# Optimal Power Generation Mix Including Distributed Generation Considering Heat Demand of the Residential and Commercial Sectors

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# Optimal Power Generation Mix including Distributed Generation considering Heat Demand of the residential and commercial sectors

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## Abstract:

As a measure against global warming, by the second half of this century in the Paris Agreement, we agreed to achieve zero greenhouse gas emissions worldwide. Japan is shown to achieve a 26% reduction in 2030 and an 80% reduction by 2050. In a low-carbon society, it is required to use energy efficiently and without waste. In order to achieve this, a distributed generation has attracted attention. The combined heat and power systems make it possible to reduce greenhouse gas emissions and improve economy by saving energy by effectively using both electricity and waste heat. Also, the use of renewable energy can reduce both fossil fuel consumption and greenhouse gas emissions. Additionally, storage batteries are expected to contribute to further promotion of the use of renewable energy. In this paper, using an optimal power plant mix model considering heat demand of the residential and commercial sectors and the power and gas transportation costs, we will examine the effects of introducing residential and commercial solid oxide fuel cell combined heat and power systems, photovoltaic power generations and storage batteries on energy systems and greenhouse gas reduction in 2030.

## Keywords:

Optimal power generation mix, Power & gas network, Combined heat & power, Distributed generation,
Solid oxide fuel cell, Photovoltaic, Battery storage.

# 1. Introduction

The Paris Agreement, an international framework for global warming countermeasures, has started full-scale since January 2020. Japan's plan is to reduce greenhouse gas emissions by 26% in 2030 compared to 2013. For the future, while maximizing the use of renewable energy, it is necessary to consider the ideal form of a disaster-resistant and economical energy system.

In order to make the new energy supply-demand structure more stable and efficient, it is necessary to consider not only the composition of primary energy but also secondary energy, which is a form in which end users use energy. In particular, to maximize energy savings, The Fifth Strategic Energy Plan [1] states that it is important to consider using the conversion to electricity and heat efficiently and to make efforts for its realization. Combined heat and power (CHP), which generates heat and electricity, is one of the most efficient ways to utilize energy by producing heat and electricity simultaneously. In addition, since it usually has a certain surplus power generation capacity, it can also be expected to play a role in backing up a power supply shortage in an emergency.

In the power sector, distributed generations such as CHP systems have been expected as measures to reduce $CO_2$ emissions, and various studies are being conducted [2,3]. Until now, the scale of the spread of distributed generation is small, so it is generally treated as an auxiliary to the power system, and in terms of $CO_2$ reduction, we considered using a $CO_2$ emissions intensity as a separate measure from the electric power network. In the case of the introduction amount of distributed power sources becomes large, it must be regarded as one of the important power sources for the power sector. As described in Document [4] as " Gas grids provide a crucial mechanism to bring energy to consumers, typically delivering more energy than electricity networks and providing a valuable source of flexibility.", it is important to consider not only the electric power network but also the gas network when introducing a distributed generation such as CHP. In this research, we constructed an evaluation model that integrated and treated the power system and the distributed power and examined the $CO_2$ reduction effect and the effect on the power system configuration by introducing and operating them cooperatively.

# 2. Outline of the evaluation model

## 2.1. Model features

This model consists of three main parts: a power network model, a gas network model, and consumer models. Each model is linked by electricity demand and city gas demand. In this model, CHP, renewable energy photovoltaic power generation, and battery storage are assumed as distributed generation. The distributed generation is given a geographical distribution, taking into account the transportation infrastructure of the transmission lines and pipelines. This model is a linear programming model that minimizes the total system cost (social cost), and is characterized by including the customer side costs. Fig.1 shows a conceptual diagram of the evaluation model. The target year is 2030 and the target area is the metropolitan area of Japan[1].

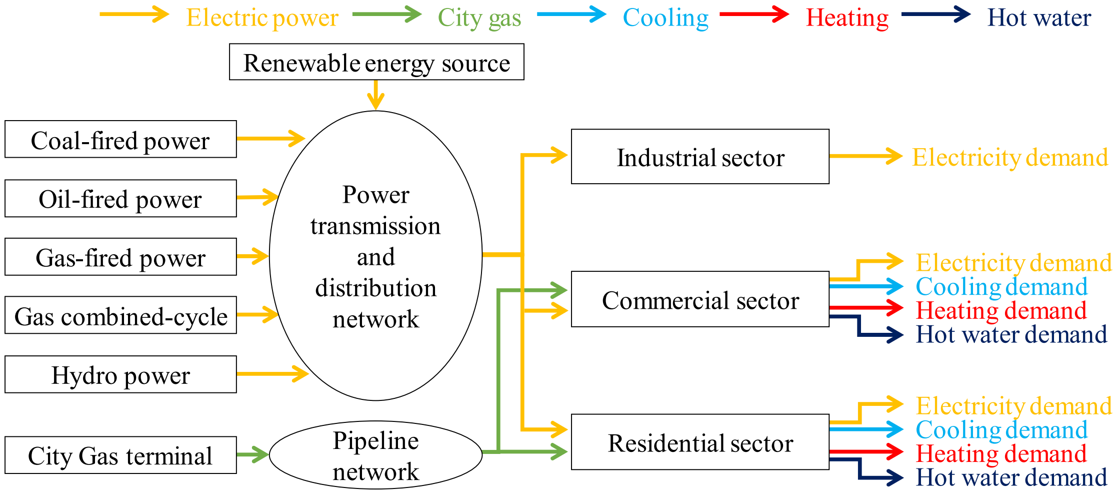

*Fig.1. Conceptual diagram of the evaluation model.*

## 2.2. Power network model

The feature of the power network model in this study is that the power plant also gives a geographical position and considers transmission lines. The target area, the metropolitan area of Japan, is divided into power plant nodes, demand nodes and relay nodes and these nodes are connected by transmission lines, taking into account transmission infrastructure. There are 10 power plant nodes, 26 demand nodes, 6 relay nodes, and 53 transmission lines. Power plant is assumed to be of six types: coal-fired, oil-fired, gas-fired, gas turbine combined cycle-fired (GTCC), hydro power and pumped hydro power. Nuclear power generation is considered in Strategic Energy Plan, but excluded from this study. The location and capacity of each power plant is assumed to be the existing capacity as of 2030, and will be the lower limit of this model. There are only two types of new power plants that can be built: gas-fired power and gas combined cycle-fired (For the following power plants, the existing capacity is set as the upper limit. Hydro and pumped hydro: new construction is difficult due to location, oil-fired: because expansion is prohibited, coal-fired: because of the global warming problem). A mega solar power plant is set as renewable energy on the power network side. The amount of mega solar installed is set at the lower limit of the amount approved by the Feed-in Tariff Scheme for Renewable Energy up to the end of September 2018 [4],

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[1] The metropolitan area of Japan is Tokyo and surrounding areas. The areas are Tokyo, Kanagawa, Chiba, Saitama, Gunma, Tochigi, Ibaraki, Yamanashi and a part of Shizuoka.

and the upper limit is set to twice the lower limit. The transmission and substation equipment will take into account the 500 kV and 275 kV high-voltage main lines and the high-voltage substation that connects them to the lower system. For the purpose of incorporating into the linear programming model, the power flow is calculated by the DC load flow method, and the transmission loss is given exogenously with a realistic loss rate. Table.1 and Table.2 show various parameters and Fig.2 shows the conceptual diagram of power network.

*Table.1. Exogenous variables of power plants.* [6]

| Type | | Coal | Oil | Gas | GTCC | Hydro | Pumped |
|---|---|---|---|---|---|---|---|
| Unit construction cost [$/kW] | | 2,470 | 2,610 | 1,890 | 1,490 | 3,640 | 2,180 |
| Life time [year] | | 40 | 60 | 40 | 40 | 60 | 60 |
| Annual O&M cost rate [%] | | 4.8 | 3.9 | 3.6 | 3.6 | 1.2 | 4.0 |
| Own consumption rate [%] | | 5.0 | 5.4 | 5.4 | 2.5 | 0.5 | 0.5 |
| Fuel cost [$/kWh] | | 0.05 | 0.18 | 0.11 | 0.09 | - | - |
| $CO_2$ emission intensity [kg-$CO_2$/kWh] | | 0.83 | 0.65 | 0.47 | 0.39 | 0 | 0 |
| Maximum increase rate of output [%/hour] | | 26.0 | 44.0 | 44.0 | 44.0 | 100 | 100 |
| Maximum decrease rate of output [%/hour] | | 31.0 | 31.0 | 31.0 | 31.0 | 100 | 100 |
| Availability [%] | Seasonal peak | 85.7 | 90.1 | 91.6 | 93.1 | 85.0 | 85.0 |
| | Summer (weekday) | 79.0 | 87.1 | 89.1 | 87.2 | 85.0 | 85.0 |
| | Summer (holiday) | 80.0 | 87.6 | 89.3 | 88.4 | 85.0 | 85.0 |
| | Winter (weekday) | 84.5 | 78.2 | 80.3 | 80.9 | 62.0 | 62.0 |
| | Winter (holiday) | 85.7 | 79.1 | 81.3 | 79.6 | 62.0 | 62.0 |
| | Spr.&Aut (weekday) | 63.3 | 71.5 | 71.3 | 81.1 | 84.0 | 84.0 |
| | Spr.&Aut (holiday) | 61.9 | 71.4 | 70.4 | 81.7 | 84.0 | 84.0 |
| Existing capacity in 2030 [MW] | | 4,400 | 1,000 | 4,006 | 16,501 | 3,009 | 10,396 |

*Table.2. Exogenous variables of transmission line and substation.* [7]

| Type | Transmission line | | Substation |
|---|---|---|---|
| | Overhead | Underground | |
| Unit construction cost | 1.55 [$/kVA/kW] | 9.09 [$/kVA/kW] | 145 [$/kVA] |
| Life time [year] | 50 | 50 | 50 |

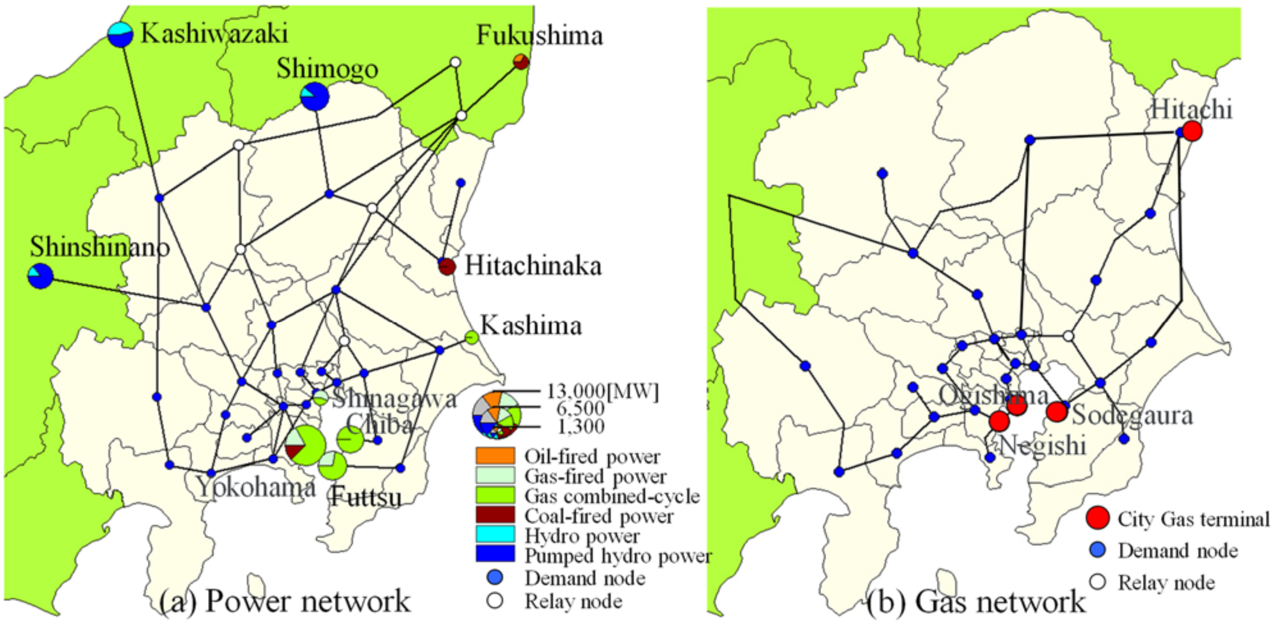

*Fig.2. Conceptual diagram of power network and gas network in the Tokyo metropolitan area.*[2]

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[2] The light-yellow part in the figure indicates the Tokyo metropolitan area.

## 2.3. Gas network model

Similar to the power network model, the gas network model is constructed. As with the transmission facilities, only the high-pressure pipelines are considered. The gas network model consists of 4 terminal nodes, 26 demand nodes, and 1 relay node, with 31 pipelines connecting the nodes. The 26 demand nodes are common to the power network and gas network. In addition, the gas demand handled in this model is limited to city gas used for residential and commercial sectors. Table.3 shows various parameters and Fig.2 shows the conceptual diagram of gas network.

*Table.3. Exogenous variables of gas network.*

| Type | | City gas terminal | Pipeline |
|---|---|---|---|
| Unit construction cost | | 140 [$/kW] | 2.91 [$/kW/km] |
| Life time [year] | | 50 | 50 |
| Annual O&M cost rate [%] | | 4.0 | - |
| City gas production cost [$/kWh] | | 0.05 | - |
| $CO_2$ emission intensity [kg-$CO_2$/kWh] | | 0.183 | - |
| Availability [%] | Seasonal peak | 90.0 | - |
| | Summer (weekday) | 90.0 | - |
| | Summer (holiday) | 80.0 | - |
| | Winter (weekday) | 90.0 | - |
| | Winter (holiday) | 80.0 | - |
| | Spr.&Aut (weekday) | 80.0 | - |
| | Spr.&Aut (holiday) | 80.0 | - |

## 2.4. Consumer models

The distributed generation is introduced for residential and commercial sectors. For commercial sector, it is represented by four categories of business: “Hotel, Hospital, Office, and Shop”. In this model, only the electricity demand is considered for industrial sector and the transportation sector is not considered as a model. The following sections explain the residential and commercial models.

### 2.4.1. Residential model

Fig.3 shows the energy flow in the residential sector. The setting of electricity and heat demand is set by multiplying the floor area of each demand node by the load pattern per unit floor area quoted from Document [8][3]. In this study, the distributed generations are fuel cell CHP, battery storage, and photovoltaic power generation. The fuel cell is a solid oxide fuel cell (SOFC), which is expected to be introduced in the future with high efficiency power generation, and the battery storage is a lithium ion battery. As in the case of mega solar, the amount of photovoltaic power generation installed is set at the lower limit of the amount approved by the Feed-in Tariff Scheme for Renewable Energy up to the end of September 2018 [4], and the upper limit is set at twice the amount. The conventional equipment is an air conditioner, a latent heat recovery type water heater and a heat pump water heater. Table.4-6 shows each parameter of distributed generations.

### 2.4.2. Commercial model

Fig.3 shows the energy flow in the commercial sector. The setting of electricity and heat demand in the commercial sector as well as the residential sector is set with reference to Document [9][4]. The setting of the distributed generations is the same as for the residential model. The conventional equipment is an electric heat pump air conditioner, a gas heat pump air conditioner, an absorption

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[3] In the residential sector of this model, demand is set assuming that all houses are detached. The power and heat demand are set by multiplying the residential floor area of each node by the load pattern per floor area.

[4] In the commercial sector of this model, the air conditioning system is set as central heating.

chiller heater, boiler, and a heat pump water heater[5]. Table.4-6 shows each parameter of distributed generations.

*Table.4. Exogenous variables of solid oxide fuel cell [11].*

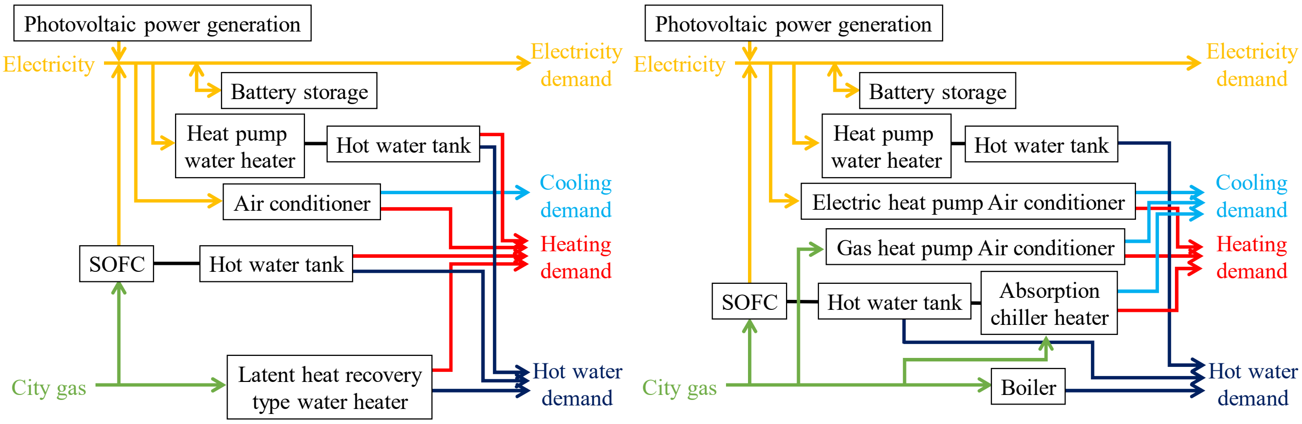
| Type | Residential | Commercial |
|---|---|---|
| Unit construction cost [$/kW] | 13,000 | 4,550 |
| Life time [year] | 15 | 15 |
| Hot water storage tank [ℓ/kW] | 20 | 40 |
| Stored hot water temperature [°C] | 70 | 60 |
| Power generation efficiency [%] | 46.8 (HHV) | 49.5 (HHV) |
| Exhaust heat recovery efficiency [%] | 31.5 (HHV) | 27.0 (HHV) |
| Minimum load factor [%] | 50 | 50 |

*Table.5. Exogenous variables of photovoltaic power generation [1].*

| Type | Residential | Non-residential |
|---|---|---|
| Unit construction cost [$/kW] | 2,350 | 2,020 |
| Life time [year] | 15 | 15 |
| Existing capacity in 2030 [MW] | 1,722 | 17,019 |

*Table.6. Exogenous variables of battery storage [10].*

| Type | Lithium ion |
|---|---|
| Unit construction cost [$/kW] | 2,270 |
| Life time [year] | 15 |
| Cycle efficiency [%] | 80 |
| Usage rate [%] | 90 |
| Electric storage capacity [kWh] | 6 |



(a) Energy flow in the residential sector (b) Energy flow in the commercial sector

*Fig.3. Energy flow of each customer.* [6]

## 3. Formulation of the evaluation model

This model is formulated as a linear programming problem[7] with the objective function (Equation (1)) to minimize the system cost in 2030 under various constraints, with one of the constraints being

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[5] In the commercial sector of this model, the air conditioning system is set as central heating. Similar to the residential sector, the power and heat demand are set by multiplying each customer floor area of each node by the load pattern per floor area of each customer.

[6] Due to Japan's electric power system restrictions, only Photovoltaic power allows reverse power flow to the grid side.

[7] In this model, a line programming is selected to reduce the calculation time..

the target value of Strategic Energy Plan, greenhouse gas reduction of 26% ($CO_2$ reduction of 26%) compared to 2013. The basic configuration is as follows.

- Objective function.

  The first to fourth lines on the right side of equation (1) represent fixed costs, and the fifth and sixth lines represent variable costs. The details of equation (1) will be described. The first line is the fixed cost of the power plant. The first term in the second line is the fixed cost of the transmission line, and the second term is the fixed cost of the substation. The first term in the third line is the fixed cost of the city gas terminal, and the second term is the fixed cost of the pipeline. The fourth line is the fixed costs for consumer equipment. The fifth line is the power generation of each facility. The sixth line is the city gas production volume of the city gas terminal. The details of the variable still list it in the end of a volume.

$$\begin{aligned}
min.Total\ Cost = {} & \sum_{Gnode}\sum_{plt} Yall_{Gnode,plt} \cdot cg_{plt}\left(\alpha g_{plt} + \alpha gu_{plt}\right) \\
& + \sum_{branch} Ball_{branch} \cdot long_{branch} \cdot cb \cdot \alpha b + \sum_{node} Tall_{node} \cdot ct \cdot \alpha t \\
& + \sum_{factory} Fall_{factory} \cdot cgg(\alpha gg + \alpha ggu) + \sum_{pipe} Pall_{pipe} \cdot plong_{pipe} \cdot cp \cdot \alpha p \\
& + \sum_{node}\sum_{Z}\sum_{equip} Cap_{node,Z,equip} \cdot cd_{Z,equip} \cdot \alpha d \\
& + \sum_{Gnode}\sum_{plt}\sum_{ptn}\sum_{hr} X_{Gnode,plt,ptn,hr} \cdot hh \cdot cf_{plt} \cdot days_{ptn} \\
& + \sum_{factory}\sum_{ptn}\sum_{hr} Make_{factory,ptn,hr} \cdot hh \cdot cfg \cdot days_{ptn},
\end{aligned} \tag{1}$$

- Constraints.

  The constraints of this model are as follows.

  $CO_2$ emission constraint, Power supply and demand constraint, Reserve electric power supply constraint, Installed capacity constraint, Power generation output constraint, Hydro power-related constraints[8], Pumped hydro power-related constraints, Load following constraint, Transmission line constraint, Substation constraint, City gas supply and demand constraint[9], City gas production constraint, Pipeline flow constraint, Consumer energy balance constraints, Consumer equipment constraints, etc.

- Other conditions.

  To take into account the power output of photovoltaic power generation, the seasonal categories are set to 19 categories as shown in Table.7. The output characteristics for each area are not taken into account.

*Table.7. Days of each weather in each season.* [12] [10]

| Weather | Sunny | Cloudy | Rainy |
|---|---|---|---|
| Seasonal peak [days] | 3 | 0 | 0 |
| Summer (weekday) [days] | 48 | 22 | 11 |
| Summer (holiday) [days] | 23 | 10 | 5 |
| Winter (weekday) [days] | 48 | 22 | 11 |
| Winter (holiday) [days] | 24 | 11 | 5 |
| Spr.&Aut (weekday) [days] | 50 | 23 | 11 |
| Spr.&Aut (holiday) [days] | 23 | 10 | 5 |

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[8] The amount of charge and discharge are set to be zero during the day. The same applies to the battery storage.

[9] Because the city gas does not need to be simultaneous equal amount, a buffer is set for each demand node so that the supply and demand on a daily basis match.

[10] We set from past weather data provided by the Meteorological Agency. The target period is from 1990 to 2010.

# 4. Simulation and discussion

## 4.1. Simulation cases

In this study, 8 cases are set as shown in Table.8. In addition to the SOFC unit construction costs set in Table.4 in 2030, the three cases are set assuming reduction of SOFC unit construction costs as a case to promote the introduction of CHP. Also, the presence or absence of a lithium ion battery storage is added to the cases.

*Table.8. Simulation cases.*

| Type | Battery storage | Residential SOFC cost | Commercial SOFC cost |
|---|---|---|---|
| Case.0 | Without | 13,000 [$/kW] | 4,550 [$/kW] |
| Case.1 | Without | 6,360 [$/kW] | 3,640 [$/kW] |
| Case.2 | Without | 4,550 [$/kW] | 2,730 [$/kW] |
| Case.3 | Without | 2,730 [$/kW] | 1,820 [$/kW] |
| Case.4 | With | 13,000 [$/kW] | 4,550 [$/kW] |
| Case.5 | With | 6,360 [$/kW] | 3,640 [$/kW] |
| Case.6 | With | 4,550 [$/kW] | 2,730 [$/kW] |
| Case.7 | With | 2,730 [$/kW] | 1,820 [$/kW] |

## 4.2. Simulation Results

### 4.2.1. Electric Power Capacity

Fig.4 shows the results of the electric power capacity in each case. In cases where the SOFC unit construction cost is the target value (Case.0 and Case.4), there is no SOFC introduction and there is no difference depending on the presence or absence of a battery storage. In both cases, the introduction of GTCC will progress, and a new capacity of about 25,000 MW will be newly constructed. With or without a battery storage, photovoltaic power generation is constructed about 6,400 MW for non-residential and about 430 MW for residential. The introduction of SOFC CHP takes the place instead of GTCC as SOFC unit construction costs drop. The introduction is proceeded in residential sector and commercial sector, hotels and hospitals where heat demand is high. In any case, the introduction is not proceeded in commercial sector, offices and shops where heat demand is low. In cases where SOFC is introduced, there is a difference in the amount introduced depending on the presence or absence of a battery storage. In particular, the result is remarkable in the residential sector. When the unit construction cost is 2,730 $/kW, in Case.3, which has no battery storage, the installed amount of SOFC is about 2,000 MW, whereas in Case.7, which has a battery storage, the installed amount of SOFC is about 5,600 MW, which is about 2.8 times. The reason for the increase in the introduction amount is that the SOFC must continue to operate at 50% or more of the rated capacity, but because the battery storage has to be charged at night, the rise in the minimum demand has increased the introduction of the SOFC.

### 4.2.2. Annual power generation

Fig.5 shows the results of the annual power generation in each case. It can be confirmed that the annual power generation amounts of GTCC and SOFC change according to the installed capacity. Table.9 shows the capacity factor of GTCC and SOFC[11]. GTCC has a constant capacity factor in each case and functions as a middle electric source. On the other hand, it suggests that SOFCs are introduced unless they function as a base electric source. However, as the unit construction costs decrease, the required the capacity factor decreases, and installation proceeds. In particular, the installation of a battery storage improves the capacity factor of SOFCs, and the introduction of SOFCs is promoted.

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[11] The capacity factor of SOFC is calculated from the power generation (kWh) against the installed capacity (kW)

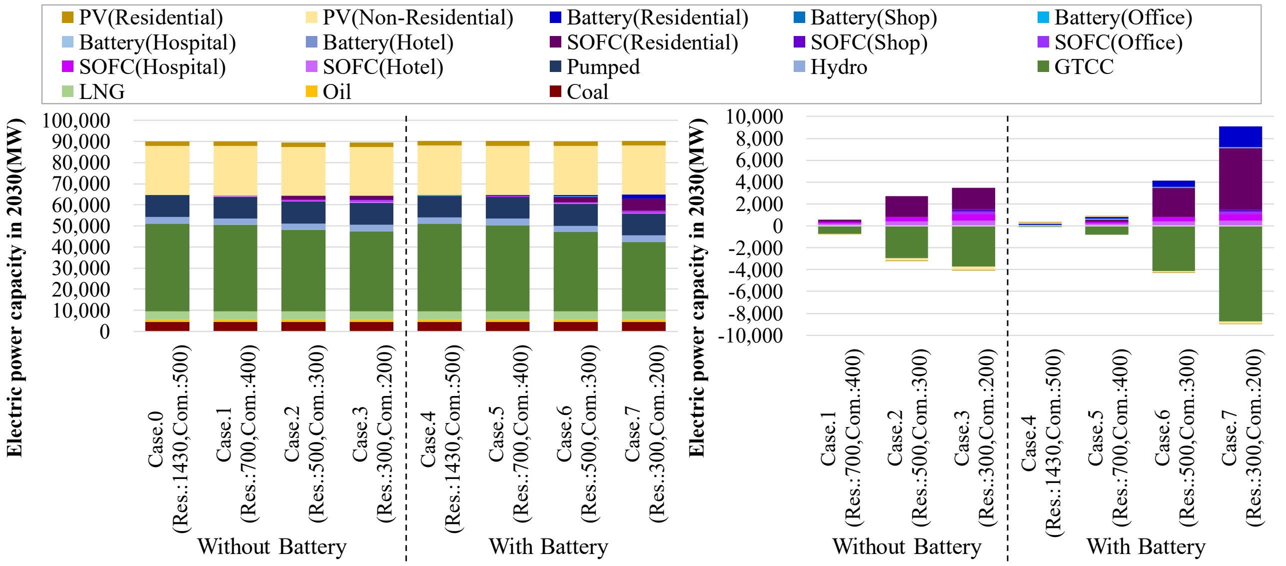


*Fig.4. Electric power capacity: The figure on the left shows the electric power capacity in each case. The figure on the right shows the difference in electric power capacity compared to Case.0.*

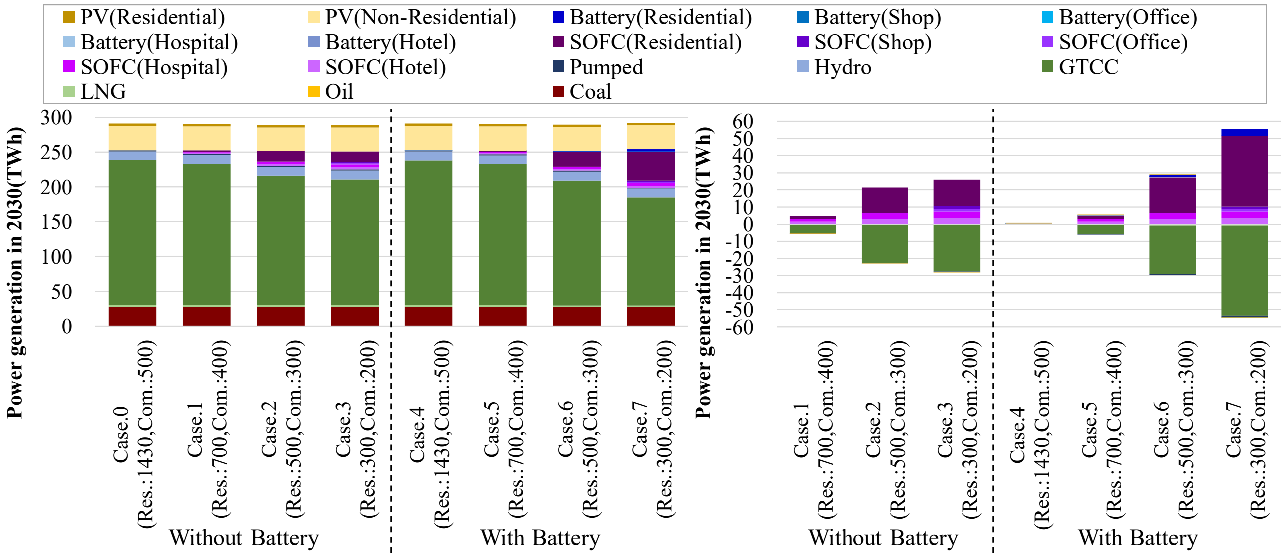


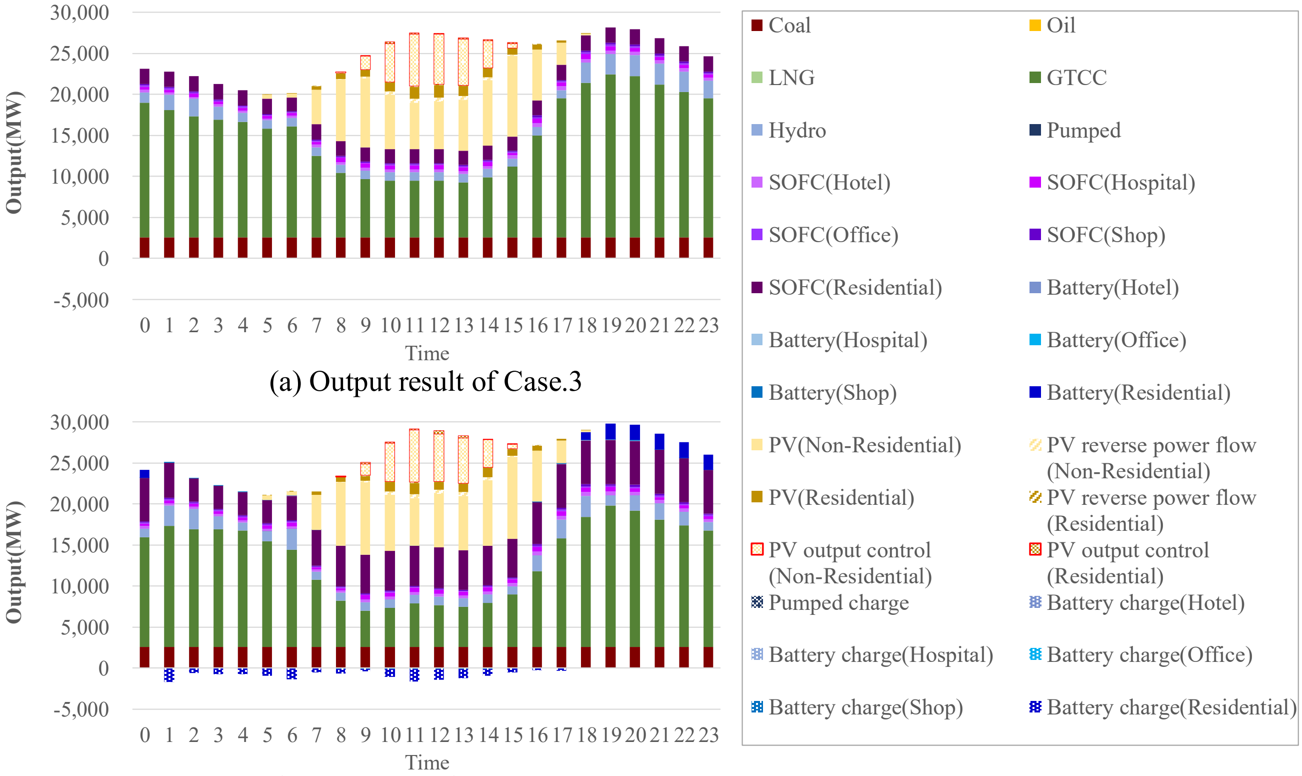
*Fig.5. Annual power generation: The figure on the left shows the annual power generation in each case. The figure on the right shows the difference in annual power generation compared to Case.0.*

*Table.9. GTCC and SOFC capacity factor of each case*

| Type | GTCC | SOFC | | | | |
|---|---|---|---|---|---|---|
| | | Hotel | Hospital | Office | Shop | Residential |
| Case.0 | 56.9% | - | - | - | - | - |
| Case.1 | 56.6% | 93.7% | 93.6% | - | - | 93.6% |
| Case.2 | 54.7% | 86.0% | 87.3% | - | - | 92.0% |
| Case.3 | 54.3% | 81.9% | 77.1% | 80.3% | 72.5% | 91.5% |
| Case.4 | 57.0% | - | - | - | - | - |
| Case.5 | 56.5% | 93.7% | 93.7% | - | - | 93.6% |
| Case.6 | 54.5% | 86.0% | 91.3% | - | - | 91.3% |
| Case.7 | 53.8% | 80.4% | 84.1% | 81.4% | 72.3% | 84.1% |

### 4.2.3. Power generation profile

As an example of the results, due to space limitations, Fig.6 shows the power generation output during the spring and autumn holiday, sunny days between Case 3 and Case 7. In the spring and autumn holiday when demand is least, on a sunny day, the output of solar power generation is suppressed, and the demand at night is not large, so the output of SOFC cannot be increased in Case.3 without a battery storage. On the other hand, if there is a battery storage, a part of the output of the SOFC at night can be used for charging the battery storage, which secures the output of the SOFC, and contributes to the increase in the introduction amount because it is a substitute for the output of GTCC .



(a) Output result of Case.3

(b) Output result of Case.7

*Fig.6. Power generation output in the case of the spring and autumn holiday, sunny*

### 4.2.4. SOFC installation location

This model gives geographical distribution to distributed generations and also takes into account the transmission infrastructure of transmission lines and pipelines. As an example of the results, Fig.7 shows the installed status of SOFC introduction in hotels. The introduction of SOFCs takes into account gas transport and will be installed near city gas terminals and in areas with high demand. This is considered to be the result of expressing the characteristics of this model in consideration of the regional characteristics.

### 4.2.5. Carbon dioxide reduction

Fig.8 shows the results of $CO_2$ emissions in each case. The existing coal-fired power plant is used as a base electric source even under the 26% $CO_2$ reduction constraint, and there is no difference in each case. Although the installed capacity of existing coal-fired power plants is small, it means that the 26% $CO_2$ reduction will be realized even if coal-fired power generation is continued. The 26% $CO_2$ reduction can be achieved by gas combined-cycle and photovoltaic power generation. For this reason, SOFCs will not be introduced at the current target cost for SOFCs, but if the unit construction cost for SOFCs are reduced, SOFCs will be introduced instead of GTCC, and power generation will be replaced accordingly. Increased power generation at SOFCs will reduce the need for natural gas, as they will cover heat demand. As a result, in Case.7, $CO_2$ emissions can be further reduced by 3.9% compared to Case.0. It is estimated that expectations for a SOFC with a high overall energy efficiency will increase as $CO_2$ emission restrictions become more stringent toward 2050.

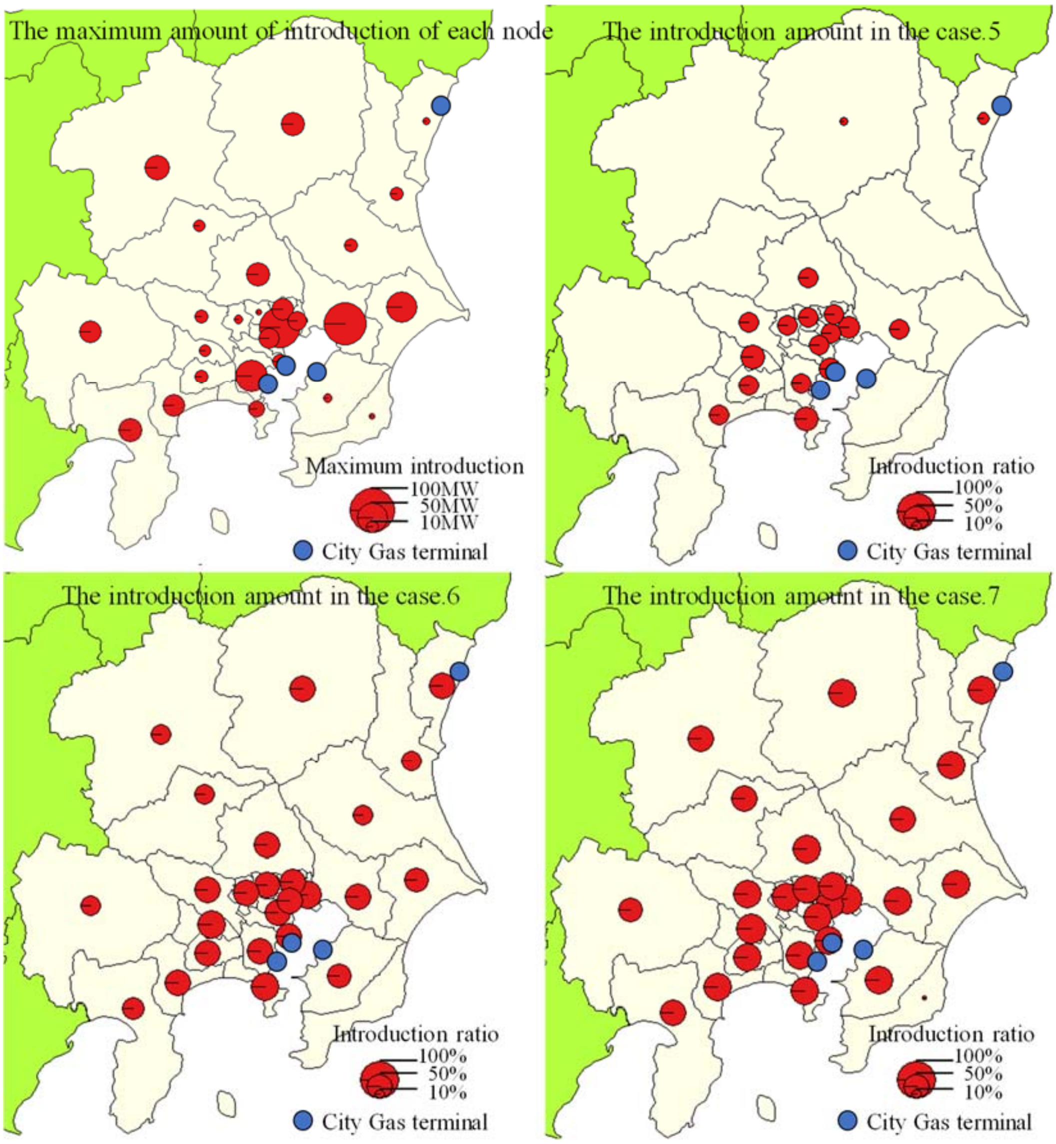


*Fig.7. In the case of hotels: SOFC introduction maximum amount of each demand node and SOFC introduction situation with each case*[12]

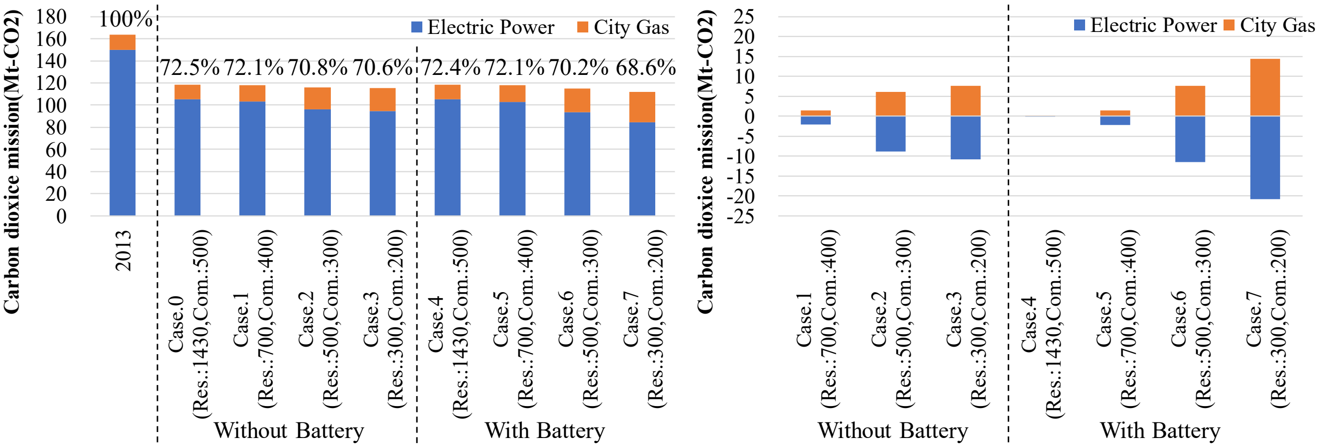


*Fig.8. Annual carbon dioxide emission: The figure on the left shows the annual carbon dioxide emission in each case. The figure on the right shows the difference in annual carbon dioxide emission compared to Case.0.*

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[12] The maximum introduction amount of SOFC of each consumer at each demand node is simulated by another simulation, and the capacity introduced based on that capacity is shown as a percentage. This result is a result when there is a battery storage, but the result is omitted in Case.5 because the SOFC introduction amount is 0.

# 5. Summary

In this paper, we constructed an evaluation model that integrated and treated the power system and the distributed power and examined the $CO_2$ reduction effect and the effect on the power system configuration by introducing and operating them cooperatively. The feature of this model is that it is mainly composed of three parts: a power network model, a gas network model, and consumer models, and each model is linked by electricity demand and city gas demand. Fuel cell CHP (SOFC CHP), renewable energy photovoltaic power generation, and lithium-ion battery storage are assumed as distributed generation. The distributed generation is given a geographical distribution, taking into account the transportation infrastructure of the transmission lines and pipelines. Using this model, we analyzed the power generation mix, the annual power generation, the geographical characteristics of the introduction, and the $CO_2$ emissions in 2030 when the diffusion of fuel cells CHP become popular.

These results suggest that distributed generations are introduced considering geographical features. It is also suggested that cooperative introduction with a battery storage would be effective for distributed generations that are difficult to shut down, such as SOFC, for the introduction of fuel cells CHP. In addition, it is confirmed that the introduction of CHP has a greater $CO_2$ reduction effect. The target of 26% $CO_2$ reduction in 2030 is achieved by utilizing the current technology, so it is not introduced at the target cost of SOFC CHP set by the government. It is also confirmed that further cost reduction is necessary for the introduction.

Towards 2050, further reduction of carbon will progress. Although zero-emission power sources such as renewable energy are attracting attention, it is also important to use energy efficiently, and in that regard, CHP will play a significant role in a low-carbon society. We plan to extend this model to a dynamic programming and evaluate the contribution of CHP to a low-carbon society in 2050.

# Explanatory variables

- Exogenous variables

  $Ball_{branch}$ : Transmission line capacity of each branch, kVA, $Cap_{node,Z,equip}$ : Each equipment capacity of each demand node and each consumer, kW, $Fall_{factory}$ : City gas terminal capacity of each terminal node, kW, $Make_{factory,ptn,hr}$ : Output of each city gas terminal of each terminal node in each seasonal category and time zone, kW, $Pall_{pipe}$ : Pipeline capacity of each branch, kW, $Tall_{node}$ : Substation capacity of each node, kVA, $X_{Gnode,plt,ptn,hr}$ : Output of each power plant of each plant node in each seasonal category and time zone, kW, $Yall_{Gnode,plt}$ : Each power plant capacity of each plant node, kW

- Endogenous variables

  $cb$ : Construction cost for transmission line, \$/(kVA・km), $cd_{Z,equip}$ : Construction cost for each equipment, \$/kW, $cf_{plt}$ : Fuel cost for each power plant, \$/kWh, $cfg$ : City gas production cost, \$/kWh, $cg_{plt}$ : Construction cost for each power plant, \$/kW, $cgg$ : Construction cost for city gas terminal, \$/kW, $cp$ : Construction cost for pipeline, \$/(kW・km), $ct$ : Construction cost for substation, \$/kVA, $days_{ptn}$ : Number of days in each seasonal category, days, $hh$ : Time width, 1hour, $long_{branch}$ : Transmission line length of each branch, km, $plong_{pipe}$ : Pipeline length of each branch, km, $\alpha b$ : Annual expense rate for transmission line, %, $\alpha d$ : Annual expense rate for each power plant, %, $\alpha g_{plt}$ : Annual expense rate for each power plant, %, $\alpha gg$ : Annual expense rate for city gas terminal, %, $\alpha gu_{plt}$ : Annual O&M cost rate for each power plant, %, $\alpha ggu$ : Annual O&M cost rate for city gas terminal, %, $\alpha p$ : Annual expense rate for pipeline, %, $\alpha t$ : Annual expense rate for substation, %

- Suffixes

  $branch$ : Transmission line index (53 lines), $equip$ : Consumer Equipment Index (9 types), $factory$ : Terminal node index (4 nodes), $Gnode$ : Plant node index (11nodes), $pipe$ : Pipeline index (31 lines), $plt$ : Power plant type index (6 types), $ptn$ : Seasonal category index (19 categories), $node$ : Demand node index (26 nodes), $Z$ : Consumer type index (5 types)

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