Grid Flexibility Offered by Distributed Combined Heat and Power Using Carbon-neutral Methane Produced from Renewable Surplus Electricity

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This study evaluated a renewable energy grid integration model (CNM-CHP) that provides grid flexibility by ramping up the output margin of combined heat and powers (CHPs) when renewable energy output reduces, using city gas decarbonized by carbon-neutral methane (CNM) blended into the city gas network. CNM is produced through methanation -reacting electrolytic hydrogen from renewable surplus electricity and CO_2 from facilities like fossil fuel-fired power plants, biomass power plants and industries. CNM being able to utilize the existing city gas network has economic advantages over hydrogen that requires new infrastructure to be delivered. CHPs expected as Virtual Power Plants (VPPs) to provide grid flexibility a need decarbonized way. With an assumption that 300 GW of solar photovoltaics, 100 GW of wind power and 34 GW of CHP are deployed in Japan, it was revealed that CNM-CHP shows the same economics as or superior to grid flexibility offered by batteries. Power-to-Gas systems using existing infrastructure have advantages in decarbonizing the entire energy system over batteries that can discharge only a fraction of stored electricity due to grid constraint when large scale renewables are deployed.

Keywords : Grid flexibility, CHP, Power to gas, Methanation, CCU

1. Introduction

As carbon-neutral methane (CN methane) is synthesized (in a methanation process) from hydrogen that is produced by renewable energy through electrolysis, and CO_2 that is emitted through biomass power plants, fossil fuel-fired power plants, and large-scale industries, it can be called as a “renewable synthetic fuel” that is produced through a combination of power-to-gas (PtG) as grid integration measures and carbon capture and utilization (CCU). CN methane reuses CO_2 that has already been emitted, and for this reason, became one of the key focuses in the Roadmap for Carbon Recycling Technologies prepared by the Agency for Natural Resources and Energy in June 2019.

One of the options of hydrogen application is its injection into city gas infrastructure.1) However, as hydrogen has a low volumetric calorific value, it has only a limited decarbonization effect on city gas. There are also other challenges, including compatibility with special applications that require carbon, such as metal carburizing and super high-temperature furnaces, and calorific adjustment of gas appliances. On the other hand, CN methane, which is a feedstock for city gas, poses few problems with regard to injection into the city gas infrastructure, and there are high expectations for it as a decarbonization technology for city gas.2) There are existing researches that show huge potential of producible CN methane in Japan and that CN methane can suppress supply costs more effectively than hydrogen that requires new infrastructure.3), 4) With these advantages, advance efforts led by Germany and other European countries, such as the demonstration of CN methane, have also been progressing in Japan in recent years.5), 6), 7), 8)

Meanwhile, distributed combined heat and power (CHP), which uses largely city gas, is expected to mitigate the output fluctuation of renewable energy by acting as a virtual power plant (VPP). In short, alongside regular CHP operations under normal conditions, output fluctuation is offset by utilizing CHP margin output capacity to increase output when the output of renewable energy falls. As CHP has high total efficiency, we can expect more reduction in CO_2 emissions through the mitigation of output fluctuation than LNG thermal power; nevertheless, CHP is accompanied by a certain degree of CO_2 emissions as it uses city gas. However, by producing CN methane from surplus electricity that is generated through the increase in output from renewable energy, and using CN methane in CHP via the city gas infrastructure, it is possible to achieve grid flexibility with lower carbon levels. Moreover, CHP was originally introduced as a cogeneration for consumers, and its application to mitigating output fluctuation may be more economically viable in comparison with output fluctuation mitigation through other energy storage techniques that need to be introduced additionally.

In light of that, this study analyzes the contributions that CHP using CN methane makes to grid flexibility, and the possibility of achieving decarbonization for electricity and city gas.

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2. Flow of analysis

2.1 Definition of the CNM-CHP model

Based on the above approach, this study defines "grid flexibility offered by distributed CHP using CN methane produced from renewable surplus electricity" (hereafter, "CNM-CHP") as follows (**Figure 1**).

- Produce CN methane from hydrogen derived from surplus electricity of variable renewable energy (solar photovoltaic and wind power) as well as CO_2 emitted intensively through biomass power plants, industries, and fossil fuel-fired power plants, and inject it into the city gas infrastructure (decarbonization of city gas).
- CHP, like other applications (such as heat demand), uses city gas that has been decarbonized by CN methane, via the city gas infrastructure.
- CHP regular operation is based on combined heat and power supply. At the same time, when the output of renewable energy falls, margin output capacity is used to increase output (CHP ramp-up = downward demand response).

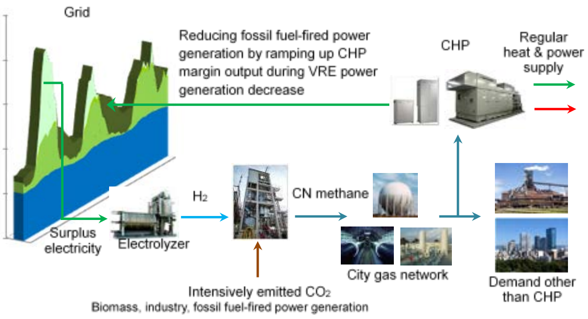

Figure 1 Structure of CNM-CHP Model

2.2 Simulation structure and assumptions

(1) Structure of the power generation mix simulation / Operation of power plants

In this study, Japan is hypothetically treated as a single region for the sake of simplification. Data granularity in the analysis is one hour, and the target period is one year. The operation of the power plants are presented as follows.

[Common operations]

- Baseload power plants (nuclear, hydro, geothermal, biomass) and regular CHP operation are assumed to be "must run". (Verified that there is no curtailment of the baseload power plants)
- Load frequency control thermal power plants are assumed to cover 10% of the hourly power demand.
- For surplus electricity, pumped-storage hydro is used first. Stored electricity is discharged immediately, whenever possible.

[CNM-CHP]

- Surplus electricity from variable renewable energy, which spill over from the grid even after the abovementioned common operation, will be used for producing hydrogen. Producible CN methane is hourly identified based on the amount of hydrogen and intensive CO_2 emissions (hourly CO_2 emissions are described later). If CO_2 emissions for CN methane production are not sufficient, surplus electricity will be curtailed.
- Only when the grid has space to accept and CHPs have margin output capacity, CHPs ramp up.
- Electricity demand - (base-load power output + LFC power output + variable renewable output + discharge from pumped storage hydro + CHP ramp-up) is met by fossil-fired power generation.

[Battery] (For comparison of economics described later)

- Surplus electricity from variable renewable energy, which spill over from the grid in the abovementioned common operation, is charged into batteries. If batteries are fully charged, surplus electricity will be curtailed.
- Batteries immediately discharge whenever possible.
- Electricity demand - (base-load power output + LFC power output + variable renewable output + discharge from pumped storage hydro + discharge from batteries) is met by fossil-fired power generation.

(2) Electricity demand / Capacity of the power generation

Taking into account long-term electrification trends and energy conservation, it is assumed that electricity demand will increase by about 10% from the current level to 1,040 TWh. Nuclear power generation is assumed to be at the level of the amount introduced for 2030 in the "Long-term Energy Supply and Demand Outlook," while power generation from small- and medium-scale hydro plants, biomass power plants, and geothermal power plants are assumed to be at a level that is slightly higher than the amount introduced for 2030 (13 GW, 8 GW, and 3 GW respectively). No assumptions are made for newly constructed large-scale hydro and pumped-storage hydro. From the long-term perspective, all thermal power generation is assumed to be LNG-fired power.

Regular CHP operation is assumed to be "must run". It is assumed that only when the grid has space to accept and CHPs have margin output capacity (when operating at a level below rated output), CHPs can ramp up. Pumped-storage hydro operation (charging and discharging or renewable energy) is prioritized. It is assumed that the capacity of CHP introduced is 30 GW for commercial and industrial use + 5.3 million stationary fuel cells for residential use ≒ 34 GW, which is the government and gas industry target.

Scenarios are established in which solar photovoltaic ranges from 70 GW to 500 GW, and wind power ranges from 10 GW to 300 GW.

(3) Hourly intensive CO_2 emissions

With regard to biomass power generation and industries, annual intensive CO_2 emissions nationwide is specified based on previous studies.2), 3) It is assumed that biomass power generation is operating at a constant output, and allocates annual CO_2 emissions volume by each hour. The hourly CO_2 emissions in industries is assumed to follow a similar profile for all power demand, and is allocated by each hour. The hourly CO_2 emissions volume for thermal power generation is specified through the operation pattern, based on the simulation for power generation mix.

(4) Identification of a regular operation pattern for CHP and technological specifications

To figure out how much CHPs can ramp up to mitigate renewable energy output fluctuations, the regular operation pattern should be identified. With regard to residential CHP, the operation pattern of PEFC is estimated based from measurement survey in the existing research.9), 10) For SOFC, a flat operation at rated output through the year is assumed (some gas companies purchase SOFC surplus electricity). All residential CHP is assumed to be fuel cells (rated output of 0.7 kW), and the ratio for the number of PEFC and SOFC is assumed to be 1:1. With regard to CHP for commercial use, the measurement data by subsector × by season × by weekday/weekend from the existing research11) are averaged weighted by introduced capacity by subsector.12) As for industrial use, it is assumed to be 80% of rated output for daytime and 65% for nighttime, based on hearings to experts.

Figure 2 shows CHP power generation patterns and margin output capacity by sector for a representative week during summer in cases where the CHP target (34 GW) is achieved. As CHP is operated mainly in the daytime, margin output capacity is larger during nighttime. It is physically possible to ramp up CHP output by about 7 to 10 GW in the daytime and about 17 GW at nighttime.

For the sake of simplification, the power generating efficiency of CHP is assumed to be 55% regardless of the type and age. Waste heat recovery efficiency is assumed to be 35% during regular operation, and 25% during ramp-up (According to interview from experts, CHPs generally suspend operations during nighttime because cheap nighttime electricity rates from the grid are favorable, but not because heat demand decreases. Therefore, it is assumed that even if CHPs are operated during nighttime, exhaust heat can be consumed by heat demand to some extent).

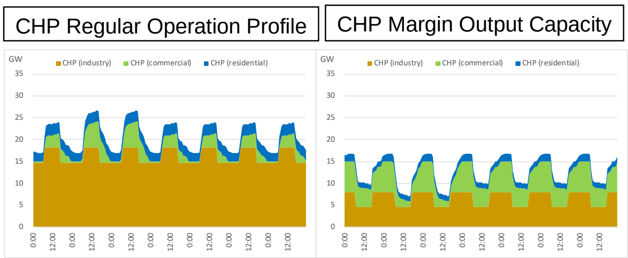

Figure 2 CHP Regular Operation Profile and Margin Output Capacity

Note: A representative week in summer. The cumulative installed CHP capacity is assumed to be 22.72GW, 0.728GW and 0.371GW in industry, commercial and residential, respectively.

(5) Technical specifications for CO_2 capture and CN methane production

Regarding energy consumption related to the CO_2 capture, the CO_2 compression accounts for the largest share of power consumption in CCS (for CCS process, CO_2 pressure is raised up to 7 MPa to make CO_2 critical state for efficient transportation to storage sites). However, higher compression is not required for CN methane production process, no more than 0.1-0.5 MPa. As a result, power consumption in CO_2 capture is 10 kWh/t-CO_2 and heat requirement is 1,800 MJ/t-CO_2 (Table 2-3), based on future estimate in the existing research13). As surplus electricity from renewable energy occurs whenever CN methane is produced, adding electricity consumption for CO_2 capture to the specific electricity consumption of CN methane (18.32 kWh/Nm^3-CH_4),2) it would be 18.34 kWh/Nm^3-CH_4. Assuming that the heat needed is supplied by city gas, heat consumption would be 4,436 kJ/Nm^3-CH_4 (assuming boiler efficiency of 80%). CO_2 capture rate is assumed to be 90%.

3. Results of analysis for the CNM-CHP model

Figure 3 shows the results of simulation for the representative one-week in summer. A part of the surplus electricity is used for the CN methane production, but its volume is dependent upon the volume of CO_2 that is available (**Figure 4**), and the rest of the surplus electricity is curtailed. It is found that CHP ramps up majorly during nighttime when CHP margin output capacity is available (**Figure 5**). As renewable energy deployment expands, wind power generates electricity during nighttime, reducing the room for CHP ramp-up. **Figure 6** shows power generation mix. As more surplus electricity is generated more frequently due to renewable energy large-scale deployment, with priority given to pumped storage hydro, a decline is observed in the grid's acceptance for accommodating CHP ramp-up. This trend is described in detail in **Figure 7**, which shows the status of use of margin output capacity of CHP.

Figure 8 shows city gas consumption and CN ratio (CN methane's share in city gas demand). City gas here represents a blend of conventional city gas and CN methane. When renewable energy introduction scale is small, there is large space for CHP ramp-up and city gas demand increases accompanying CHP ramp-up. However, as surplus electricity from renewable energy is limited, CN methane production (and city gas consumption for CO_2 capture) is also limited. Producible CN methane volume is 8.4 billion Nm^3-CH_4 with 3GW of solar PV + 100GW of wind power, and 22.5 billion Nm^3-CH_4 with 5GW of solar PV + 3GW of wind power, equivalent to 21% - 57% of the methane calorific value equivalent of city gas consumption in FY2016 (39.7 billion Nm^3-CH_4). The city gas consumption required for CO_2 capture accounts for a small percentage of overall city gas consumption.

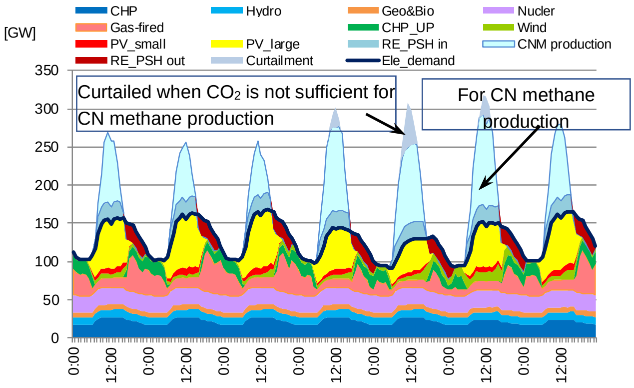

Figure 3 Hourly Power Generation Mix (CNM-CHP)

Note: A representative week in summer. 300GW of Solar PV + 100 GW of wind

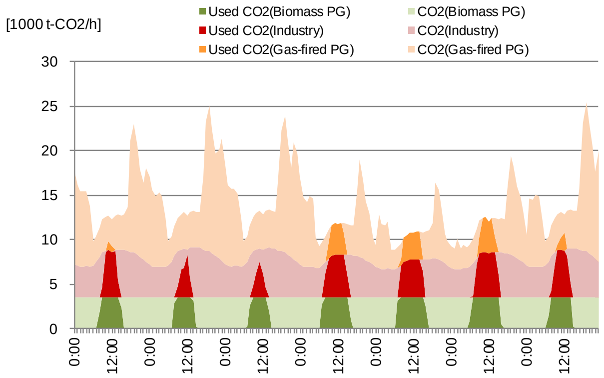

Figure 4 CO_2 utilization for CN methane production (CNM-CHP)

Note: A representative week in summer. 300GW of Solar PV + 100 GW of wind

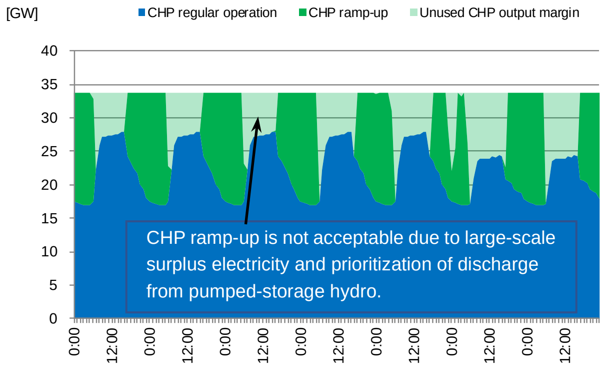

Figure 5 CHP ramp-up (CNM-CHP)

Note: A representative week in summer. 300GW of Solar PV + 100 GW of wind

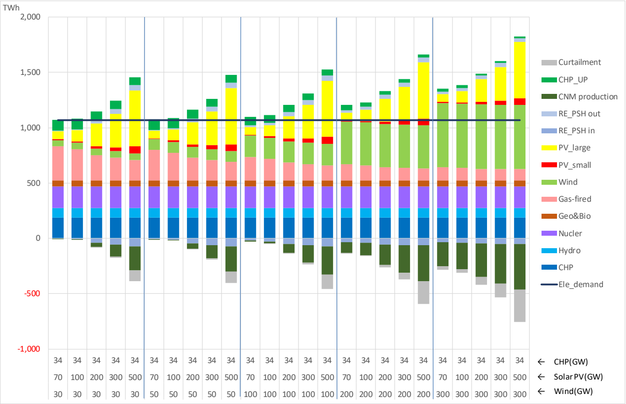

Figure 6 Power Generation Mix (CNM-CHP)

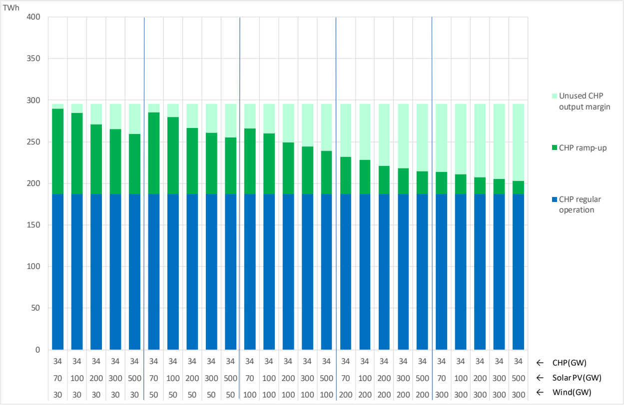

Figure 7 Utilization Status of CHP Output Margin

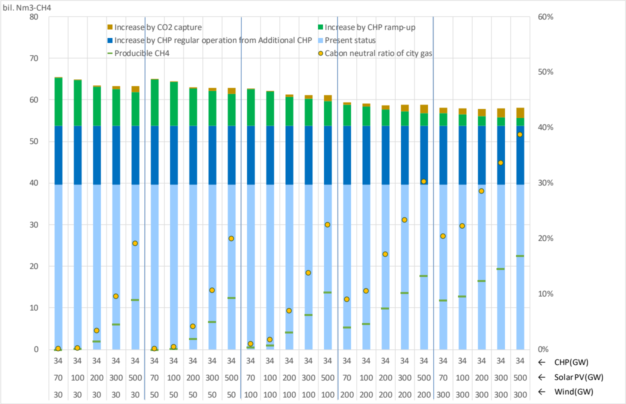

Figure 8 City Gas Demand and Carbon Neutral Ratio

Note: Carbon neutral ration = CN methane production/city gas demand. City gas demand is expressed by methane calorific equivalent.

4. Analysis of economics

Batteries are chosen to compare with CNM-CHP. At present, batteries are increasingly used for load frequency control as short-term application mainly in Europe and the United States where the markets have been developed. As battery prices decline, however, batteries are expected to be used for long-term application to charge and discharge surplus renewable electricity, which is a similar function as that performed by CNM-CHP. In comparing the “CNM-CHP case” and the “Battery case,” the total CO_2 emissions from electricity and city gas combined is used as an indicator. The capacity of CHP introduced for both cases is fixed at 34 GW, with the following assumptions:

- In the “CNM-CHP case,” margin output capacity of CHP is utilized as a means of mitigating output fluctuation of renewable energy by ramping up CHP output.
- In the “Battery case,” the regular operation of CHP is set to be “must run”, and additionally introduced battery is used for mitigation of output fluctuation of renewable energy (2.2).

The following is a comparison of economics between the “CNM-CHP case” and the “Battery case,” under conditions where CO_2 emissions are at the same level, and capacity is identified. The charge/discharge efficiency of the battery is assumed to be 90%×90%, while self-discharge rate is assumed to be 0.02%/h.

4.1 Hourly generation mix (“Battery case”)

Figure 9 shows the hourly power generation mix for a representative one-week period in summer. The curtailment of surplus electricity from renewable energy is dependent upon the storage capacity of the battery (kWh).

Figure 10 shows the power generation mix. In four scenarios where solar PV + wind power is 100 GW + 30 GW, 200 GW + 50 GW, 300 GW + 100 GW, and 500 GW + 300 GW respectively, battery storage capacity ranges from 0 to 500 GWh.

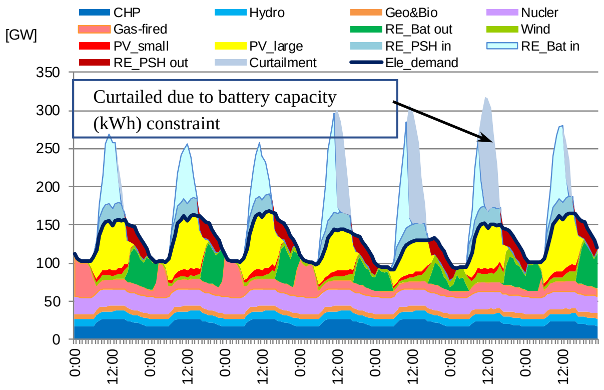

Figure 9 Hourly Power Generation Mix (Battery case)

Note: A representative week in summer. 300GW of Solar PV + 100 GW of wind. The scale of battery is 0.386 TWh (153 GW) based on the analyses hereafter.

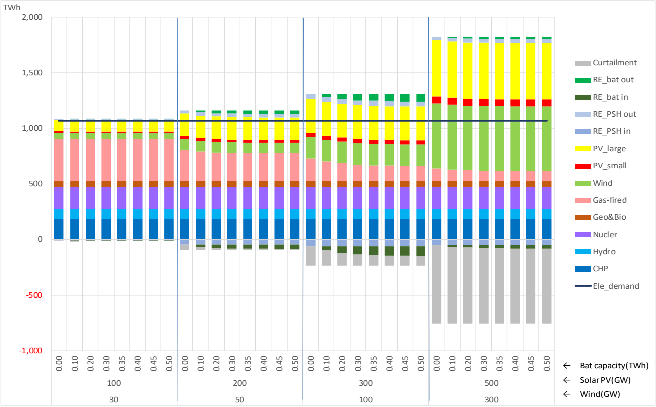

Figure 10 Power Generation Mix of “Battery case”

Charging and discharging are rarely operated in the presence of limited surplus electricity for a 100 GW of solar PV + 30 GW of wind power. Therefore, expanding battery capacity is meaningless, failing in replacing fossil-fired power generation.

As surplus electricity increases in line with renewable energy capacity expansion, opportunities for batteries to charge and discharge electricity increase. Then, expanding battery capacity leads to a remarkable decrease in fossil-fired power generation. However, if renewable energy expands to 500 GW of solar PV + 300 GW of wind power, battery capacity expansion does not necessarily lead to greater decrease in fossil-fired power generation. This is because as massive solar PV and wind power deployment boosts the frequency and amount of surplus electricity throughout the year, opportunities for batteries to discharge electricity decrease substantially. In such a situation, battery capacity expansion does not make sense.

It is observed that when renewable energy capacity is small, CHP ramp-up exceeds the battery discharge (**Figure 6**). This is because CHP plants can ramp up irrespective of CN methane production while batteries cannot discharge electricity in the absence of sufficient electricity stored.

4.2 CO_2 emissions volume of electricity and city gas

Figure 11 shows CO_2 emissions from power generation and city gas in the “CNM-CHP case” and the “Battery case” by renewable energy deployment scenario. The four clusters represent the four scenarios of solar PV + wind power introduced. In each cluster, the right-end bar represents the CO_2 emissions for “CNM-CHP case” and the remaining eight bars represent CO_2 emissions for the “Battery case.” In case of 100 GW of solar PV + 30 GW of wind power, surplus electricity, or in short, CN methane production volume, is extremely low. However, CHP ramp-up, regardless CN methane production, can reduce the CO_2 emissions (even with CN methane production limited) because of higher total efficiency of CHP than LNG-fired power generation.

When the surplus electricity increases alongside an expansion in the scale of renewable energy introduced, the charge/discharge operation of the battery becomes effective. Hence, increasing the storage capacity of batteries bring about the CO_2 emissions reduction by replacing thermal power generation. However, the impact diminishes gradually.

When renewable energy deploys up to 500 GW of solar PV + 300 GW of wind power, CN methane production rises substantially to promote the decarbonization of city gas. In the "Battery case", however, battery capacity expansion cannot curb CO_2 emissions to a lower level than in the "CNM-CHP case"

Figure 11 Comparison of CO_2 emissions in CNM-CHP and battery cases

4.3 Identification of Capacity

Taking the scenario of solar PV 300 GW + wind power 100 GW as an example, the situation is identified where CO_2 emissions volume becomes the same for both the "CNM-CHP case" and the "Battery case".

According to simulations, the maximum hourly CO_2 capture comes to 13,180 t-CO_2/h. With the CO_2 capture rate at 90%, CO_2 capture capacity is identified 14,650 t-CO_2/h. The maximum electricity input into CN methane production process is 122.65 GW. With the specific electricity consumption for CN methane production including CO_2 capture, CN methane production capacity is 6.69 million Nm^3-CH_4/h.

In the scenario of solar PV 300 GW + wind power 100 GW + CHP 34 GW, CO_2 emissions for the "CNM-CHP case" is 157 million t-CO_2.

The scale of battery with which the CO_2 emissions in the "Battery case" is the same as the "CNM-CHP case" is found at 386 GWh of storage capacity with 153 GW of rated input/output (the larger of input and output).

4.4 Comparison

(1) Assumptions

The assumptions shown in **Table 1** are made based on the existing research[3)] on CN methane production and the Strategic Roadmap for Hydrogen and Fuel Cells. Assumptions for CAPEX related to CO_2 capture are presented in **Table 2** based on the existing research[13)]. The CAPEX of batteries is assumed to be 40,000 yen/kW for power conditioner systems (PCS) and 10,000 – 20,000 yen/kWh for battery cells.

Table 1 CAPEX Assumption for CN Methane Production

	CAPEX	Number of unit
Water electrolysis	JPY 0.215 mil /(Nm3-H2/h)	4
Methanation	JPY 0.50 mil /(Nm3-CH4/h)	1
CN methane production system	JPY 1.36 mil /(Nm3-CH4/h)	1

Table 2 CAPEX Assumption for CO_2 Capture

Equipment	Item		Assumption
CO_2 capture	Scale		118t-CO_2/h
	CAPEX		JPY 6.67 bln
	Annual OPEX	Capital-relevant	JPY 0.6 bln /year
		Solvent	JPY 0.12 bln /year
		Sub-total	JPY 0.72 bln /year
	CAPEX per unit CO_2 capture scale		**JPY 92 mil /(t-CO_2/h)**
Boiler	Scale		127t-CO_2/h (260t-s/h of steam)
	CAPEX		JPY 5.42 bln
	CAPEX per unit CO_2 capture scale		**JPY 43 mil /(t-CO_2/h)**
TOTAL per unit CO_2 capture scale			**JPY 0.134 bln /(t-CO_2/h)**

(2) Energy costs

It is assumed that the electricity needed for CO_2 capture is provided by surplus electricity from renewable energy, and is reflected in the specific power consumption for CN methane production. In the "CNM-CHP case" and the "Battery case", the difference in energy consumption lies in natural gas and city gas. **Table 3** shows the demand for city gas and natural gas in the "CNM-CHP case" and the "Battery case". In the "CNM-CHP case," city gas demand increases mainly through an increase in CHP output, while demand for city gas derived from natural gas is less than that in the "Battery case" due to CN methane production. On the other hand, demand for natural gas from gas-fired power generation is higher in the "CNM-CHP case". As there is no significant gap in total demand for city gas and natural gas between the two cases, the difference in energy cost is disregarded.

Table 3 City gas and Natural gas Consumption

	City Gas			Natural gas	
(Billion Nm^3-CH_4 Methane equivalent)	Total	CNM	Natural gas	Gas-fired PG	Total
No measures	53.8	0	85.3	31.5	85.3
CNM-CHP	61.2	8.4	75.4	22.6	75.4
Battery	53.8	0	75.5	21.7	75.5

(3) Comparison of CAPEX

CAPEX is shown in **Figure 12**. In the “CNM-CHP case”, total CAPEX is 11 trillion yen. On the other hand, total CAPEX comes up to 14 trillion yen in the “Battery case” (If the cost of battery cells is reduced to 10,000 yen/kWh, total CAPEX would be 10 trillion yen).

In this study, Japan is regarded as a single region. In reality, however, CO_2 capture, CN methane production, and batteries are introduced in a regionally distributed manner, there is a need to carry out an analysis that takes economies of scale into consideration. Nevertheless, the results of the analysis conducted in this study showed that the economics of CNM-CHP, which makes use of existing city gas infrastructure and CHP, is comparable to batteries as a means of mitigating output fluctuations in the introduction of large scale renewable energy.

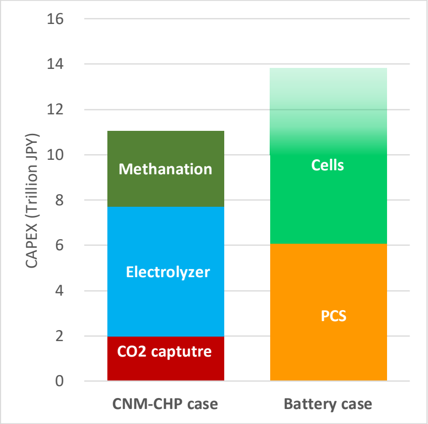

Figure 12　CAPEX Comparison

5. Conclusion

This study assessed a “CNM-CHP model” that offers grid flexibility through offsetting renewable energy output fluctuations by utilizing the margin output capacity of existing combined heat and power (CHP) for ramping-up, while blending carbon-neutral (CN) methane, that is produced from surplus renewable electricity, into the existing city gas network to decarbonize city gas.

There is trade-off relation that the room for CHP ramp-up declines while CN methane production grows as renewable energy increasingly deploys. Nevertheless, even if the room for CHP ramp-up decreases, there is an advantage that CN methane can be used for city gas consumption other than CHP, which brings about significant decarbonization. This is an advantage over batteries, which have fewer opportunities to discharge when the large scale renewable energy is deployed, even if charging were possible.

In the economic analysis based on the premise of the introduction of 300GW of solar PV + 100 GW of wind power + 34 GW of CHP, it was shown that the CNM-CHP model offers the same level of economics as the model for mitigating output fluctuations of renewable energy through batteries.

Batteries play a role in the grid integration of the renewable energy to a certain extent, but there is a limit to how much they can contribute with regard to the large-scale integration of renewable energy. This is due to the limitations of the “power to power” approach, which considers the integration of renewable energy within the closed system of a power grid. On the other hand, the “power to gas” approach, in which surplus electricity from renewable energy flows from the power grid to city gas and the transport sector, encompasses the concept of sector integration. Hence, it is able to go beyond the unique constraints in “power to power” and achieve decarbonization of the whole energy system while accommodating large-scale renewable energy. In the “power to gas” approach, CN methane, unlike hydrogen, has the advantage of being able to utilize existing city gas infrastructure. Moreover, CHP, which is expected to serve as VPP, is able to achieve grid integration that utilizes margin output capacity with less carbon, through the use of CN methane.

CN methane poses issues that should be reviewed technically, including the enhancement of the efficiency of electrolysis and Sabatier reaction, and the application of SOEC co-electrolysis and bioreactors. Nevertheless, as this study showed, it contributes significantly to the decarbonization of energy systems. As existing city gas infrastructure includes gas pipelines, satellite terminals and gas production plants representing a huge energy storage system, and also CHPs as discharging equipment, only adding a CN methane production system as a function to charge surplus renewable electricity may contribute to the decarbonization of electricity and city gas, as well as to the mitigation of renewable energy output fluctuations in a lower carbon manner.

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