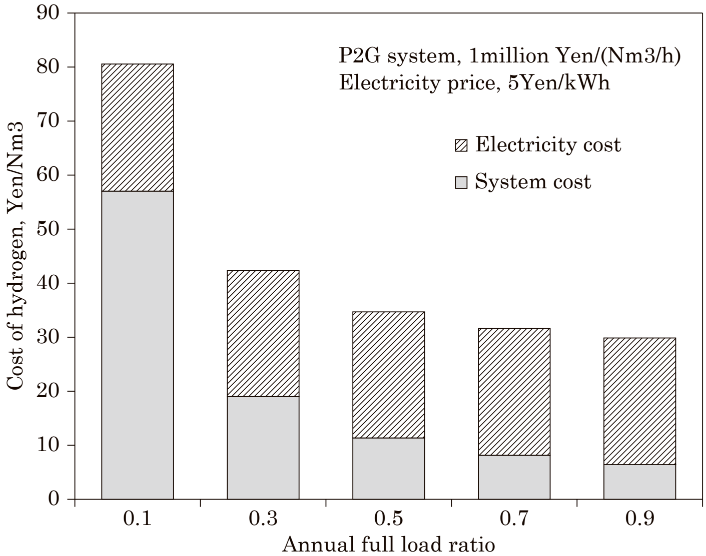


Table 1 Technical and economic parameters of renewable to gas system

Variables	Value
P2G system, Yen/(Nm^3/h)	1000000
Lifespan, year	20
Conversion efficiency, kg/kWh	0.019
Electricity price, Yen/kWh	5
Density of Hydrogen, kg/Nm^3	0.089

Fig.11 Cost of power to hydrogen



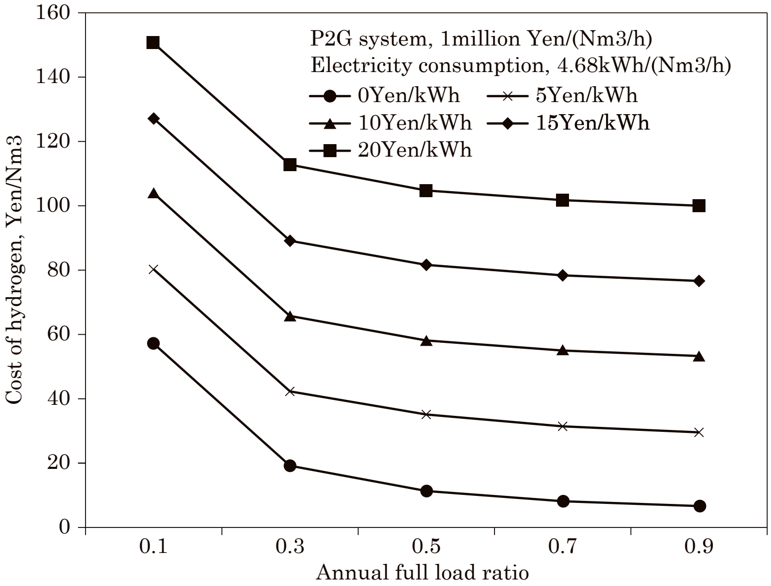
the optimal capacity of electrolysis with largest conversation potential of renewable energy to hydrogen. As illustrated in Fig.10, the slope line refer to the sorted surplus PV production under grid flexible requirement, the intersection of the dash line refers to the maximum value of the rectangle surface area under specific gross PV share level of the public grid. We can observe that the rising surplus PV production raises the number of full load operational hour (from 697 hours at 30% gross penetration level to 1203 hours at 60% gross penetration level) of electrolysis, then rising rate will become less with increasing PV penetration level.

To analyze the economically viable of renewable to hydrogen, Table 1 shows the assumed renewable to hydrogen system specific technical parameters, capital expenses and electricity price. Electricity price was assumed according to lower spot trade price.

Total cost of P2G aggregates all costs over levelized capacity cost of facility and electricity price. Fig.11 illustrated the cost scenario of renewable to hydrogen, capacity investment would dominate the cost of P2G, it will drop sharply with rising annual utilization ratio.

Fig.12 present the impact of two sensitive parameters, annual utilization ratio of electrolysis and electricity price on cost of P2G, electricity price presents a larger impact on overall cost when the electrolysis can operate in longer period with full load condition. Capital costs dominated the overall cost of hydrogen production due to the lower utilization rates. High penetration of intermittent renewable sources leads real time production exceeds demand, zero marginal cost refers to converting curtailed renewable energy into hydrogen, it indicated an obvious economic potential at higher annual

Fig.12 Impact of electricity price on economic performance of P2G



utilization ratio.

5. Conclusions

Future low carbon energy system has to face the challenges in handling the increasing intermittent renewable productions. Renewable power to hydrogen provides a promising opportunity to recover surplus renewable production considering grid flexible requirement.

In this paper, we first analyzed the condition of Kyushu public grid in Japan, considering the rising renewable integration and its impact on wholesale market price. Results indicate that PV integration has significantly shaped the curve of residual grid load, rising renewable penetration leads the drop in spot market price that enables the potential economic benefits of renewable conversion. Higher penetration level of variable renewable integration lead to obvious surplus renewable production due to grid flexible requirement. Surplus PV production features with short available hours, electrolysis has to operate with short duration hours of full load operation, even with large amount of surplus PV production. Sensitive impacts of facility utilization ratio and electricity price on performances of P2G were carried out, capital costs would dominate the generation cost of renewable to hydrogen, electricity price presented larger impacts on economic performance of P2G at higher utilization rate. In order to improve the cost effective of renewable to hydrogen system, future efforts may focus on rising converting efficiency of P2G and reducing capacity cost of electrolysis.

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