Factor of determining marginal abatement cost of CO_2 under carbon neutrality

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Abstract

Toward carbon neutrality, cost assessment for reducing CO_2 is essential. Although marginal abatement cost (MAC) is often used in the several previous studies, the factor determining MAC has not necessary been identified. Hence, it is important to clarify how MAC was determined in cost assessment. This study has developed Technology selection model to assess the optimized combination of energy technologies under constraints and identified technologies to determine MAC under 4 scenarios: (i) Base scenario, (ii) No nuclear scenario, (iii) Low CCS scenario, (iv) High fuel price scenario. As a result, this study showed MAC in 2050 was 478‒743 USD/ t‒CO_2. In the base scenario and no nuclear scenario, liquid synthetic fuel was additionally consumed instead of fossil fuel to reduce last 1,000 t‒CO_2 toward carbon neutrality. Hence, liquid synthetic fuel was key factor to determine MAC. On the other hands, in the low CCS scenario hand high fuel price scenario, DAC was additionally installed. Thus, key technology or fuel to determine MAC was different. The approach to identify key factor determining MAC can be expected to contribute to policy making for expanding key technologies or reducing total cost toward carbon neutrality.

Key words: Energy model, Carbon neutrality, Marginal abatement cost, Energy policy, Cost analysis.

1. Background

Japan has declared its goal of achieving carbon neutrality by 2050, which is to reduce overall greenhouse gas emissions to zero. To achieve this ambitious goal, there is a growing need to radically transform Japan's energy demand and supply structure by introducing various energy technologies such as renewable energy and using highly cost-effective technologies. For this, it is important to clarify the costs associated with reducing greenhouse gases and the specific factors that affect cost, and to formulate measures toward the adoption of technologies that are important for achieving carbon neutrality.

To date, there have been numerous studies assessing the costs associated with reducing greenhouse gases[1-3]. In previous studies, the trend had been to use the marginal abatement costs (MAC) of CO_2, which is the cost required to reduce an additional 1 t of CO_2, as one of the evaluation indices for cost. On the other hand, while MAC is estimated through the shadow price of the CO_2 emission constraint formula in the optimization model, the determining mechanism is not simple, and the factors determining MAC are not necessarily clear.

In light of that, this study examines the evaluation methods for MAC using a technology selection model in order to evaluate the costs associated with reducing greenhouse gases and its determining factors more clearly. In this study, two methods are considered as methods for estimating MAC: evaluation through the shadow price of CO_2 emissions, and a differential calculation method that performs optimization calculations twice before and after making infinitesimal changes to the CO_2 emission constraint. The MAC in each case and the factors determining MAC are then identified.

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2. Method

2.1 Technology Selection Model

In this study, the technology selection model developed by Otsuki et al[4] and Kawakami et al[5], which targets Japan's overall energy system, was used as the basis for conducting the evaluation. This model uses the capital cost of each energy technology as the input value, and based on the linear programming method, generates as output the amount of energy technology introduced that minimizes the cost of the overall energy system under various constraints related to emissions constraint, power demand and supply, and other factors. Approximately 300 technologies were identified for selection in the respective sectors of energy transition, industry, transport, household, and business, and the following flow was established: from primary energy supply to energy transition, secondary energy, inter-regional transportation, and final consumption (Figure 1).

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This model takes the sum of technology k, capital cost $ivc_{k,y}$ [USD /year]at point y [year], fuel cost $voc_{k,y}$ [USD/year], O&M cost $foc_{k,y}$ [USD /year], and energy procurement cost $flc_{k,y}$ [USD /year] as the total cost $ac_{k,y}$ [USD /year], and calculates the amount of each technology introduced $x_{k,y}$ so as to minimize the discounted cumulative cost through the objective function shown in Formula (1). All prices were treated as real prices of 2019. In this study, the final fiscal year y_e was taken to be 2080, and calculations were made for the interim years of 2019, 2030, 2040, 2050, and 2065. While the main target year of analysis was 2050, calculations were performed up to 2080 in consideration of the end effect.

$$min \sum_{k=1}^{n} \sum_{y}^{y_e} ac_{k,y} \cdot \left(\sum\nolimits_{y_2 \in YEAR_y} (1+DR)^{BY-y_2} \right) \tag{1}$$

$$ac_{k,y} = x_{k,y} \cdot \left(ivc_{k,y} + foc_{k,y} + voc_{k,y} + flc_{k,y} \right) \tag{2}$$

In the formula, $YEARy$ is the set of years represented by the point in time y (for example, 2030 is 2026‐2035), and BY is the first year of analysis (=2019).

The representative constraints include CO_2 emission constraints, the balance of power demand and supply at each hour, the upper limit constraints on the amount of each type of power introduced depending on the location conditions, reserve capacity constraints, and load-following constraints, among others[4].

This study describes the linear model using Mosel and obtains a solution by using the solver Xpress.

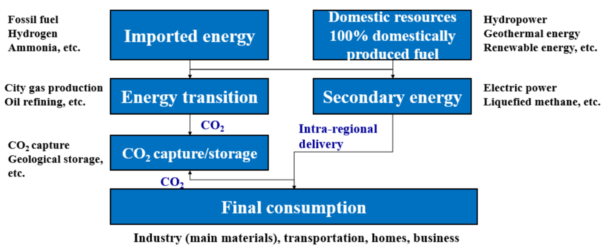

Figure 1 Modeled energy system

2.2 MAC Evaluation

In this study, MAC was estimated using two methods. The first method, like methods frequently used in previous research, takes the shadow price of the CO2 emission constraint formula obtained as the optimal solution of the dual problem, as MAC. The formulation of this is shown as Formula (3). In this method, while it is possible to obtain MAC through one optimization calculation, it is difficult to identify the specific factors that determine MAC.

$$MAC_y = \frac{\partial}{\partial CO_2} \sum_{k=1}^{n} ac_{k,y} \tag{3}$$

The second method performs the optimization calculation twice before and after infinitesimal changes are made to CO_2 emission constraints, and evaluates MAC based on the infinitesimal change $\Delta x_{k,y}$ of the amount of each technology introduced in the results of the two calculations, and the various costs given in the assumptions. This method is taken as the differential calculation method in this study, and its formulation is shown as Formula (4). While the differential calculation method takes twice the calculation time in comparison with the method of calculating the shadow price of CO_2 emission constraints, it is able to identify the specific technologies that determine MAC.

$$MAC_y = \sum_{k=1}^{n} \frac{\partial x_{k,y}}{\partial CO_2} \cdot \left(ivc_{k,y} + foc_{k,y} + voc_{k,y} + flc_{k,y} \right) \tag{4}$$

3. Assumptions

3.1 Case setting

Taking into account the following elements that are assumed to affect MAC—whether or not nuclear power is used, CO_2 storage capacity through CCS, and fuel prices, this study sets out the four scenarios shown in Table 1: (1) Base scenario, (2) No nuclear scenario, (3) Low CCS scenario, and (4) High fuel price scenario.

In (1) base scenario, it was assumed that only existing nuclear power plants and those under construction will operate for 60 years, and that 23 reactors (23.7 GW) will remain in 2050. Only domestic storage was considered for CO_2 storage capacity through CCS, and the median value was set as 180 million t-CO_2/year, taking reference from the domestic storage capacity of 120‐240 million t-CO_2/year set out in Japan's CCS Long-term Road Map Intermediate Summary[6]. Fuel prices were set based on the Sustainable Development Scenario (SDS) in the International Energy Agency's (IEA) World Energy Outlook 2021[7] (solid lines shown in Figure 2).

Next, the (2) no nuclear scenario was assumed to be the scenario in which no nuclear power was used, based on the base scenario. In the (3) low CCS scenario, it was assumed that adequate CO_2 storage capacity cannot be secured due to geographical factors and other reasons, so CO_2 storage capacity was set at 60 million t/year, equivalent to one-third that of the base scenario. In (4) high fuel price scenario, it was assumed that fuel prices as of 2022 continue to increase till 2030, reaching twice the fuel price in SDS by 2050 (dotted lines shown in Figure 2).

In all scenarios, hydrogen import price in 2050 was assumed to be 0.32 USD¢/ Nm^3-H_2, ammonia fuel price was assumed to be 447 USD/t, and the import price of synthetic methane was assumed to be 157 USD/toe.

Table 1 Case setting

	Nuclear power	CO_2 storage capacity	Fuel price
(1) Base	Yes	180 million t/year	Based on WEO 2021
(2) No nuclear	No		
(3) Low CCS	Yes	60 million t/year	
(4) High fuel price		180 million t/year	Equivalent to twice that of WEO 2021 (2050)

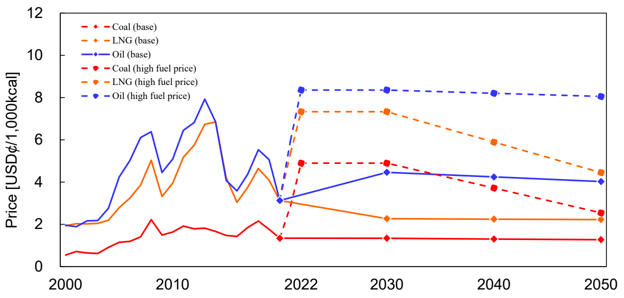

Figure 2 Assumptions of primary energy fuel prices [USD¢/1,000 kcal]

3.2 Energy Service Demand

A total of 37 types of energy service demand (hereafter, "service demand") were considered: industry (steel, chemicals, cement, pulp and paper, other industries), transport (passenger, cargo), household (lights, cooling, heating, cooking), and business (lighting, cooling, heating, cooking). In the model, service demand in each department was further subdivided. For example, transport (passenger) was subdivided into five categories: passenger cars, buses, ships, rail, and aircraft.

Service demand to 2080 was estimated recursively based on forecasts of per capita GDP and other factors. Taking the example of steel production, for instance, GDP by industry was used as the explanatory variable to predict steel production volume into the future (horizontally after 2030). Table 2 shows the estimation results for the representative forms of service demand. GDP and population in the table are explanatory variables for the regressive prediction of some service demand, and are shown for reference.

Electricity demand and heat demand were determined endogenously through the amount introduced for each technology selected to fulfill the respective forms of service demand. For example, in the case where an electric furnace is selected for steel production, electricity demand in the model increases accordingly.

Table 2 Main types of service demand and macro assumptions

	Unit	2019	2030	2050
Steel production volume	Million t	98.4	90.4	90.4
Ethylene production volume	Million t	6.28	5.70	6.20
Cement production volume	Million t	58.1	5.56	5.96
Paper production volume	Million t	25.0	21.6	23.2
Passenger car transport volume	Billion people・km	90.96	83.02	68.74
Truck transport volume	Billion t・km	21.54	23.16	27.68
Real GDP (2015 as base year)	Trillion USD	5.51	6.65	9.30
Population	billion people	1.26	1.18	1.03

3.3 CO_2 Capture and Storage Technologies

For CO_2 capture, pre-combustion and post-combustion capture, and direct air capture (DAC) were used in this study. Pre-combustion capture was assumed to be installed in IGCC or coal gasifier, etc. based on the physical absorption method, while post-combustion capture was assumed to be installed in gas-fired power generators or blast furnaces, etc. based on the solid absorbent method. For all capture technologies, both the cases of installation in existing plants, assumed to be modified, and installation in new plants, were considered.

Total capital cost of CO_2 capture and O&M costs in 2050 were assumed to be 9.52 USD/(t-CO_2/year) (pre-combustion capture), 7.81 USD/(t-CO_2/year) (post-combustion capture), and 41.1 USD (t-CO_2/year) (DAC) (including CO_2 compression and liquefaction costs), taking reference from various sources[8), 9)]. Power consumption in CO_2 capture was assumed to be 355 kWh/t-CO_2

(pre-combustion capture), 184 kWh/t-CO_2 (post-combustion capture), and 1,316 kWh/t-CO_2 (DAC). CO2 storage cost, including CO2 transport cost (domestic transport, 300 km) was assumed to be 49.6 USD/t-CO_2, taking reference from various sources[10), 11)].

3.4 Upper Limit of Solar and Wind Power Installation

The capital costs of solar and wind power generation were estimated through the learning curve based on the premise that production costs fall with cumulative production volume, based on the capital costs estimated by the 2021 Power Generation Cost Verification Working Group / Procurement Price Calculation Committee, etc. With regard to solar power generation, capital costs were ranked in three tiers in consideration that capital costs vary depending on the scale of installation, and taking reference from the top 15%, 50%, and bottom 15% of the capital costs set out by the Procurement Price Calculation Committee.

The values for capital costs in 2050 were assumed to be 1,060–1,440 USD/kW (ground-mounted solar power system), 1,270–2,370 USD/kW (solar power system installed in buildings), 3,020 USD/kW (onshore wind power system), 3,360 USD/kW (fixed-bottom offshore wind power system), 4,370 USD/kW (floating-type offshore wind power system).

The upper limit on the amount of ground-mounted solar power and wind power introduced was estimated using GIS data as of April 2021, following the reference sources[12),13)] and under the premise that power generation facilities are installed in places where the impact on the natural environment is considered to be small, such as weed land, bamboo-covered land, bare land, and desolate farmland that is difficult to regenerate, and in seas that are targeted as Project Promoting Zones based on the Act on Promoting the Utilization of Sea Areas for the Development of Marine Renewable Energy Power Generation Facilities, and assumed to be 65.4 GW for ground-mounted solar power systems, 23.4 GW for offshore wind power systems, and 405.1 GW for onshore wind power systems. The amount introduced for solar power generation systems installed on buildings was assumed to be 166.9 GW for systems installed on detached houses and 288.3 GW for systems installed on other buildings, taking reference from the Ministry of the Environment[14)].

4. Results of Technology Selection in 2050

4.1 Passenger Car Transport

To verify the status of energy technology introduced in each scenario, the passenger car transport volume, which is one of the forms of service demand, was taken as one example. The number of passenger cars owned in 2050 is shown in Figure 3.

The passenger cars selected for this study were gasoline vehicles, plug-in hybrid vehicles, hybrid vehicles, electric vehicles, diesel vehicles, fuel cell vehicles, biofuel vehicles, and CNG vehicles. However, assuming that there is a given number of users travelling long distances, for electric vehicles which are assumed to have a short cruising distance and the amount introduced was limited to no more than 80% of all vehicle types.

From among these vehicles, gasoline vehicles (costing 21,200 USD per vehicle) or electric vehicles (costing 22,400 thousand USD per vehicle) were selected based on the premise of using DAC, taking into account power prices (marginal cost of electric power under the model) that vary depending on car prices, fuel prices, region, time period, and other factors.

Focusing on the differences between each scenario, in the low CCS scenario, the results showed that more electric vehicles are introduced in comparison with the other scenarios and greater electrification is carried out. This is because while it is more cost-effective to combine DAC with gasoline vehicles than with electric vehicles under the conditions of the assumed car prices, fuel prices, and marginal cost of power in 2050 which is the model solution (low CCS scenario: Region/Annual average of 16.3 USD¢/kWh), electric vehicles that have a relatively higher cost are introduced due to the strict constraints of CO_2 storage capacity in the low CCS scenario.

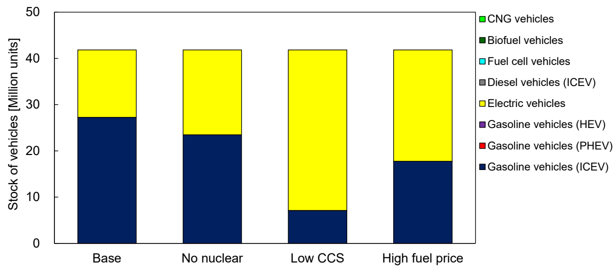

Figure 3 Number of passenger cars owned in 2050 [Million units]

4.2 Power Sector

Figure 4 shows the amount of power generated in 2050. The results show that in the base scenario, approximately 50% of all power generated is covered by renewable energy, while the remaining 50% is covered by nuclear power, gas-fired thermal power with CCS, and ammonia/hydrogen thermal power.

In the no nuclear scenario, more offshore wind power is introduced than nuclear power in comparison with the base scenario, and renewable energy ratio is approximately 70%. In the low CCS scenario, the introduction of DAC is suppressed due to CO_2 storage capacity constraints, and power consumption using DAC is reduced. For this reason, overall power generated is lower than in the other scenarios. Moreover, as CO_2 storage by CCS installed in gas-fired thermal power is also constrained, more ammonia/hydrogen thermal power is introduced in place of thermal power with CCS. In the high fuel price scenario, more offshore wind power is introduced in place of some gas-fired thermal power, and renewable energy ratio is approximately 70%.

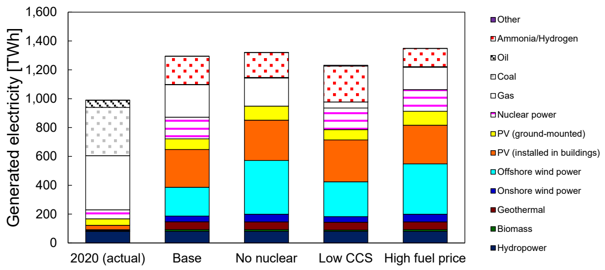

Figure 4 Generated electricity in 2050 [TWh]

4.3 CO_2 Storage Capacity

Figure 5 shows the breakdown of CO_2 storage volume in 2050. In the same figure, the red line shows the upper limit of CO_2 storage capacity given as the constraint condition, showing that in all scenarios, CO_2 is stored up to the upper limit of storage capacity.

In the base scenario, no nuclear scenario, and high fuel price scenario, about half of all CO_2 stored is captured through DAC, and CO_2 in the transport sector and CO_2 from boilers in the industrial sector, etc. are captured through DAC.

In the low CCS scenario, CO_2 storage primarily from gas-fired thermal power and biomass thermal power are prioritized, and the ratio of DAC to all CO_2 storage is relatively smaller compared to the other scenarios.

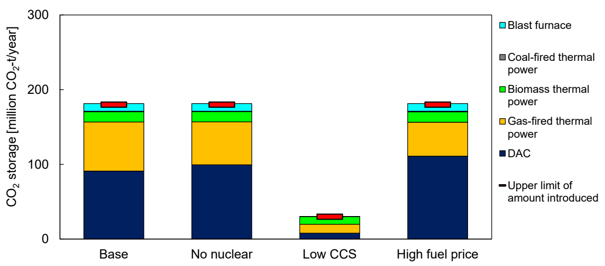

Figure 5 Breakdown of CO_2 storage in 2050 [million CO_2-t/year]

5. MAC Evaluation Results

5.1 Shadow Prices of CO_2 Emission Constraints

Figure 6 shows the changes in the shadow prices of CO_2 emission constraints when CO_2 emission constraints are assumed to be 680 million t-CO_2 in 2030 (46% lower than FY2013), 340 million t-CO_2 in 2040, and 0 t-CO_2 in 2050, across the four hypothetical scenarios.

The shadow price of CO_2 emission constraints in the base scenario and no nuclear scenario was estimated to be 574 USD/t-CO_2. Shadow price in the low CCS scenario was 743 USD/ t-CO_2, the highest among the four scenarios examined. Shadow price in the high fuel price scenario was the lowest among all the scenarios at 478 USD/ t-CO_2. However, the costs for additional reduction of CO_2 seem small due to the smaller cost difference between conventional fossil fuel-based technologies that discharge CO_2, and low-carbon technologies.

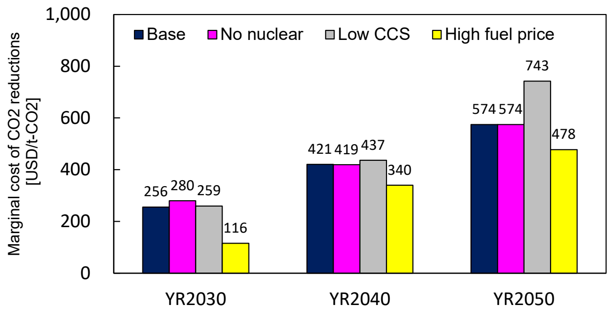

Figure 6 Shadow prices of CO_2 emission constraints [USD/ t-CO_2]

5.2 Factors Determining MAC in the Base Scenario

Two types of calculations were performed for the base scenario: the case in which CO_2 emission constraints in 2050 was assumed to be 0 t-CO_2, and that in which it was assumed to be 1,000 t-CO_2. Based on the differential in the amount of each type of technology introduced in the respective scenarios, an analysis was carried out on the facilities, costs, etc. that are additionally introduced in the reduction of the final 1,000 t-CO_2 to achieve zero CO_2 emissions (Figure 7).

The result of the analysis confirmed that in the base scenario, an additional 14 million toe of synthetic methane is imported to achieve the additional reduction of the final 1,000 t-CO_2. The additional combustion cost for this synthetic methane, divided by the amount of CO_2 reduction (1,000 t-CO_2), is 888 USD/ t-CO_2. The amount of LNG imported falls as a result of this additional import of synthetic methane, and LNG import costs also fall accordingly. Furthermore, it was confirmed that the amount of DAC introduced that consumes power also falls due to the fall in the consumption of LNG that discharges CO_2 into the atmosphere, and the amount of ammonia fuel imported for power generation purposes also falls. In this way, while synthetic methane is additionally introduced to discharge the final 1,000 t-CO_2 in the base scenario, MAC is determined through the interaction of various technologies.

Based on this, the cost after subtracting the decrease in these costs from the increase in synthetic methane fuel costs was 574 USD/t-CO_2, which generally matched the shadow price of the CO_2 emission constraints evaluated in Section 5.1. Hence, the differential calculation method examined in this study is effective in clarifying the factors determining MAC.

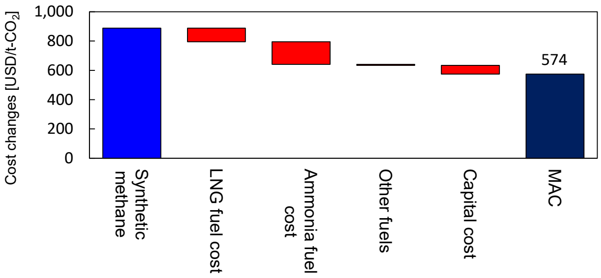

Figure 7 Changes in technology introduced and fuel costs in the differential calculation method (base scenario, 2050) [USD/t-CO_2]

5.3 Differences in Determining Factors of MAC in Each Scenario

To see the differences in the determining factors of MAC in each scenario, an analysis was carried out on the facilities, etc. additionally introduced to achieve the final 1,000 t-CO_2 reduction in the low CCS scenario, for which MAC was the highest in 2050 (Figure 8).

The result of the analysis confirmed that primarily DAC is introduced additionally (922 t-CO_2) to achieve an additional reduction of 1,000 t-CO_2 in the low CCS scenario. However, as the CO_2 storage capacity shown in Figure 5 has reached the upper limit, in order to store CO_2 through DAC under the model, CO_2 storage volume is reduced through gas-fired thermal power with CCS, and gas-fired thermal power with CCS is replaced by ammonia thermal power. It was also confirmed that reduction of the remaining 78 t-CO_2 is achieved through the introduction of electric vehicles and other means. Based on this, the value obtained by subtracting the cost of gas-fired thermal power, etc. from the additional costs of DAC and ammonia thermal power, etc. was 728 USD/t-CO_2, which generally matched the shadow price of the CO_2 emission constraints.

Here, focusing on the amount of natural gas supplied in primary energy supply, it would be 45 Mtoe in the base scenario, of which CO_2 is captured during combustion through CCS for 16 Mtoe, and through DAC for the remaining 29 Mtoe. On the other hand, the amount of natural gas supplied in the low CCS scenario is 6 Mtoe, and CO_2 is captured during combustion through CCS for almost all of the natural gas. The consumption of natural gas is suppressed in the low CCS scenario and room for CO_2 reductions through synthetic methane is limited. For this reason, it is supposed DAC is introduced instead of synthetic methane to achieve the final 1,000 t-CO_2 of reduction.

Based on the same method as used so far, the factors determining MAC across all four hypothetical scenarios were analyzed, and the results are shown in Figure 9. The results showed that while synthetic methane is additionally imported in the base scenario and no nuclear scenario to achieve the final 1,000 t-CO_2 reduction, cost increases significantly in the low CCS scenario and high fuel price scenario due to an increase in the amount of ammonia fuel imported. The identification of detailed factors for this increase in the amount of ammonia fuel is an issue to be reviewed in the future, and is believed to be related to DAC as mentioned previously.

In the high fuel price scenario as well, the increase in the amount of ammonia fuel is a factor determining MAC and is also believed to be related to the additional introduction of DAC (698 t-CO_2). In this scenario, the introduction of renewable energy in place of gas-fired thermal power advances due to soaring fuel prices (Figure 4), and the price of power consumed through DAC is reduced. The regional/annual average marginal cost of power in this scenario was 16.1 USD¢/kWh, which was the lowest in comparison with the other scenarios (base scenario: 17.0 USD¢/kWh, no nuclear scenario: 16.6 USD¢/kWh, low CCS scenario: 16.3 USD¢/kWh). For this reason, to achieve the last 1,000 t reduction, it is more economical to additionally introduce DAC rather than import synthetic methane, and it is inferred that DAC is a factor determining MAC.

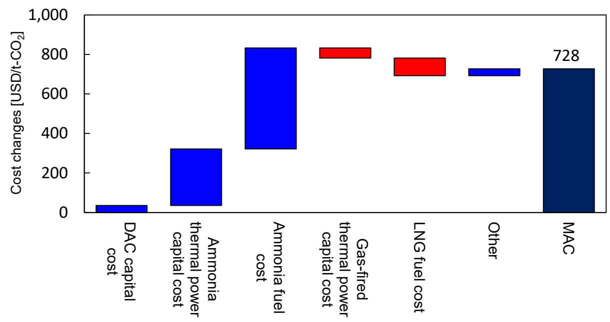

Figure 8 Changes in technology introduced and fuel costs in the differential calculation method (low CCS scenario, 2050) [USD /t-CO_2]

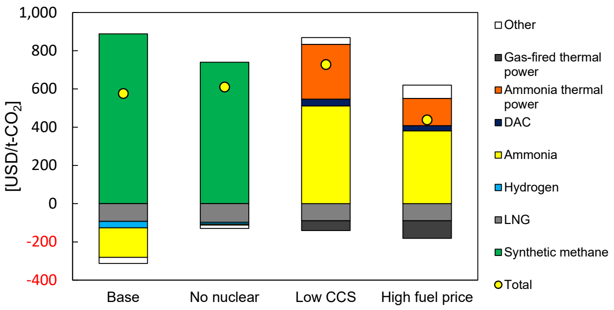

Figure 9 Analysis of factors determining MAC in 2050 [USD/t-CO_2]

6. Conclusion

This used the differential calculation method to evaluate the factors determining MAC in the case where net CO_2 emissions are assumed to be 0 t-CO_2 in 2050. This clarifies the factors determining MAC more effectively compared to the method of estimating MAC through the shadow prices of CO_2 emission constraints. Under the specific scenarios established in this study, it was confirmed that synthetic methane, DAC, etc. are factors determining MAC. However, to reduce MAC toward the realization of carbon neutrality, it is also helpful to consider reducing infrastructural costs and power costs associated with technologies that determine MAC, in addition to the cost reduction from such technologies. Moreover, for technologies with particularly high MAC, it may also be necessary to review policies that promote technological innovation, such as R&D.

In this study, while the MAC for achieving 0 t-CO_2 emissions in 2050 and its determining factors were identified, evaluation based on the differences in target years and CO_2 emission constraints is an issue. Moreover, clarifying the hierarchical relationship of technology introduction costs, estimated based on assumptions and model calculation results, will also be important in the future. Through these studies, we expect to be able to identify the important technologies corresponding to the levels of CO_2 emission reductions.

In policy evaluations, etc. to date have also referred to evaluations using cost indicators such as MAC, it is important to clarify the calculation process. This study anticipates that this will contribute to the review of measures toward the promotion of important technologies in the large-scale reduction of CO_2 as well as concrete measures to reduce MAC.

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