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

- Power to Gas, Carbon Recycling, Utilization of Existing City Gas Network -

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Summary

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 (equivalent to downward demand response), while blending carbon-neutral (CN) methane, that is produced from surplus renewable electricity and CO_2 emitted intensively from biomass power generation, large-scale industrial production and fossil-fired power generation, into the existing city gas network to decarbonize city gas.

CN methane is a renewable synthesized fuel produced from combination of PtG (power to gas) as a grid integration measure and CCU (carbon capture and utilization). CN methane as being feedstock for city gas is expected to decarbonize city gas and to reduce supply cost of renewable hydrogen by using existing city gas network without major adjustments inherently required for supplying hydrogen. Thanks to these advantages in CN methane, activities such as demonstration projects have been pioneered in European countries such as Germany and followed by Japan in recent years. CN methane, as representing one of the carbon recycling technologies using CO_2 once emitted, is drawing attention from the Carbon Recycling Promotion Office established at the Agency for Natural Resources and Energy, Japan in February 2019.

Meanwhile, CHPs as distributed resources in VPP (virtual power plants) are expected to provide a function for mitigating renewable energy output fluctuations. In addition to the regular heat and power supply operation, CHPs ramp up the margin output capacity to offset declines in renewable energy output. Although CHP higher total efficiency contributes to more CO_2 reduction than LNG-fired power plants used for the same purpose, CHPs emit CO_2 to some extent as long as consuming natural gas-based city gas. However, the combination of CN methane production from renewable surplus electricity and consumption of CN methane by CHPs through city gas network may realize enhancement of grid flexibility in a lower-carbon manner. As the “CNM-CHP model” uses CHPs introduced for the original objective, supplying heat and power to customers in a cost-saving manner, for grid flexibility, there may be economic advantages over other energy storage technologies that should be introduced additionally.

The “CNM-CHP model” can be regarded as a grid flexibility option that uses huge energy storage system that is composed of the existing city gas network including CHPs.

According to "CNM-CHP" analysis results from power generation mix model assuming Japan as as a single region for the sake of simplicity, the following were found out:

[Impact of CN methane utilization by CHP]

- With an assumption that future total CHP installed capacity is 34 GW (30 GW for the commercial and industrial sectors and 5.3 million fuel cells for the residential sector), regular CHP operation annually produces 187 TWh of electricity and margin capacity can ramp up 109 TWh.
- If 100 GW of solar PV and 30 GW of wind power is introduced, CHP can ram up 98 TWh. Since capacity of the grid to accept CHP ramp-up declines as renewable energy deploys largely, CHP ramp-up falls to 57 TWh for 300 GW of solar PV + 100 GW of wind power and to 16 TWh for 500 GW of solar PV + 300 GW of wind power.
- On the other hand, as surplus electricity increases in line with renewable energy deployment, potential producible CN methane increases. CN methane production is no more than 100 million Nm^3-CH_4 for 100 GW of solar PV + 30 GW of wind power, but increases up to 8.4 billion Nm^3-CH_4 for 300 GW of solar PV + 100 GW of wind power and up to 22.5 billion Nm^3-CH_4 for 500 GW of solar PV + 300 GW of wind power, corresponding to 57% of the present city gas demand at 39.7 billion Nm^3-CH_4 on a methane calorific value equivalent.
- In other words, 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. If 300 GW of solar PV + 100 GW of wind power is introduced, CO_2 emissions from power generation and city gas is 157 million t-CO_2, bringing about 21 million t-CO_2 reduction, equivalent to 25% of the current emissions from city gas. If renewable energy expands up to 500 GW of solar PV + 300 GW of wind, massive CN methane is used also for non-CHP city gas consumption, leading to CO_2 emissions to be substantially curbed to 106 million t-CO_2 from 148 million t-CO_2 without CNM-CHP model.

[Economics of CN methane utilization by CHP]

- For the analysis on the economics, the "CNM-CHP case" is compared with "Batteries case" where battery is used for long-term application. At present, batteries are increasingly used for short-term application for load frequency control mainly in Europe and the United States where the market has been developed. As battery prices decline, however, the batteries are expected to be used for long-term application to charge and discharge surplus renewable electricity. Therefore, the battery used for long-term application can be a candidate to be compared with the CNM-CHP model.
- Under a scenario for 300 GW of solar PV + 100 GW of wind power with 34 GW of CHP capacity, the "CNM-CHP case" is compared with the "Battery case" in which regualr CHP operations are combined with additional batteries introduced to mitigate renewable energy output fluctuations. Capacity sizes were identified to equalize CO_2 emissions from power generation and city gas

consumption in the two cases. In the “CNM-CHP case”, CO_2 capture capacity was identified at 14,600 t-CO_2/h and CN methane production capacity at 123 GW on an input power basis. In the “Battery case”, battery capacity was identified at 386 GWh (rated input-output at 153 GW). The CAPEX for the “CNM-CHP case” is JPY 11 trillion, close to JPY 10-14 trillion for the “Battery case”.

Generally, batteries are increasingly expected to mitigate renewable energy output fluctuations as their prices have rapidly declined in recent years. However, as renewable energy deploys largely, scale and frequency of surplus electricity hamper discharging opportunities. Even if battery storage capacity is expanded, the impact of decarbonization of power generation is diminishing. This reveals the limitation on the power-to-power approach that addresses renewable energy deployment only in the electric grid as a closed system.

On the other hand, the power-to-gas approach represents “Sector-Coupling” concept that enhances one-way flow of surplus renewable electricity from the power grid to the city gas network and also to the transportation sector. It can overcome the limitation inherent to the power-to-power approach, allowing the entire energy system to promote decarbonization by accomodating large renewable energy. In the power-to-gas system, CN methane unlike hydrogen has an economic advantage of utilizing existing city gas infrastructure. If CN methane is used by a CHPs as a VPP to make their margin output capacity available for enhancing grid flexibility, renewable energy output fluctuations may be mitigated in a lower carbon manner.

CN methane with a relatively higher technological maturity is expected to become the core of the carbon capture, utilization and recycle (CCUR) technologies that are recently drawing much attention as means to avoid CCS challenges such as social acceptance, location selection and legislation. To allow CN methane to be installed into the energy system, water electrolysis and methanation costs are required to be reduced, with production efficiency improved. Although the present mainstream methanation technology is the chemical Sabatier reaction, other technologies in the research phase, including the solid oxide electrolyzer cell (SOEC) co-electrolysis that electrolyze water and CO_2 simultaneously to efficiently produce methane, as well as a biological reaction using methane bacteria should be addressed.

The most important requisite for improving the economics of CN methane is substantial cost reduction in renewable energy. A conceivable option that this study did not address may be utilization of overseas lower-cost renewable energy for producing CN methane to be imported into Japan. This option has an advantage of utilizing the existing liquefied natural gas supply chain.

CN methane still has technological challenges to be overcome as described above. In addition, there are institutional challenges in feed-in of CHP ramp-up. However, as indicated by this study, CN methane can be expected to contribute much to the decarbonization of the entire energy system. 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.

Introduction

Carbon-neutral methane (CN methane) is synthesized from hydrogen, which is produced from renewable energy through electrolysis, and CO_2 emitted from facilities like biomass power plants, fossil-fired power plants, large-scale industry. Therefore, it can be called “renewable synthesized fuel” produced through the combination of power to gas (PtG) as a grid integration technology and carbon capture and utilization (CCU). CN methane as being feedstock for city gas is expected to decarbonize city gas [1]. Existing studies [2][3] show that there is huge CN methane production potential in Japan and that CN methane supply cost can be far less than hydrogen supply cost, due to the fact that CN methane can be supplied through existing city gas infrastructure. Thanks to CN methane’s advantages such as contributions to the grid integration of renewable energy, decarbonization of fossil fuels and the utilization of existing infrastructure, activities for CN methane like demonstration projects have been pioneered in European countries such as Germany and followed by Japan in recent years [4][5][6][7]. CN methane, as representing one of the carbon recycling technologies using CO_2 once emitted, is drawing attention from the Carbon Recycling Promotion Office established at the Agency for Natural Resources and Energy in February 2019.

Meanwhile, distributed combined heat and power (CHP), large part of which use city gas in Japan, are expected to serve as virtual power plants (VPP) to provide their margin output capacity for power demand-supply balancing increasingly required in line with renewable energy deployment.

This study addresses contributions of CN methane-using CHP to mitigating renewable energy output fluctuations and decarbonization of power grid and city gas.

1. Advantages of use of CN methane by distributed CHPs

CHP plants are expected to mitigate renewable energy output fluctuations. In addition to the regular operation as heat and power supply, CHPs will increase their output to offset renewable energy output decline. Given their higher total efficiency including heat and power supply, CHP plants can reduce more CO_2 emissions than LNG-fired power plants used for the same purpose. Nevertheless, as CHPs consume natural gas-based city gas, CO_2 is emitted to some extent.

However, the combination of CN methane production from renewable surplus electricity and consumption of CN methane by CHPs through city gas network may realize mitigation of renewable energy output fluctuations in a lower-carbon manner.

CHPs are in general introduced for supplying heat and power to customers in a cost-saving manner. If CHPs introduced for this original purpose are utilized for mitigating renewable energy output fluctuations by consuming CN methane, it may emit less CO_2 and bring about more economic advantages than output fluctuation mitigation by using other energy storage technologies.

2. Methodology

Based on the abovementioned ideas, this study defines “utilization of CN methane by distributed

CHPs" (hereinafter referred to as "CNM-CHP") as follows (Figure 2-1):

- CN methane is produced from hydrogen, which is produced from surplus electricity from variable renewable energy (solar PV and wind power), and CO_2 emitted intensively from the industrial sector, biomass power plants and fossil-fired power plants.
- CN methane is blended into the existing city gas infrastructure (decarbonization of city gas).
- CHPs consume city gas decarbonized by CN methane, through city gas infrastructure as is the case with their regular operations to supply heat and power.
- While operating regular heat and power supply, CHPs use their margin capacity to increase output (CHP ramp-up = downward demand response) when renewable energy output declines.

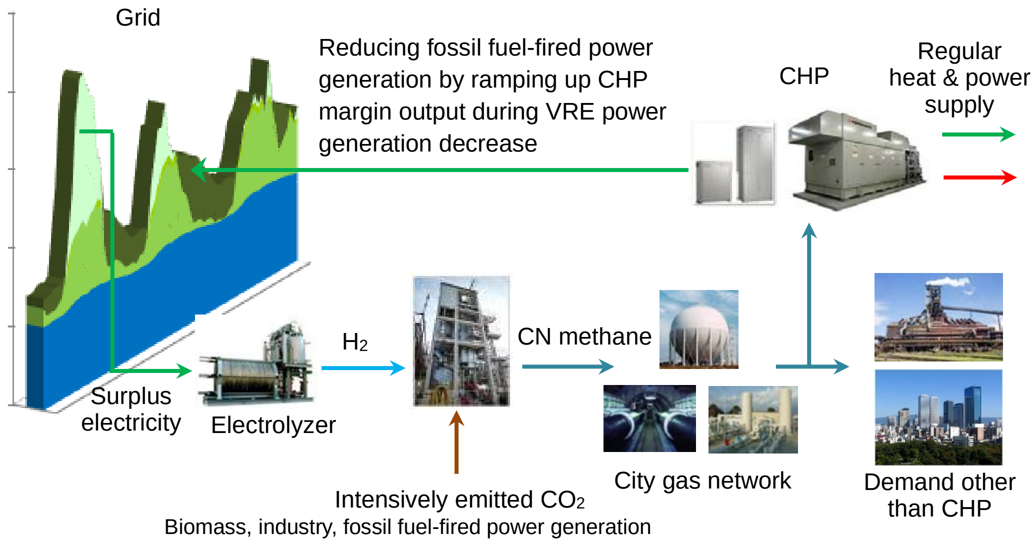


Figure 2-1 Structure of CNM-CHP Model

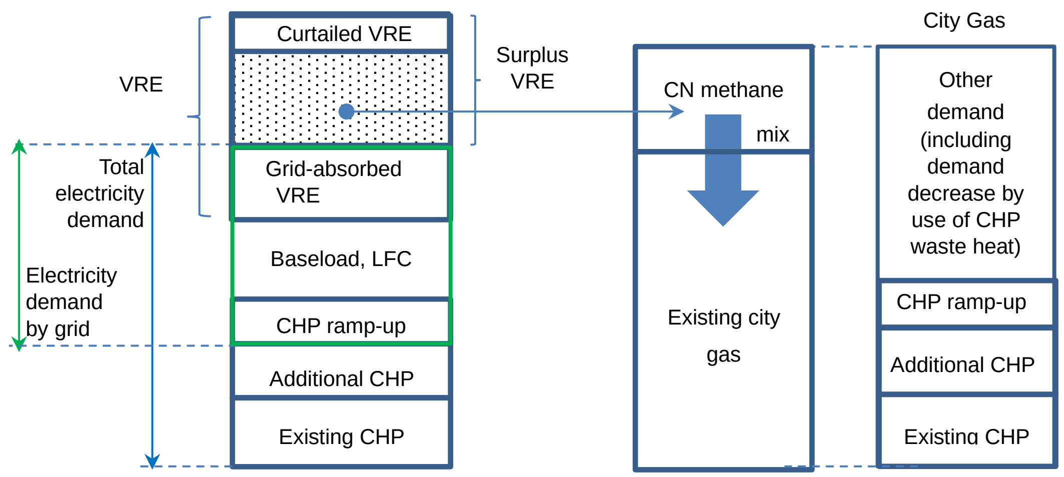


Figure 2-2 Energy Balance of Electricity and City Gas in CNM-CHP Model

Figure 2-2 shows a thumbnail of the electricity and city gas energy balance in the CNM-CHP model. Electricity demand is met by CHPs, base-load power plants, fossil-fired power plants and renewable energy absorbed into the grid, as well as CHP ramp-up. CN methane produced from part of renewable surplus electricity is blended into city gas that is used for CHP regular operations and other demand, as well as CHP ramp-up.

A power generation mix model is used to identify hourly CHP ramp-up contribution and amount of hourly surplus electricity that is compared to the intensively emitted CO_2 [3] to figure out producible amount of CN methane for an assumed renewable energy capacity.

2.1. Estimating CHP regular operation patterns

To figure out how much CHPs can ramp up to mitigate renewable energy output fluctuations, the regular operation pattern should be identified. Regarding residential CHPs, the hourly operation patterns by month are identified based on average measurement data for polymer electrolyte fuel cells (PEFCs) at 39 households in existing studies [8][9]. In the absence of measurement data for solid-oxide fuel cells (SOFCs), a flat operation at rated output through the year is assumed (some gas companies purchase SOFC surplus electricity). PEFCs and SOFCs are assumed to be introduced on a 50-50 basis (although gas engine CHP systems have also been introduced, fuel cells are assumed to dominate CHPs market in the future). The rated output is assumed to be 0.7 kW. Regarding commercial CHPs, hourly operation patterns by month are identified based on measurement data by business type [10]. Data on gas CHPs capacity by business type (Advanced Cogeneration and Energy Utilization Center JAPAN) is used to determine a weighted average pattern for the entire commercial sector. As for industrial CHPs, information from interviews with experts is used to assume operation at 80% of rated output during daytime and 65% during nighttime, as no existing study is available.

Figure 2-3 shows CHP power generation patterns and margin output capacity by sector for a representative week each in winter, spring/autumn and summer for a case in which the government's and gas industry's CHP deployment target (totally 34 GW, 30 GW in the commercial and industrial sectors and 5.3 million residential fuel cells) is achieved. Margin output capacity is presented by difference between rated output capacity and actual output.

As CHPs in general operate mainly during daytime, nighttime margin output capacity is greater. The entire CHPs may be able to ramp up 7-10 GW during daytime and about 17 GW during nighttime, although depending on season or day of week. Nighttime margin output capacity of industrial CHP plants featuring large installed capacity (about 23 GW) and high capacity factor is close to that of commercial CHP plants featuring smaller installed capacity (about 7.3 GW) and low capacity factor. Maximum nighttime margin output capacity for residential CHP plants stands at around 1.7 GW.

2.2. Power generation mix simulation

2.2.1. Simulation structure

It may be desirable to divide Japan into regions and assume renewable energy power generation and CHP capacity by region and also surplus electricity trades between regions through interregional transmission lines. As this approach needs a number of parameters and scenarios that complicates the interpretation of analysis results, this study assumes the whole of Japan as a region for the sake of simplicity. The temporal granularity for simulation is one hour for one year (8,760 hours). Electricity load curve data and solar PV and wind power generation patterns are from the IEEJ database [2].

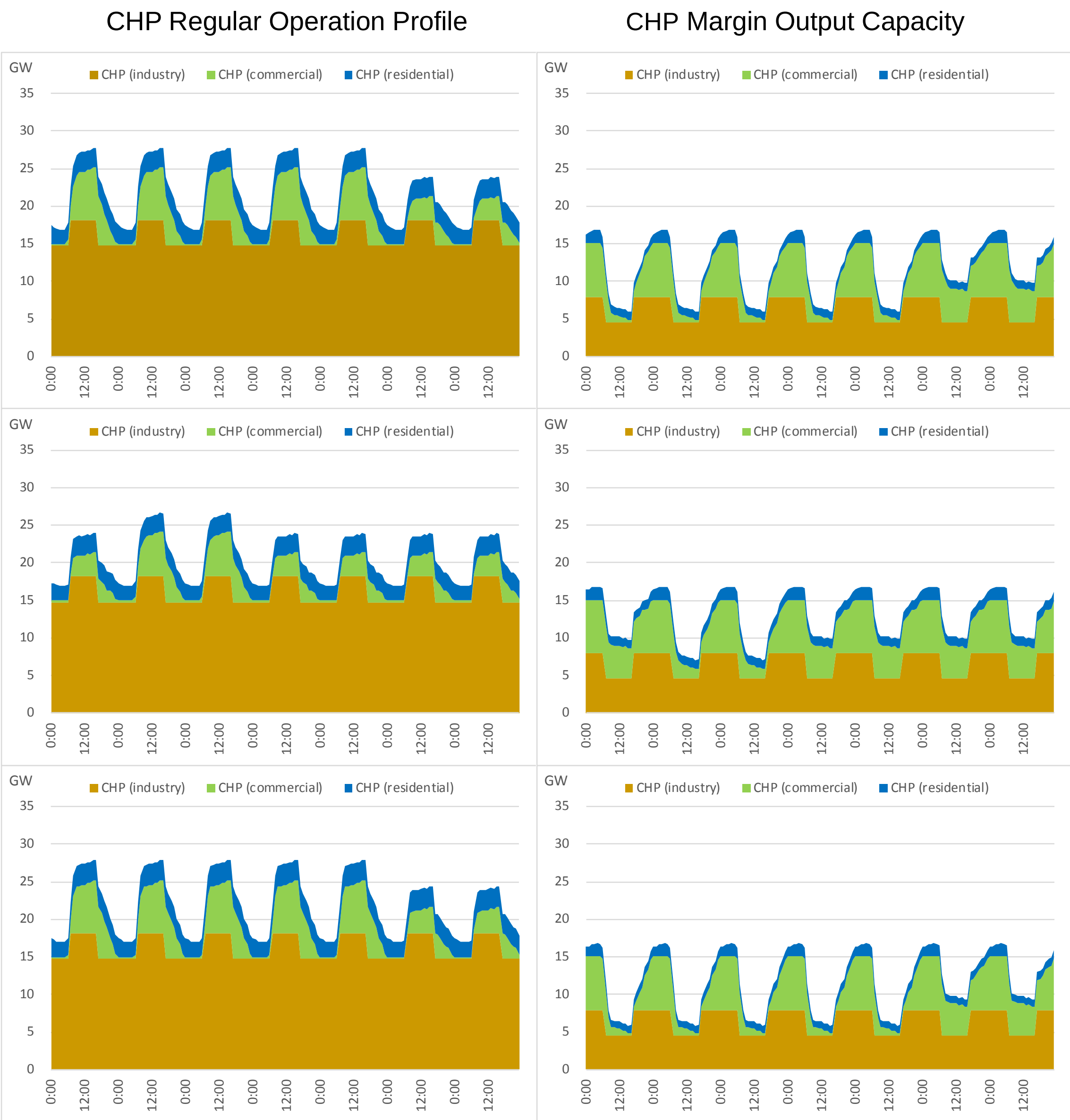


Figure 2-3 CHP Regular Operation Profile and Margin Output Capacity

Note: Figure from top to bottom shows a representative week in winter, spring/autumn, summer, respectively.

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

Note: Margin output capacity = Rated capacity – Output at regular operation

2.2.2. Assumptions

(1) Electricity demand, Base-load power generations, Fossil-fired power generation

As a long-term viewpoint is required for considering the CN methane introduction potential, electricity demand is assumed to increase 1.13-fold from 919 TWh at present to 1,036 TWh, with electrification trends and energy efficiency improvements taken into account (Total electricity demand including electricity demand met by auto-producer is assumed at 1,170 TWh). As this electricity demand is the grid-based demand, hourly output from existing CHP plants (limited to gas CHP plants with capacity at about 6.2 GW) is added.

Nuclear power generation is assumed at the same level as 193 TWh as targeted for 2030 in the “Long-term Energy Supply and Demand Outlook”, accounting for 21% of total power generation in 2030. No new large-scale hydro and pumped storage hydro are assumed. Small and medium-scale hydro, biomass and geothermal power generation is assumed as shown in Table 2-1. This assumption represents a small addition to the “2030 Long-term Energy Supply and Demand Outlook”.

From a long-term viewpoint, fossil-fired power generation is assumed to be provided only by LNG-fired power generation. LNG-fired power generations are assumed to cover 10% of hourly electricity demand as load frequency control (LFC).

Table 2-1 Assumption of Cumulative Installed Capacity of Small & Medium-Hydro, Biomass and Geothermal

		S&M hydro	Biomass	Geothermal
2030, Long term energy supply & demand outlook, METI	Min	10.99 GW	6.02 GW	1.40 GW
	Max	11.70 GW	7.28 GW	1.55 GW
Assumption in this study		**13 GW**	**8 GW**	**3 GW**

(2) CHP

CHP regular operation is set at must run. A ramp-up of CHP is assumed to come from existing and new CHPs only when they have margin output capacity (in the period of operation at below rated capacity). In addition, the CHP ramp-up is subject to grid acceptable capacity (with priority given to pumped storage hydro operation for charging and discharging renewable surplus electricity).

CHP capacity is assumed at 34 GW including 30 GW in the commercial and the industrial sectors and 5.3 million residential fuel cells, representing the target of the government and the gas industry.

(3) Variable renewable energy

Deployment capacity of solar PV and wind power are set as independent variables, as indicated below. Massive renewable energy introduction is required for actualizing CN methane.

Solar PV power generation: 70-500 GW
Wind power generation: 10-300 GW

(4) Power generation operation pattern

Assumed as follows:

[Common operation]

- As noted above, this study envisions the massive deployment of variable renewable energy and consequently large-scale LFC fossil-fired power plants are required. So, all fossil-fired power generations are LNG-fired.
- Base-load power generations (nuclear, hydro, geothermal and biomass) and CHP regular operation are must run.
- 10% of hourly electricity demand is met by LNG-fired power generations as LFC.
- In order to maximize absorption of variable renewable energy, pumped storage hydro is utilized first, after utilized for nuclear.
- Pumped storage hydro immediately discharges 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 fossile-fired power generation.

[Batteries] (to be addressed in the later economic comparative analysis)

- 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 fossile-fired power generation.

(5) Hourly intensive CO_2 emissions

Intensive CO_2 emissions from biomass power plants and the industrial sector are identified based on an existing study [3]. Biomass power plants are assumed to operate at a constant output (= rated output x capacity factor) throughout the year. Annual CO_2 emissions are then divided in 8760 hours. Regarding the industrial sector, annual intensive CO_2 emissions are devided into 8760 hours based on the total electric lorad curve pattern. Regarding fossil-fired power generation, all plants are assumed as located intensively in industrial regions. Hourly CO_2 emissions are determined in line with fossil-fired plant operation pattern based on power generation mix simulation.

2.3. Technological specifications for CHP

The CHP power generation efficiency, though depending on plant types, vintage and future technological advancement, is uniformly assumed to be 55% for simplification. The exhaust heat recovery efficiency is assumed at 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. This is the reason why the exhaust heat recovery efficiency is assumed to be 25% during CHP ramp-up.

CHP CO_2 emission coefficients (with the efficiency at 80% for boilers to be replaced by exhaust heat recovery) are shown in Table 2-2.

Table 2-2 Assumption of CHP Performance

		efficiency	CO_2 intensity
Power generation		55%	＋0.34kg-CO_2/kWh
Waste heat recovery	Regular operation	35%	－0.15kg-CO_2/kWh
	Ramping-up operation	25%	－0.11kg-CO_2/kWh

Note: Waste heat recovery efficiency is net efficiency that includes heat loss from thermal storage.

2.4. Technological specifications for CN methane production

The CN methane production efficiency including hydrogen production (water electrolysis) from renewable electricity and methanation (Sabatier reaction) from hydrogen and CO_2 is assumed as 18.32kWh/Nm^3-CH_4 [2]. Based on hourly surplus renewable electricity and hourly intensive CO_2 emissions, producible amount of CN methane is identified.

2.5. Technological specifications for CO_2 capture

Regarding energy consumption related to the CO_2 capture, the CO_2 compression accounts for the largest share of power consumption in CCS, according to an existing study [11]. For CCS process, CO_2 pressure is raised up to 7 MPa to make CO_2 critical state for efficient transportation to storage sites, then CO_2 is injected. 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 [11].

As surplus electricity from renewable energy occurs whenever CN methane is produced, power consumption on CO_2 capture is added to unit power consumption of CN methane production. As 1.97 kg-CO_2 is required for producing 1 Nm^3 of methane, 10 kWh/t-CO_2 means 0.02 kWh/Nm^3-CH_4. Therefore, the unit power consumption on CN methane production rises slightly from 18.32 kWh/Nm^3-CH_4 to 18.34 kWh/Nm^3-CH_4. The heat required for CO_2 capture is assumed to be met by city gas. The heat requirement for producing 1 Nm^3 of methane is 3,549 kJ/Nm^3-CH_4 (if the boiler efficiency is assumed at 80%, city gas consumption is 4,436 kJ/Nm^3-CH_4). The CO_2 capture efficiency is assumed at 90%.

Table 2-3 Energy Consumption for CO_2 Capture

			New coal-fired power plant	Existing coal-fired power plant	Iron & steel	Future target
Heat requirment		MJ/t-CO_2	3,000	3,000	3,000	**1,800**
Electricity requirement	Motor	kWh/t-CO_2	28.4	28.4	29.7	**10**
	Pressure rising	kWh/t-CO_2	115	115	115	100
	injection	kWh/t-CO_2	16	16	16	―

Source: "FY2015 CO_2 Fixation/Effective Utilization Technology Project: Underground CO_2 Storage Technology R&D Report" (March 2016) Research Institute of Innovative Technology for the Earth
Note: Data in the shaded area is employed.

3. CNM-CHP analysis results

3.1. Power generation mix, CHP ramp-up, CO_2 capture

Figure 3-1 shows simulation results for a representative week in each season. While surplus electricity is partially used for CN methane production (left figure: "CNM production"), the production volume depends on the available CO_2 volume (right figure: deeper color areas). It is also observed that CHP ramp-up occurs only when no surplus electricity is generated (left figure).

Figure 3-2 shows CHP operation patterns. The left side is for a case of 300 GW of solar PV + 100 GW of wind power, while the right side is for a case of 500 GW of solar PV + 300 GW of wind power. It is found that CHP ramps up majorly during nighttime when CHP margin output capacity is available. As renewable energy deployment expands, wind power generates electricity during nighttime, reducing the room for CHP ramp-up.

Figure 3-3 shows simulated power generation mixes. 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. It must be noted that the degree of decarbonization in CHP ramp-up (as well as in regular CHP operations) depends on CN methane production from surplus electricity (as described later).

Figure 3-4 shows how CHP margin output capacity is used. Although annual power generation from 34 GW of CHP plants is 187 TWh and annual margin output is as much as 108 TWh, the usable margin output decreases according to renewable energy deployment scale.

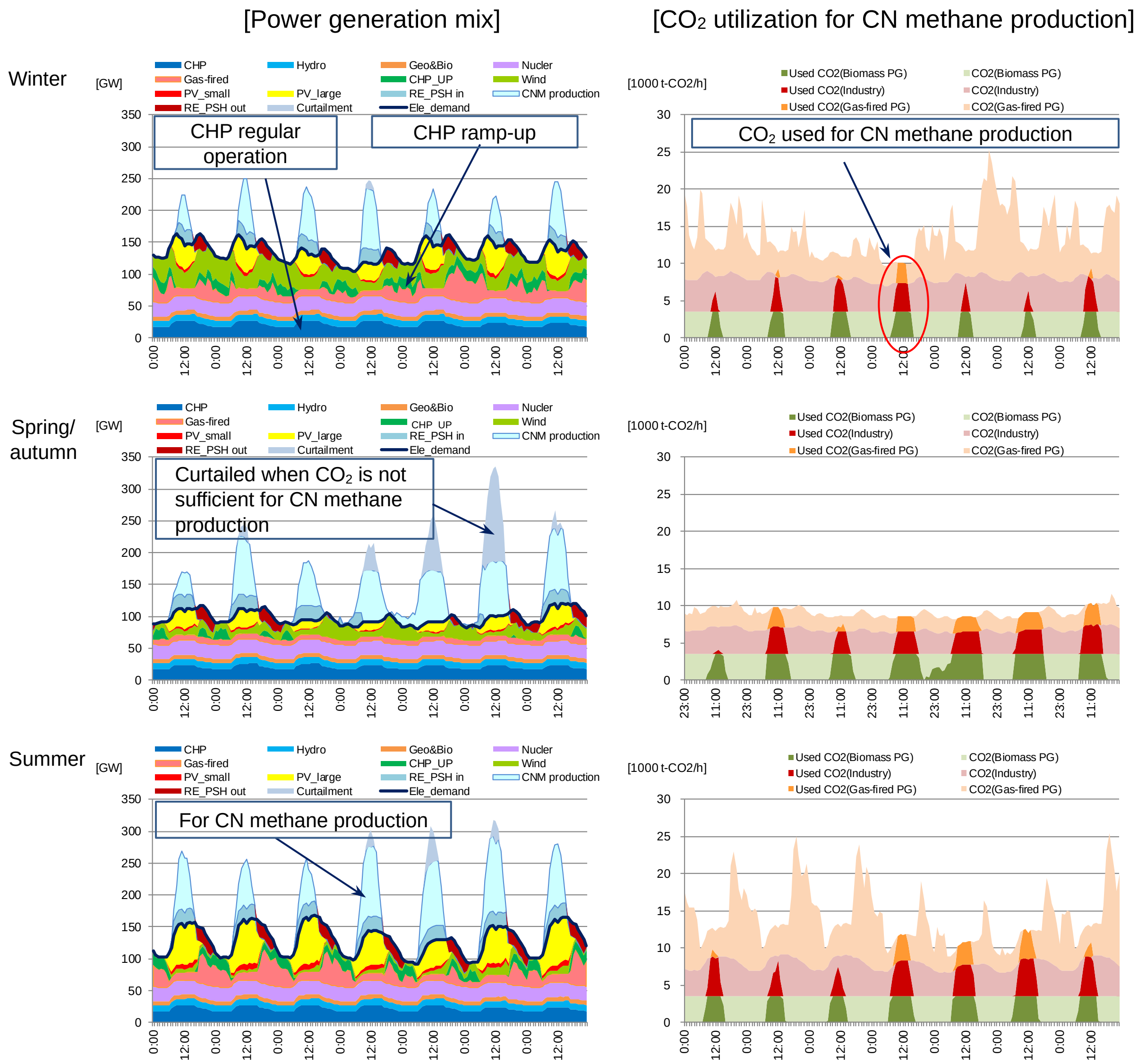
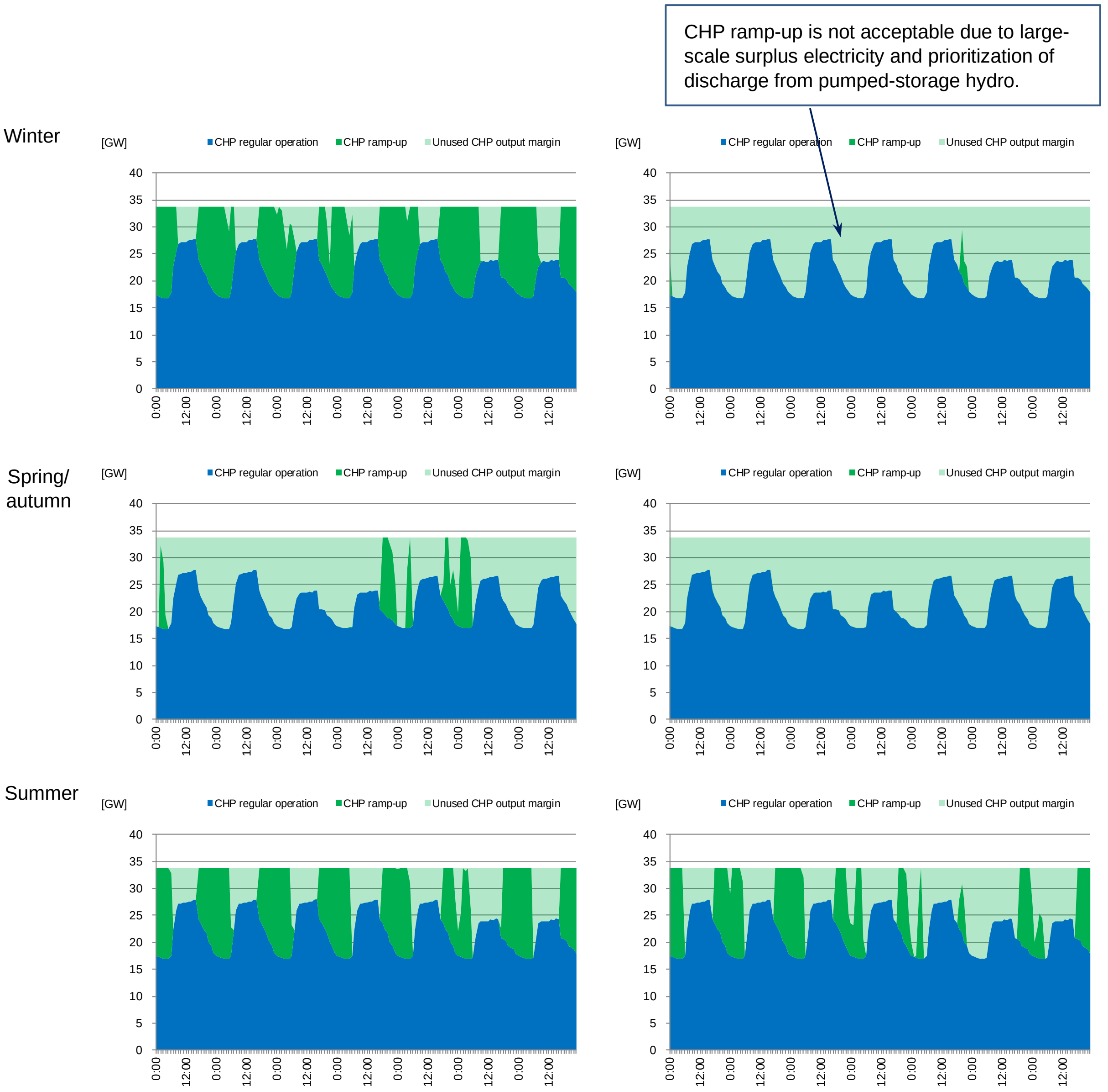


Figure3-1 Simulation of Power Generation Mix and CO_2 Utilization for CN Methane Production (300GW of solar PV + 100GW of Wind + 34GW of CHP)

Note: "CHP_UP" is not necessarily carbon-free. Carbon intensity of "CHP_UP" depens on producible CN methane.

Note: Figure from top to bottom shows a representative week in winter, spring/autumn, summer, respectively.



(300GW of Solar PV + 100GW of Wind + 34GW of CHP) (500GW of Solar PV + 300GW of Wind + 34GW of CHP)

Figure 3-2 Simulation of CHP Ramp-up

Note: Figure from top to bottom shows a representative week in winter, spring/autumn, summer, respectively.

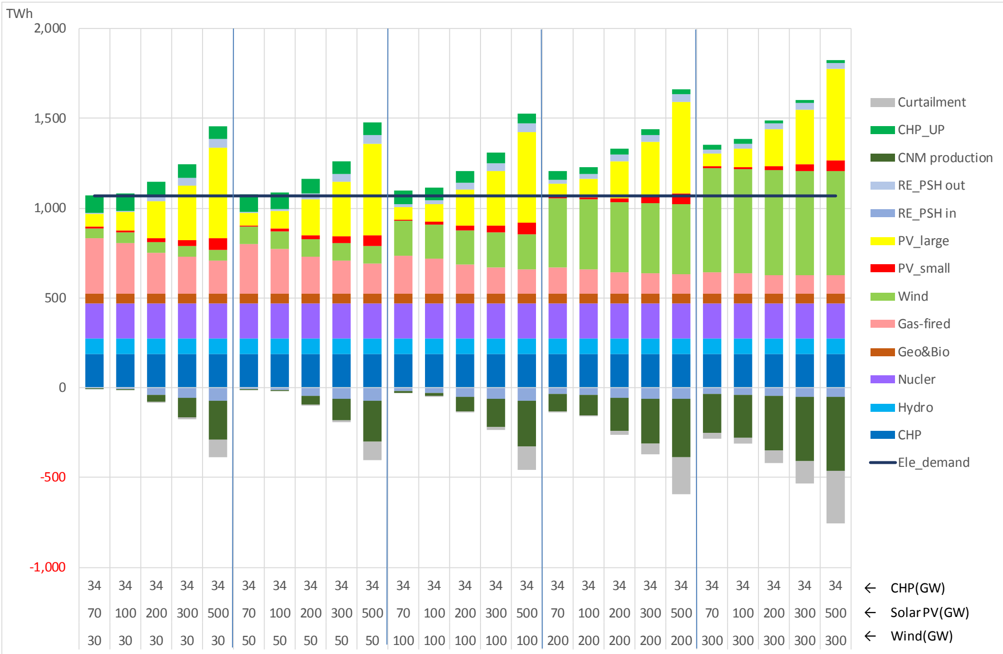


Figure 3-3 Power Generation Mix (34GW of CHP)

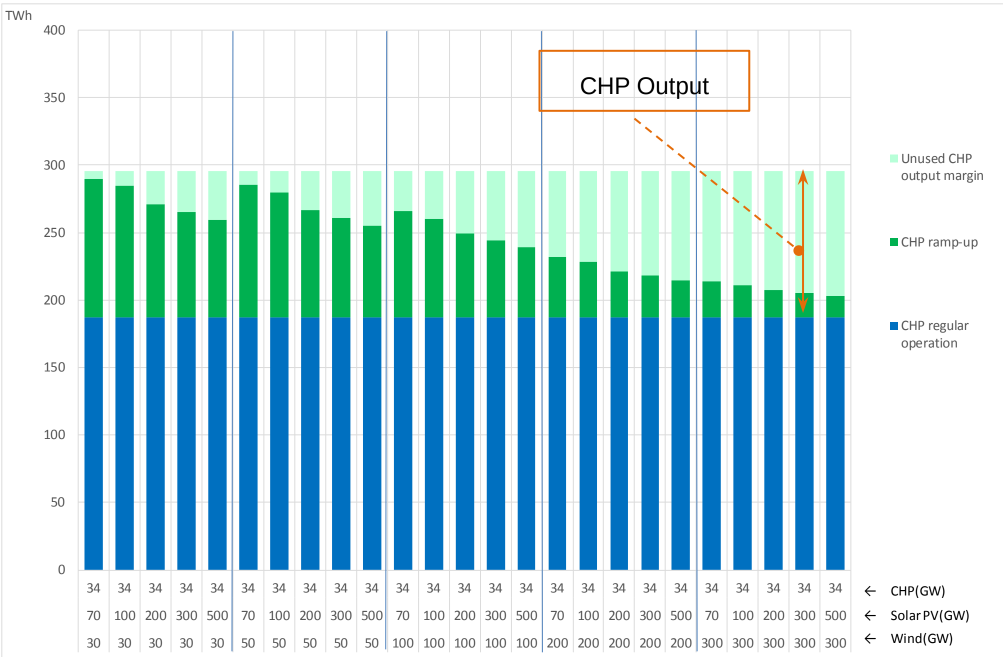


Figure 3-4 Utilization Status of CHP Output Margin as Ramp-up (34GW of CHP)

3.2. Producible CN methane volume, contributions to decarbonization

Figure 3-5 shows potential CN methane production and city gas consumption for CHP ramp-up. Potential CN methane production is 8.4 billion Nm^3-CH_4 for 300 GW of solar PV + 100 GW of wind power and 22.5 billion Nm^3-CH_4 for 500 GW of solar PV + 300 GW of wind power, amounting to 21%-57% of FY2016 city gas consumption (37.7 billion m^3) converted into 39.7 billion Nm^3-CH_4 in methane calorific value. In case of smaller-scale renewable energy introduction, CHP ramp-up is larger while CN methane production is less. In case of larger-scale renewable energy introduction, however, CHP ramp-up is smaller while methane production is larger.

Figure 3-6 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 intordaction 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, and CN ratio is small. Although city gas consumption required for CO_2 capture increases in line with growth in CN methane production, this consumption share in total city gas consumption is limited.

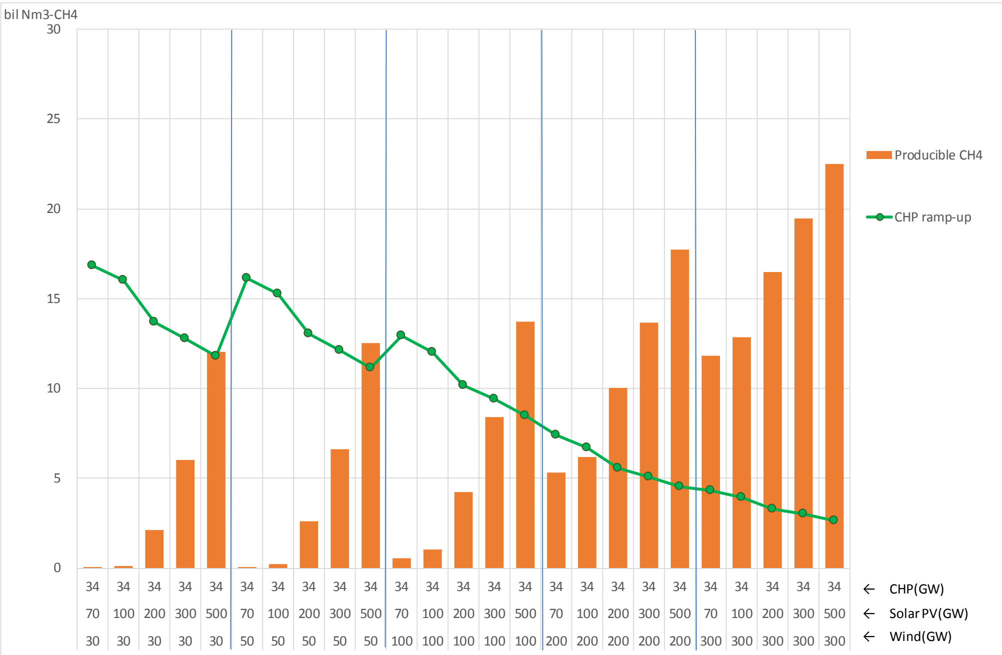


Figure 3-5 Producible CN Methane (34GW of CHP)

Note: As CN methane is blended into city gas, the blended city gas that is used for CHP ramp-up is decarbonized, but not carbon-free.

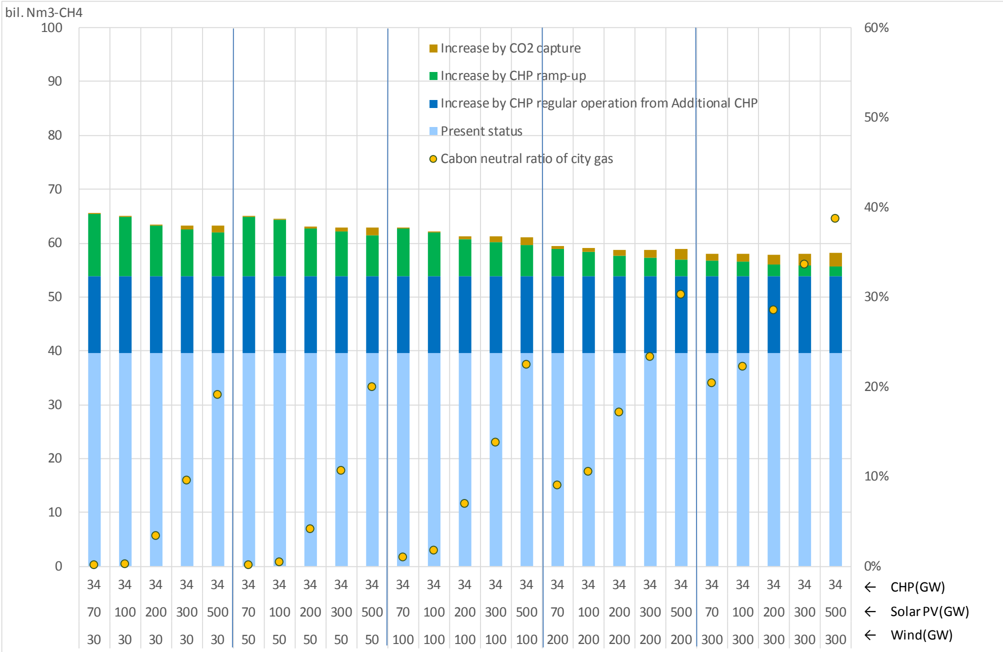


Figure 3-6 City Gas Demand and Carbon Neutral Ratio (34GW of CHP)

Note: Carbon neutral ratio = Produced & Blended CN methane/City gas demand

Note: City gas demand is expressed by methane calorific equivalent. City gas is mix of the conventional city gas and CN methane, and CO_2 intensity of city gas depends on Carbon neutral ratio.

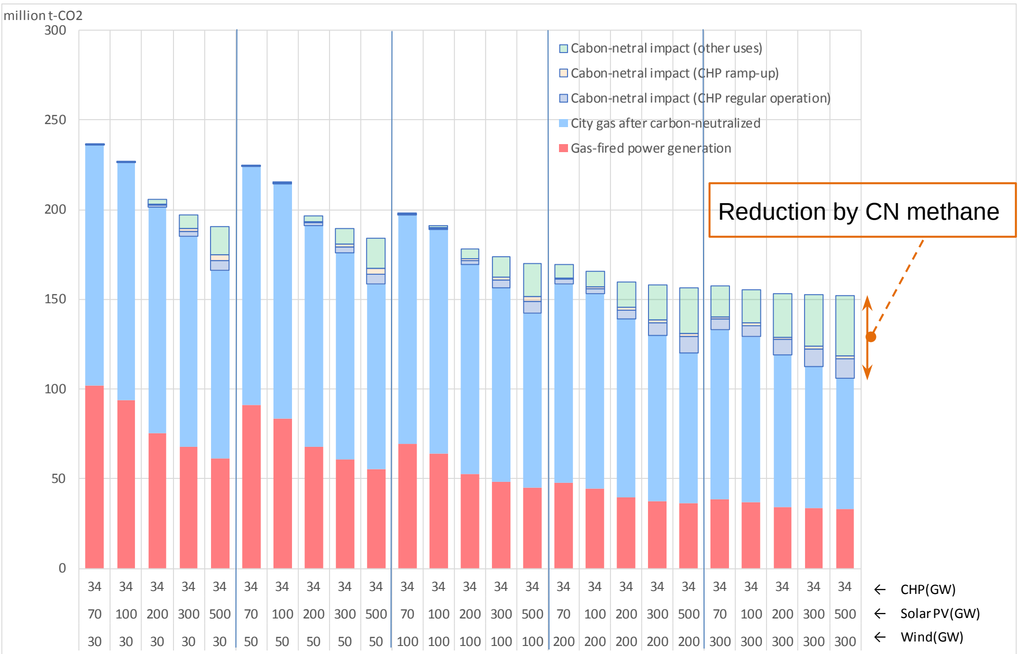


Figure 3-7 CO_2 Emission from Grid and City Gas (34GW of CHP)

Figure 3-7 shows CO_2 emissions from power grid and city gas. There are lesser opportunities for CHP ramp-up as renewable energy deploys, then CO_2 emission reduction effect of CHP ramp-up decreases. On the other hand, CN methane production volume increases, which leads to enhancement of the reduction of CO_2 emissions from city gas use for regular CHP plant operation and other purposes. Overall, additional CO_2 emission reduction through CN methane production and utilization becomes greater as renewable energy deployment expands.

3.3. Advantages of CNM-CHP

Figure 3-8 shows the impacts of the CNM-CHP, including the effective utilization of surplus renewable electricity, the replacement of fossil-fired power generation, the decarbonization of city gas and the reduction of CO_2 emissions.

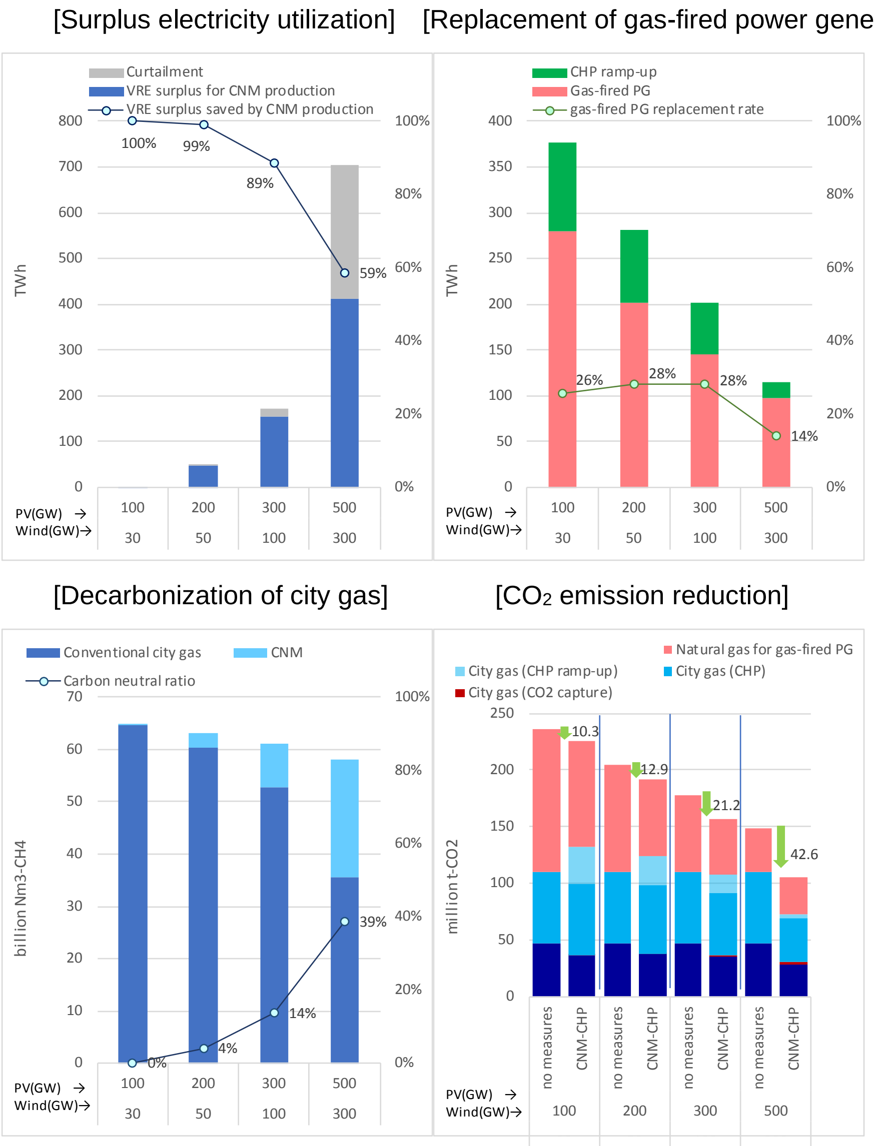


Figure 3-8 Advantages of CNM-CHP (34GW of CHP)

Surplus renewable electricity increases as renewable energy power generation capacity grows. In case of 200 GW of solar PV + 50 GW of wind power, 99% of 48 TWh surplus electricity is utilized for CN methane production. As renewable energy capacity expands, CO_2 available for CN methane production falls short comparing to growth in surplus electricity, leading the decline in effective utilization rate of surplus renewable electricity. Nevertheless, 89% of surplus electricity is still effectively utilized for CN methane production in a case of 300 GW of solar PV + 100 GW of wind power. The rate decreases to 59% for a case of 500 GW of solar PV + 300 GW of wind power.

CHP ramp-up occurs upon renewable energy output decline, replacing fossil-fired power generation. The rate of replacement of fossil-fired power generation by CHP ramp-up remains nearly 30% for a case of up to 300 GW of solar PV + 100 GW of wind power. This is because CHP ramp-up opportunities declines along with decrease in fossil-fired power generation as renewable energy increases. If renewable energy deployment grows up to 500 GW of solar PV + 300 GW of wind power, CHP ramp-up decreases.

As renewable energy capacity expands, CN methane produced from surplus renewable electricity increases. In case of 300 GW of solar PV + 100 GW of wind power, 14% of city gas is decarbonized with CN methane. The decarbonization rate rises to 39% in case of 500 GW of solar PV + 300 GW of wind power.

Replacement of fossil-fired power generation by CHP ramp-up for mitigating renewable energy output fluctuations, the decarbonization of city gas with CN methane produced from surplus renewable energy electricity and CHP plant's utilization of decarbonized city gas are combined to curb CO_2 emissions by 21 million t-CO_2 from the level for the absence of these measures in a case of 300 GW of solar PV + 100 GW of wind power and by 43 million t-CO_2 in case of 500 GW of solar PV + 300 GW of wind power. Given that the present CO_2 emissions from city gas is 80 million t-CO_2, impacts from these measures turn out to be substantial.

4. Analysis of CNM-CHP economics

There are some studies that compared supply costs between CN methane and hydrogen and showed advantage of CN methane using existing infrastructure over hydrogen requiring new supply infrastructure [2][3]. This chapter compares the CNM-CHP with batteries from the viewpoint of energy storage technologies that enhance grid flexibility.

4.1. Concept

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. Therefore, batteries and the CNM-CHP as key energy storage technologies for large scale deployment of renewable energy will be compared here.

Given that CN methane is designed primarily for decarbonizing city gas and that CHPs impact the electric grid through power generation and also city gas through exhaust heat recovery, both electricity and city gas must be included for comparing the CNM-CHP with batteries. The CO_2 emissions from both electricity and city gas are compared between two cases; “CNM-CHP case” and “Battery case”. For both cases, CHP capacity is fixed at “30 GW (commercial and industrial) + 5.3 million fuel cells (residential) ≒ 34 GW” representing the CHP capacity target of the government and the gas industry. With the CHP capacity as a given;

- In the “CNM-CHP case”, CHP margin output capacity is used for CHP ramp-up to mitigate renewable energy output fluctuations.
- In the “Battery case”, CHP plants are operated on a regular basis (must run) and batteries are introduced to mitigate renewable energy output fluctuations (see 2.2.2).

The following analyzes power generation mixes and CO_2 emissions from the electric grid and city gas to identify CN methane production scale and battery capacity for the same CO_2 emissions in the two cases and compare the economics of the two cases. Charging and discharging efficiencies of batteries are assumed to be 90% x 90% and the self-discharge rate to be 0.02%/h.

4.2. Power generation operation

Figure 4-1 shows simulated power generation patterns for a representative week in each season. Renewable energy curtailment depends on CO_2 emissions available for CN methane production in the “CNM-CHP case” and on battery capacity (kWh) in the “Battery case”. Figure 4-2 shows power generation mixes for the “CNM-CHP case” and “Battery case”. The “CNM-CHP case” power generation mix is the same as shown in Figure 3-3. The “Battery case” assumes four scenarios; 100 GW of solar PV + 30 GW of wind power, 200 GW + 50 GW, 300 GW + 100 GW, and 500 GW + 300 GW. In each scenario, battery capacity ranges from 0 to 500 GWh as a variable. Scenarios surrounded by red lines in the upper and lower parts of Figure 4-2 are compared.

The interpretation of power generation mix simulation results for “CNM-CHP case” is described in 3.1. In the “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, exapnading 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. 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 (However, the decarbonization of CHP ramp-up is affected by CN methane's share of city gas supply).

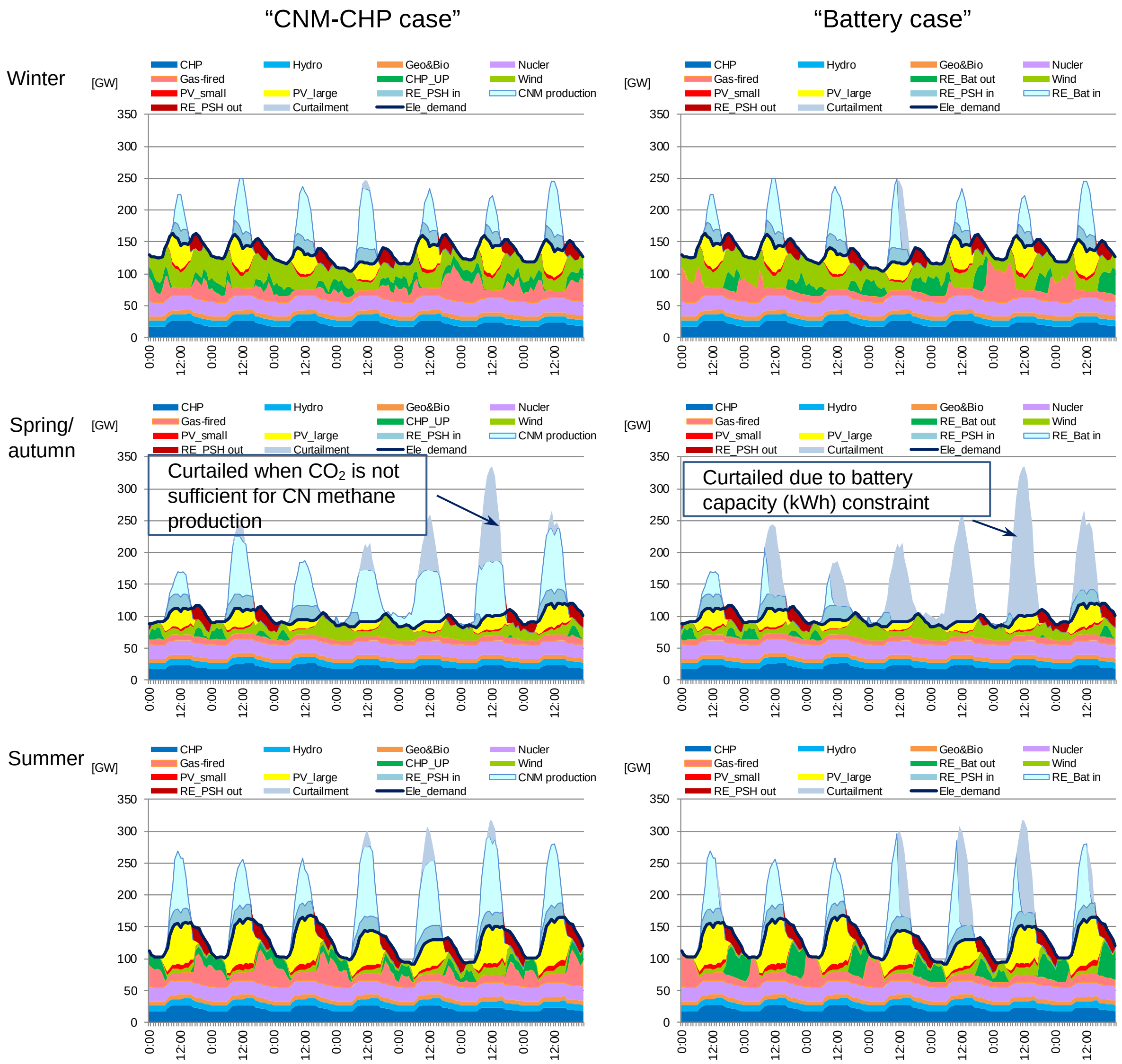
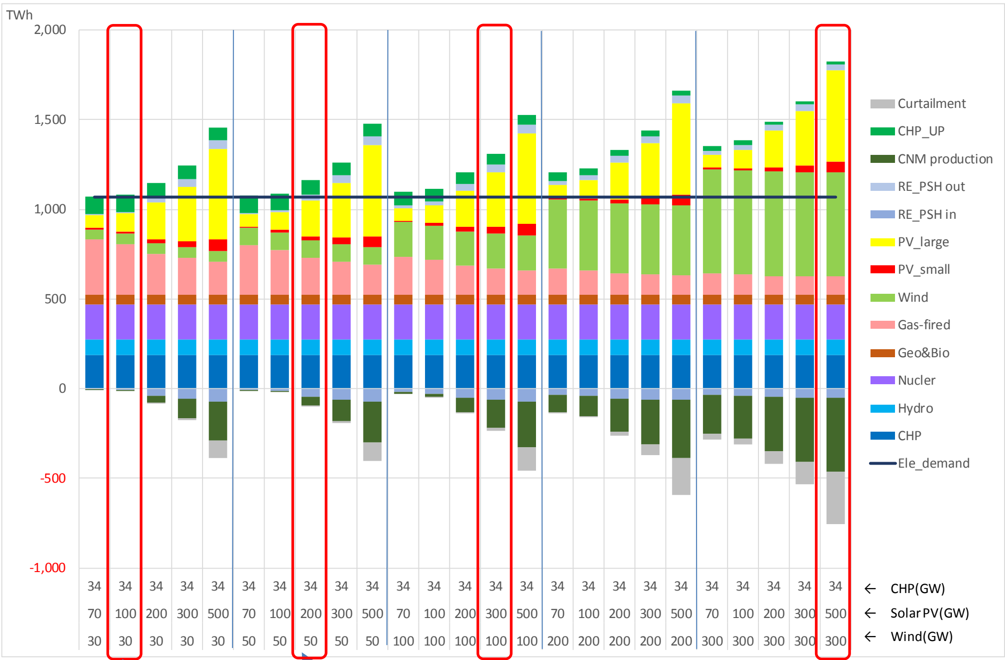


Figure 4-1 Power Generation Mix from Simulation

Note: Figure from top to bottom shows a representative week in winter, spring/autumn, summer, respectively.
Note: 300GW of solar PV + 100GW of wind + 34GW of CHP for both cases.
Note: For "Battery case", the scale of battery is 0.386 TWh (153 GW) based on the analyses hereafter.
Note: "CHP_UP" is not necessarily carbon-free. Carbon intensity of "CHP_UP" depens on producible CN methane.

"CNM-CHP Case" (Reposting Figure 3-3)



"Battery Case"

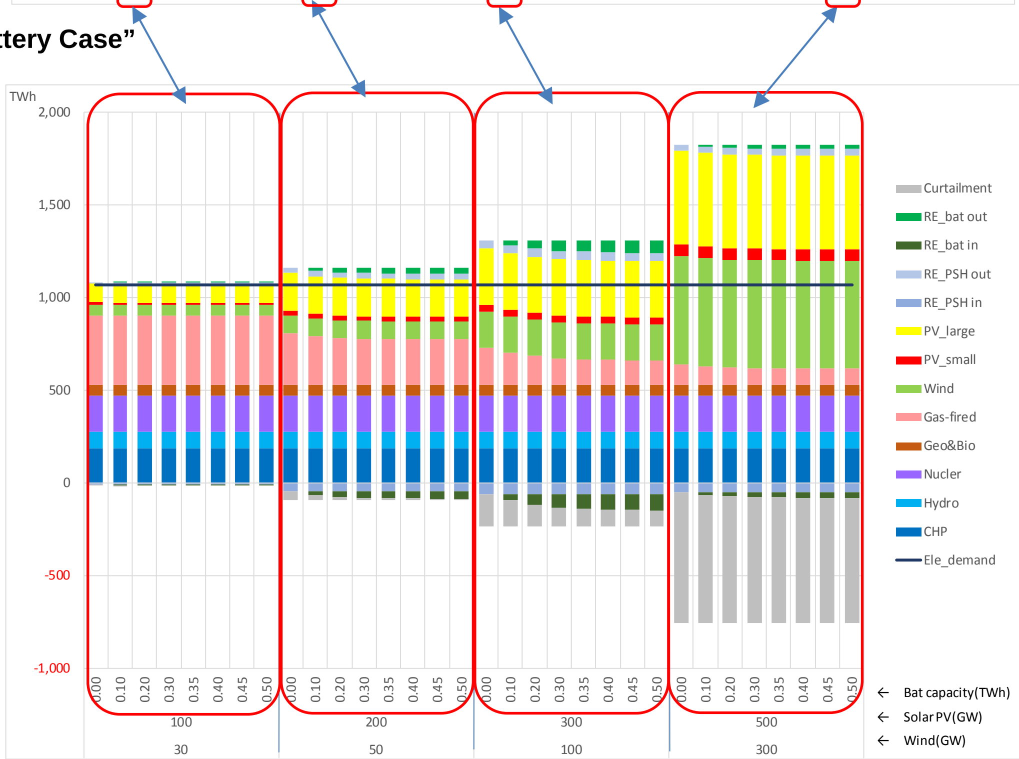


Figure 4-2 Comparative Power Generation Mix between "CNM-CHP case" and "Battery case"

Note: "CHP_UP" is not necessarily carbon-free. Carbon intensity of "CHP_UP" depens on producible CN methane.

Note: "Battery case" simulated for 0TWh~0.5TWh of battery storage capacity.

4.3. CO_2 emissions from power generation and city gas

Figure 4-3 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 four renewable energy deployment scenarios; 100 GW of solar PV + 30 GW of wind power, 200 GW + 50 GW, 300 GW + 100 GW, and 500 GW + 300 GW. 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 battery capacity ranging from zero to 500 GWh in the “Battery case”.

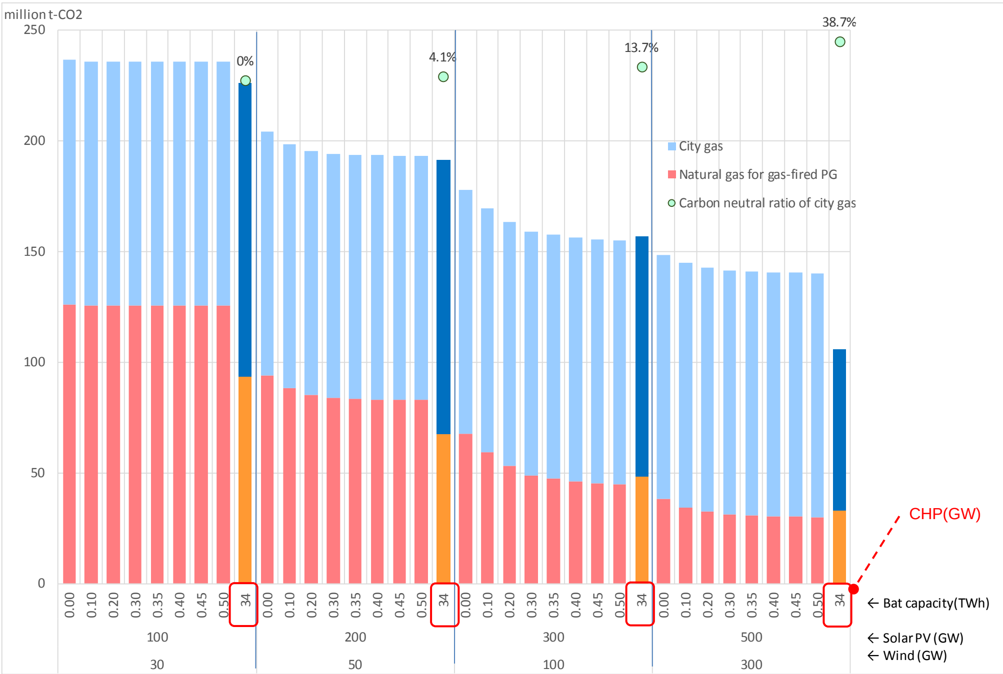


Figure 4-3 Comparison of CO_2 emissions in CNM-CHP and battery cases

In case of 100 GW of solar PV + 30 GW of wind power, as surplus electricity is limited, battery introduction does not make sense. Even if battery capacity scales up, the capacity is not fully used and CO_2 emissions do not decline proportionately. In the “CNM-CHP case”, however, CHP ramp-up can reduce the CO_2 emissions (even with CN methane production limited) because of higher total efficiency of CHP than LNG-fired power generation. While batteries cannot discharge electricity in the absence of enough electricity stored, CHP plants can ramp up irrespective of CN methane production situation. CHPs raplace less efficient gas-fired power plants, contributing to reducing CO_2 emissions.

In case of 200 GW of solar PV + 50 GW of wind power, surplus electricity increases to make charging and discharging operations of batteries effective. As CO_2 emissions can be reduced in line with battery capacity expansion, the capacity expansion allows CO_2 emissions to be equal to those in the “CNM-CHP case”. However, the emission reduction impact of battery capacity expansion gradually weakens.

In case of 300 GW of solar PV + 100 GW of wind power, surplus electricity further increases, which is sufficiently charged into batteries for subsequent discharging, then, replacing more fossil-fired power generation. Scale-up of battery capacity can lead to an increase in replacement of fossil-fired power generation. The “Battery case” may emit less CO_2 than the “CNP-CHP case” by scaling up battery capacity.

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”.

In summary, an increase in the amount of electricity stored in batteries resulting from renewable energy deployment increase may allow CO_2 emissions in the “Battery case” to slip below those in the “CNM-CHP case” by scaling up battery capacity. However, when renewable energy deployment exceeds a certain level, the impact of scaling-up of battery capacity gradually weakens. At the same time, CN methane’s share of city gas expands, leading CO_2 emissions in the “CNM-CHP case” to stay below those in the “Battery case”.

4.4. Identifying installation capacity

Based on the analysis results shown above, the conditions in which the CO_2 emissions from power generation and city gas in the “CNM-CHP case” and “Battery case” become same under a scenario for 300 GW of solar PV + 100 GW of wind power are identified for comparing the two cases on a level playing field.

4.4.1. CO_2 capture + CN methane production

According to simulations, the maximum hourly CO_2 capture comes to 13,180 t-CO_2/h (Figure 4-4). 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. Given that the specific electricity consumption for CN methane production including CO_2 capture is 18.34 kWh/Nm^3-CH_4 (see 2.5), CN methane production capacity is 6.69 million Nm^3-CH_4/h.

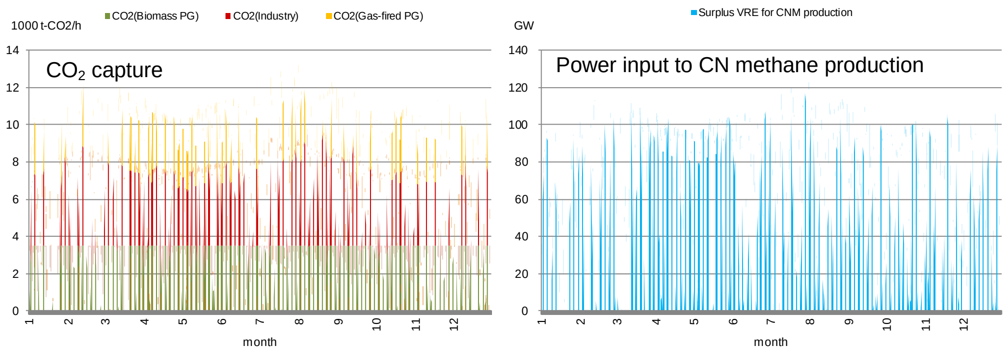


Figure 4-4 Hourly CO_2 capture and hourly power inputo to CN methane production

4.4.2. Batteries

As 300 GW of solar PV + 100 GW of wind power and 34 GW of CHP are fixed, CO_2 emissions from power generation and city gas in the "CNM-CHP case" are determined at 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) (Figure 4-5).

Figure 4-6 shows how charge/discharge happens throughout the year. The rated input/output is 81 GW (charge/discharge = 81GW/59GW) for 100 GWh of storage capacity, and 187 GW (charge/discharge = 187GW/69GW) for 500 GWh. Compared with Japan's present pumped storage hydro capacity (27 GW × 5h[1] = 135 GWh), it is found that 386 GWh of battery storage capacity with 153 GW of rated input/output are significantly huge.

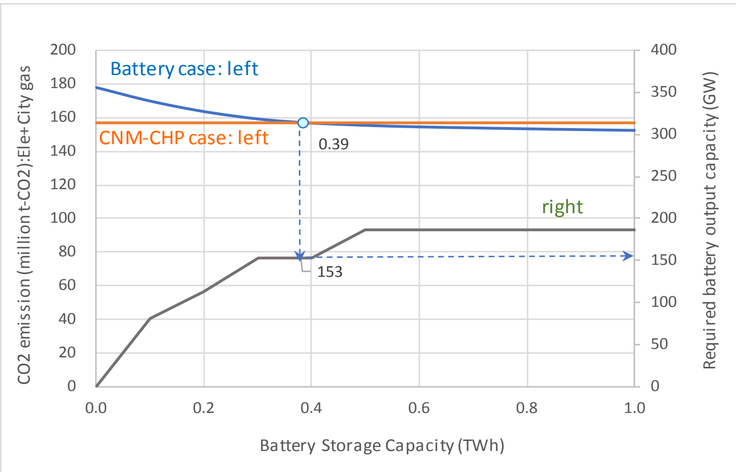


Figure 4-5 Identification of Battery Capacity (TWh and GW) in the "Battery Case"

[1] Estimated based on various data.

Battery capacity = 0.1TWh
➔ Charge/Discharge = 81GW/59GW

Battery capacity = 0.5TWh
➔ Charge/Discharge = 187GW/69GW

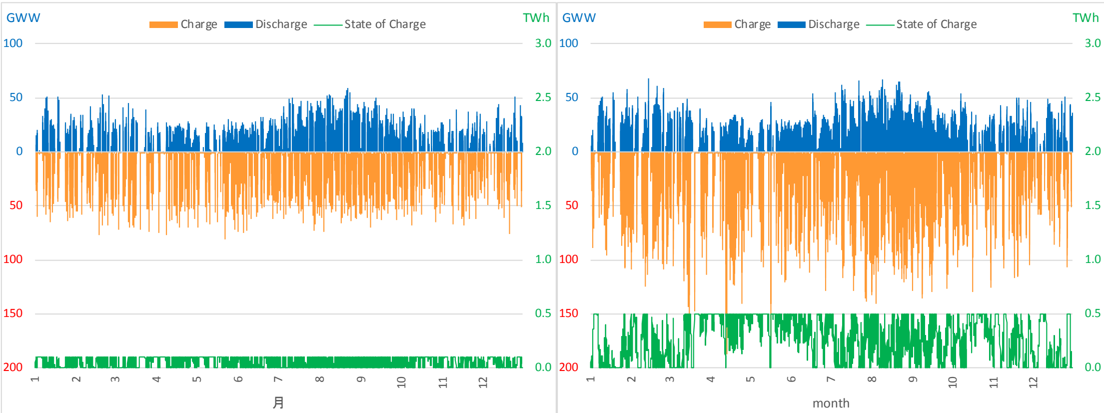


Figure 4-6 Chargin and Discharging (300GW of solar PV + 100GW of wind)

4.5. Economics

4.5.1. Assumptions for costs and technical specifications

(1) CAPEX of CN methane production

Based on an existing study [2] and the "Strategic Road Map for Hydrogen and Fuel Cells" (March 12, 2019), CAPEX of CN methane production are assumed in Table 4-1. The "Strategic Road Map for Hydrogen and Fuel Cells" sets 2030 targets for water electrolyzer CAPEX at JPY50,000/kW and unit electricity consumption of hydrogen production at 4.3 kWh/Nm^3-H_2, which means JPY 215,000/(Nm^3-H_2/h). Although compressor is required to blend CN methane into city gas infrastructure, the cost is considerably small [2] and is ignored in this study.

Table 4-1 CAPEX Assumption for CN Methane Production

	CAPEX	Number of unit
Water electrolysis	JPY 0.215 mil /(Nm^3-H_2/h)	4
Methanation	JPY 0.50 mil /(Nm^3-CH_4/h)	1
CN methane production system	JPY 1.36 mil /(Nm^3-CH_4/h)	1

(2) CAPEX of CO_2 capture

According to [11], the total CAPEX of CO_2 capture is assumed to be JPY 10.8 billion for 118 t-CO_2/h of capacity, including JPY 6.67 billion of CAPEX per se, JPY 720 million of annual cost including an absorbing liquid cost (Table 4-2) with operation period of 15 years. Then, the unit cost becomes JPY 92 million/(t-CO_2/h). The heat supply boiler costs JPY 5.422 billion with 127 t-CO_2/h of capacity or JPY 43 million /(t-CO_2/h).

Table 4-2 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)**

Source: "FY2015 CO_2 Fixation/Effective Utilization Technology Project: Underground CO_2 Storage Technology R&D Report" (March 2016) Research Institute of Innovative Technology for the Earth

Note: A case for a steel plant is adopted. Although the report gives the repair cost at 215 million yen/y, the repair cost is not taken into account in the following comparison of economic efficiencies of the CNM-CHP and storage battery cases.

(3) CAPEX of Battery

A battery system consists of a power conditioner system (PCS) and a storage battery cell. The prices of these components are assumed as shown in Table 4-3, based on their recent downtrends and future outlook.

Table 4-3 CAPEX Assumption for Battery

PCS	JPY 40,000/kW
Cell	JPY 20,000/kWh

(4) Energy cost

As indicated in 2.4 and 2.5, surplus renewable electricity is assumed to cover electricity consumption for CO_2 capture and included in the CN methane conversion efficiency.

Differences in energy consumption between the "CNM-CHP case" and "Battery case" are derived from natural gas and city gas. Natural gas consumption depends on gas-fired power generation that is affected by CHP ramp-up in the "CNM-CHP case" and by discharge in the "Battery case". City gas consumption increases by CHP ramp-up and CO_2 capture, while part of city gas is covered by CN methane produced from surplus renewable electricity. Table 4-4 shows city gas and natural gas demand in the "CNM-CHP case" and "Battery case". In the "CNM-CHP case", although city gas demand increases mainly by CHP ramp-up, demand for city gas from conventional natural gas is less than in the "Battery case" due to CN methane produced and blended. On the other hand, as there is more replacement of gas-fired power generation in the "Battery case", natural gas demand in the "CNM-CHP case" is greater than in the "Battery case". As total city gas and natural gas demand in the "CNM-CHP case" is almost same as in the "Battery case", the energy cost gap between the two cases is ignored in this study.

Table 4-4 City gas and Natural gas Consumption

	Billion Nm^3-CH_4 Methane equivalent				
	City gas			Natural gas	TOTAL
	Total	CN methane	Natural gas	Gas-fired PG	
No measures	53.8	0	85.3	31.5	853
CNM-CHP	61.2	8.4	75.4	22.6	754
Battery	53.8	0	75.5	21.7	755

Note: The unit is in calorific value of methane.

4.5.2. Comparative analysis

As the energy costs in the "CNM-CHP case" and "Battery case" are almost equal, only CAPEXs are compared between the two cases.

Table 4-5 shows CAPEX calculated based on installation capacity and unit cost in the "CNM-CHP case". The CAPEX required is JPY 11 trillion in total. In the "Battery case", the CAPEX is 14 trillion yen, which is 153 GW × JPY 40,000/kW + 390 GWh × JPY 20,000/kWh (the CAPEX falls to 10 trillion yen if the battery cell price declines to JPY 10,000/kWh).

Table 4-5 CAPEX for CNM-CHP

	Unit CAPEX	Scale	CAPEX
CO_2 capture (including boiler)	JPY 0.135 bln /(t-CO_2/h)	14.65 kt-CO_2/h	JPY2.0 tril.
CN methane production (electrolyzer + methanation)	JPY 1.36 mil /(Nm^3-CH_4/h) = 0.215 mil X 4+ 0.5 mil	Output: 6.69 mil Nm^3-CH_4/h Input: 122.65 GW	JPY 9.1 tril.
TOTAL	―	―	JPY 11.1 tril.

This study analyzes the whole of Japan as a single region and assumes that CO_2 capture, CN methane production and battery facilities are installed intensively. As these facilities would in reality be geographically distributed, costs may increase for CO_2 capture and methanation facilities for which the economy of scale works. However, the analysis here reveals that the economics of the "CNM-CHP" representing a power-to-gas approach is comparable to that of batteries as far as renewable energy deployment scale is large.

Given massive renewable energy deployment, the "CNM-CHP" may become more advantageous over batteris as the decarbonization effect of batteries representing a power-to-power technology declines gradually in line with battery capacity expansion due to limited discharge opportunities.

4.6. Energy balance and CO_2 emissions

Based on the above analyses, Figure 4-7 shows the energy balance and CO_2 emissions from power generation and city gas in the situation where CO_2 emissions in the two cases are equal. The "Battery case" features greater curtailment (electricity dumping) than the "CNM-CHP case" (left side of Figure 4-7). This is because charging is limited under constraints on battery storage capacity (kWh). In the "CNM-CHP case", the effective utilization of surplus renewable electricity for methanation is affected by the hourly availability of CO_2. However, since constraints on intensive CO_2 emissions are relatively small (see Figure 3-1), there is less curtailment. On the other hand, the CN methane conversion efficiency including from production to utilization (=33% covering from CO_2 capture to hydrogen production, methanation and CHP power generation, or about 50% if the exhaust heat recovry efficiency is included) is lower than batteries' charge/discharge efficiency (=76% including self-discharge loss), indicating a large conversion loss.

Loss caused by surplus renewable electricity curtailment and loss derived from conversion in the two cases offset each other and as a result, the total loss in the "CNM-CHP case" is 116.6 TWh, not so different from 110.6 TWh in the "Battery case" (out of 534.9 TWh of solar PV + wind power generation, direct absorption into the grid accounts for 297.2 TWh, pumped storage hydro discharging for 44.8 TWh, pumped storage hydro loss for 19.2 TWh and surplus electricity for 173.7 TWh).

While CHP ramp-up ("CHP_UP") in the "CNM-CHP case" is 57.1 TWh due to constraint of CHP margin output capacity, discharging from batteries in the "Battery case" is 63.1 TWh, indicating greater replacement of fossil-fired power generation. Meanwhile, the "CNM-CHP case" can utilize CHP exhaust heat for reducing city gas consumption and CN methane can contribute to decarbonizing city gas, as described by CO_2 emissions (right side of Figure 4-7). It is observed that while CO_2 emissions from gas-fired power generation are slightly larger, CN methane accounting for 14% of city gas demand contributes to reducing CO_2 emissions from city gas.

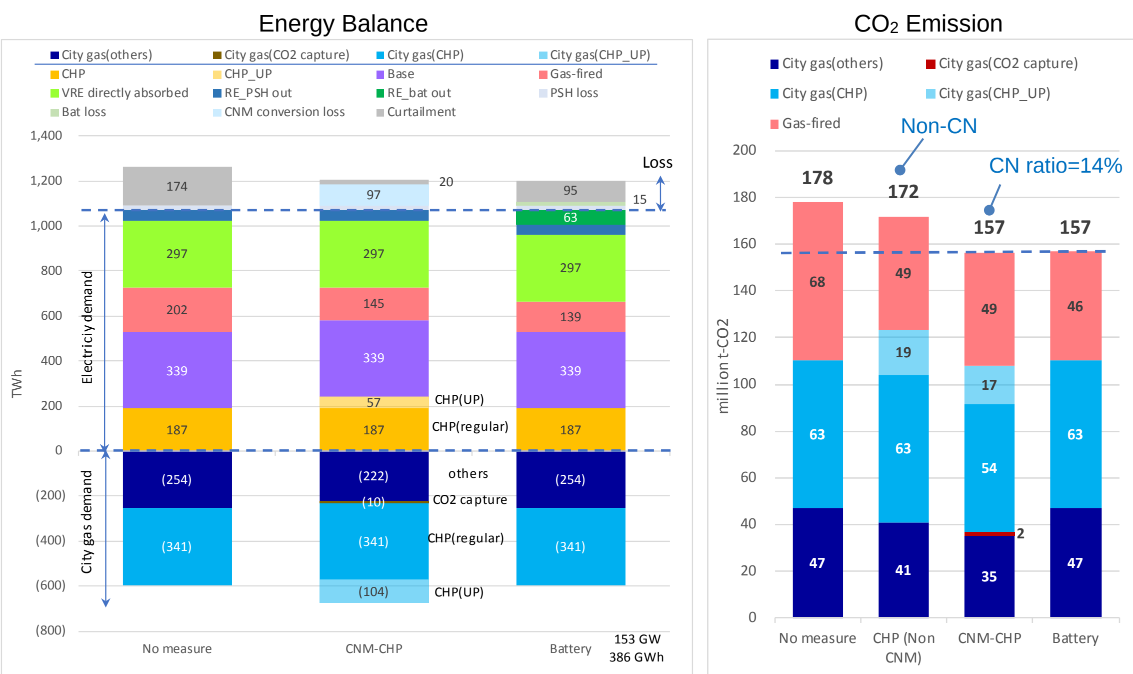


Figure 4-7 Energy Balance and CO_2 Emission of Power Generation and City Gas

Note: "No measure" means that surplus electricity is curtailed. "Battery loss" includes loss from roundtrip efficiency and self-discharge. It should be noted that city gas consumption of CHP and CHP power generation should not be double counted.

5. Conclusion

This study assessed a "CNM-CHP model" that mitigates renewable energy output fluctuations by ramping up the existing CHP utilizing the margin output capacity (equal to downward demand response) when renewable energy output declines, while blending carbon-neutral (CN) methane produced from surplus renewable electricity into city gas network. By carrying out an analysis of a power generation mix model for the whole of Japan as a single region for the sake of simplicity in the analysis structure and the interpretation of results, this study found the following:

[Impact of CN methane utilization by CHP]

- With an assumption that future total CHP installed capacity is 34 GW (30 GW for the commercial and industrial sectors and 5.3 million fuel cells for the residential sector), regular CHP operation annually generates 187 TWh of electricity and margin capacity can ramp up 109 TWh of electricity.
- If 100 GW of solar PV and 30 GW of wind power is introduced, CHP can ram up 98 TWh annually. Since capacity of the grid to accept CHP ramp-up declines as renewable energy deploys largely, CHP ramp-up falls to 57 TWh for 300 GW of solar PV + 100 GW of wind power and to 16 TWh for 500 GW of solar PV + 300 GW of wind power.
- On the other hand, as surplus electricity increases in line with renewable energy deployment, potential producible CN methane increases. CN methane production is no more than 100 million Nm^3-CH_4 for 100 GW of solar PV + 30 GW of wind power, but increases up to 8.4 billion Nm^3-CH_4 for 300 GW of solar PV + 100 GW of wind power and up to 22.5 billion Nm^3-CH_4 for 500 GW of solar PV + 300 GW of wind power, corresponding to 57% of the present city gas demand at 39.7 billion Nm^3-CH_4 on a methane calorific value equivalent.
- In other words, 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. If 300 GW of solar PV + 100 GW of wind power is introduced, CO_2 emissions from power generation and city gas is 157 million t-CO_2 for CNM-CHP model, bringing about 21 million t-CO_2 reduction equivalent to 25% of the current emissions from city gas. If renewable energy expands up to 500 GW of solar PV + 300 GW of wind, massive CN methane is used also for non-CHP city gas consumption, leading to CO_2 emissions to be substantially curbed to 106 million t-CO_2 from 148 million t-CO_2 without CNM-CHP model.

[Economics of CN methane utilization by CHP]

- For the analysis on the economics, the "CNM-CHP case" is compared with "Batteries case" where battery is used for long-term application. At present, batteries are increasingly used for short-term application for load frequency control mainly in Europe and the United States where the market has been developed. As battery prices decline, however, the batteries are expected to be used for long-term application to charge and discharge surplus renewable electricity. Therefore, the battery used for long-term application can be a candidate to be compared with the CNM-CHP model.

- Under a scenario for 300 GW of solar PV + 100 GW of wind power with 34 GW of CHP capacity, the "CNM-CHP case" is compared with the "Battery case" in which regualr CHP operations are combined with additional batteries introduced to mitigate renewable energy output fluctuations. Capacity sizes were identified to equalize CO_2 emissions from power generation and city gas consumption in the two cases. In the "CNM-CHP case", CO_2 capture capacity was identified at 14,600 t-CO_2/h and CN methane production capacity at 123 GW on an input power basis. In the "Battery case", battery capacity was identified at 380 GWh (rated input-output at 153 GW). The CAPEX for the "CNM-CHP case" is JPY 11 trillion, close to JPY 10-14 trillion for the "Battery case".

Generally, batteries are increasingly expected to mitigate renewable energy output fluctuations as their prices have rapidly declined in recent years. However, as renewable energy deploys largely, scale and frequency of surplus electricity hamper discharging opportunities. Even if battery storage capacity is expanded, the impact of decarbonization of power generation is diminishing. This reveals the limitation on the power-to-power approach that addresses renewable energy deployment only in the electric grid as a closed system.

On the other hand, the power-to-gas approach represents "Sector-Coupling" concept that enhances one-way flow of surplus renewable electricity from the power grid to the city gas and transportation sectors. It can overcome the limitation inherent to the power-to-power approach, allowing the entire energy system to promote decarbonization by accomodating large renewable energy generation. In the power-to-gas system, CN methane unlike hydrogen has an economic advantage of utilizing existing city gas infrastructure. If CN methane is used by a CHPs as a virtual power plant (VPP) to make their margin output capacity available for enhancing grid flexibility, renewable energy output fluctuations may be mitigated in a lower carbon manner.

CN methane with a relatively higher technological maturity is expected to become the core of the carbon capture, utilization and recycle (CCUR) technology that is recently drawing much attention as means to avoid CCS challenges such as social acceptance, location selection and legislation. To allow CN methane to be installed into the energy system, water electrolysis and methanation costs are required to be reduced, with production efficiency improved. Although the present mainstream methanation technology is the chemical Sabatier reaction, other technologies in the research phase, including the solid oxide electrolyzer cell (SOEC) co-electrolysis that electrolyze water and CO_2 simultaneously to efficiently produce methane, as well as a biological reaction using methane bacteria should be addressed.

The most important requisite for improving the economics of CN methane is substantial cost reduction in renewable energy. A conceivable option that this study did not address may be utilization of overseas lower-cost renewable energy for producing CN methane to be imported into Japan. This option has an advantage of utilizing the existing liquefied natural gas supply chain.

CN methane still has technological challenges to be overcome as described above. As indicated by this study, however, CN methane can be expected to contribute much to the decarbonization of the entire energy system. 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 of a CN methane production system as charging 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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