A Study on the Effects of Negative Emission Technologies on Alleviating the CO_2 Abatement Cost

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Abstract

As global attention increasingly turns to a decarbonized energy system, the government of Japan has set a long-term greenhouse gas reduction target of realizing a carbon-neutral energy system as soon as possible in the second half of the century. Since some energy sectors such as industry and transport are heavily dependent on fossil fuels and cannot easily switch to electricity, negative emission technologies such as bio-energy with carbon capture and storage (BECCS) and CO_2 direct air capture and storage (DACS) have attracted attention as a means of accomplishing carbon neutrality. This paper presents the effects of negative emission technologies on alleviating the CO_2 abatement cost using a bottom-up energy system optimization model which incorporates a high-temporal-resolution power sector. Seven scenarios for a decarbonized energy system ranging from 80% to 100% CO_2 reduction in Japan are modeled for 2050. Simulation results reveal that the use of BECCS could alleviate the CO_2 marginal abatement cost in 2050 by 10,000 yen per tonne of CO_2 in the 80% reduction scenario and that the effect would grow as severer decarbonization targets are imposed. Furthermore, it is found that to reduce CO_2 by more than 90%, it is essential to install negative emission technologies.

Keywords: BECCS, DACS, Battery Installation, Variable Renewables, Energy System Optimization Model

1. Introduction

Japan has presented a goal of reaching carbon neutrality as soon as possible in the second half of this century under its Long-Term Strategy under the Paris Agreement released in 2019, and in October 2020, Prime Minister Suga declared a goal of achieving net-zero greenhouse gas emissions (GHG) by 2050. While Japan is heading toward large-scale decarbonization of its energy system, abandoning fossil fuels is not easy for sectors such as transport (particularly aviation) and parts of industry (such as steel). To achieve carbon neutrality while allowing CO_2 emissions from those sectors where it is extremely difficult to eliminate emissions, it is essential to introduce negative emission technologies such as biomass-fired power with CCS (BECCS). Thus, it is important to quantitatively analyze their roles in pursuing carbon neutrality of Japan's energy system.

In addition to being a negative emission technology, another notable feature of BECCS is that it is a thermal power source that allows dispatchable operation and provides synchronous inertia and can therefore contribute to power system stability when large amounts of variable renewable electricity (VRE) sources are introduced in the future. However, steam power generation, a widely-used generation technology for solid biomass fuels, has a somewhat lower output adjustment capability compared to gas turbine generation. In analyzing the role of BECCS in decarbonizing the energy system, it is important to consider these characteristics of BECCS as a thermal power source and its ability to replace and/or complement other zero-emission power sources, and vice versa. Using an energy system optimization model suited for this purpose, this study analyzes the roles of BECCS and other negative emission technologies in achieving the reduction target and alleviating the abatement cost as Japan pursues large-scale decarbonization of its energy system by 2050. Previous studies on BECCS as a decarbonization technology include an analysis on Japan using a TIMES model with a relatively simplified power sector[1)], and analysis on the feasibility of achieving a carbon-neutral power system in Europe, using a mixed integer programming model and targeting only the power sector[2)]. The novelty of this study is that it analyzes the large-scale decarbonization, including 2050 carbon neutrality, of Japan focusing on negative emission technologies using an energy system optimization model that incorporates a highly detailed power sector, as Japan becomes increasingly committed to reaching carbon neutrality in reality.

2. Analytical Framework

This analysis used an energy system optimization model[3),4)], which the author has developed and used in previous studies, with a more detailed biomass power generation model incorporated for this analysis. It is a dynamic linear programming model that minimizes the discounted total energy system costs, which is the objective function, over the analysis period under multiple constraints. The power sector and electrolyzed hydrogen supply were modeled with an hourly time resolution (8,760 time slices per year). The analysis was conducted for the period up to 2050

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(at 5-year intervals starting from 2015) for 5 regions (Hokkaido, Tohoku, Kanto, West Japan, and Kyushu).

One type of steam power generation was adopted for biomass thermal power assuming the use of solid fuel, and, as with other thermal power technologies, the minimum output constraint, annual maintenance scheduling, load-following capability constraint, and percentage of DSS operation, etc. were taken into account. Since the total CO_2 emissions from biomass over its lifecycle are considered to be neutral regardless of combustion, the emissions from biomass would be net negative by collecting and storing the emissions from combustion.

Other negative emission technologies such as the combination of direct air capture (DAC) and storage (hereafter, DACS) were also considered. Furthermore, CCU technologies such as FT synthesis, methanation, and methanol production were considered though they are not negative emission technologies. CCU technologies for non-energy use were not considered.

3. Assumptions

3.1 Assumptions about biomass power

The following assumptions were made regarding the performance of the biomass power technology based on Reference 2 and others: maximum load-following capability (versus rated output) of 36% hour^{-1}, generator-end efficiency of 38%, minimum output rate of 30% and DSS operation of 0%. Generation costs and the service life of facilities were set based on Reference 5. The cost for domestic biomass supply was set based on Reference 6, and the maximum amount of supply was set to 90 PJ year^{-1}. The cost for imported biomass supply was set to 831 yen/GJ^{-1} 7) and the maximum amount of supply to 406 PJ year^{-1}. This maximum amount is equivalent to 24 million tonnes8), which equals the global trade quantity of wood pellets in 2018. We assumed that this amount of wood pellets would be available in Japan by 2050 because wood pellet production is growing and supplies are likely to increase as demand rises, and considering that other biomass fuels also exist. See Reference 4 for other assumptions for the power sector (such as the specifications of power generation and storage technologies, maximum new VRE capacities, transmission line capacity, and constraints on the use of nuclear power).

3.2 Other assumptions

For DAC, another negative emission technology, the capital expenditure for DAC plants for collecting 1 million tonnes of CO_2 (2050) was estimated about US$780 million based on the energy intensity and costs described in Reference 9. Natural gas and unutilized heat energy were specified as the heat sources for collecting CO_2. The CO_2 from burning the natural gas used as the heat source will also be collected.

We assumed that 95% of the CO_2 from power plants and the industry sector will be collected, and set the CO_2 storage potential in 2050 to 91 million t-CO_2/year10) as the reference case. For assumptions on other promising key decarbonization technologies such as imported hydrogen, hydrogen production by electrolysis, hydrogen storage, and methanation, see Reference 4. In this paper, the maximum amount of ammonia import was set to half the amount set for hydrogen (under Japan's basic hydrogen strategy) in calorific terms (30 million tonnes).

3.3 Scenarios

Seven scenarios were formulated as shown in **Table 1**. CO_2 constraints were applied only to energy-related emissions, and reduction rates by 2050 were set to 80%, 90%, and 100% from FY2013 levels. The 2030 emissions were set to the level indicated in the Long-Term Energy Supply-Demand Outlook and the emissions for each year up to 2050 were set through linear interpolation. Under each CO_2 target scenario, the impact of using or not using BECCS on technological options and CO_2 abatement cost was analyzed. For the 100% CO_2 reduction scenarios, a scenario with a higher annual CO_2 storage potential (150 million tonnes) in 2050 was also formulated.

Table 1 Scenarios

Scenario name	CO_2 reduction rate	Net negative emission technology	Maximum CO_2 strorage capacity
C80	80%	BECCS, DACS	91 Mt yr^{-1}
C80_NoBECCS	80%	DACS	91 Mt yr^{-1}
C90	90%	BECCS, DACS	91 Mt yr^{-1}
C90_NoBECCS	90%	DACS	91 Mt yr^{-1}
C100	100%	BECCS, DACS	91 Mt yr^{-1}
C100_NoBECCS	100%	DACS	91 Mt yr^{-1}
C100_CCS+	100%	BECCS, DACS	150 Mt yr^{-1}

4. Results

4.1 Decarbonization of the power sector

To reduce CO_2 emissions by at least 80% by 2050, it is important to reduce the CO_2 emissions from the power sector by accelerating its progress toward zero or negative emissions while advancing electrification in the final demand sector. However, a feasible solution for reaching carbon neutrality (a 100% reduction of CO_2) was not obtained under the reference CO_2 storage potential regardless of the use of BECCS, and was achieved only under the higher storage potential scenario.

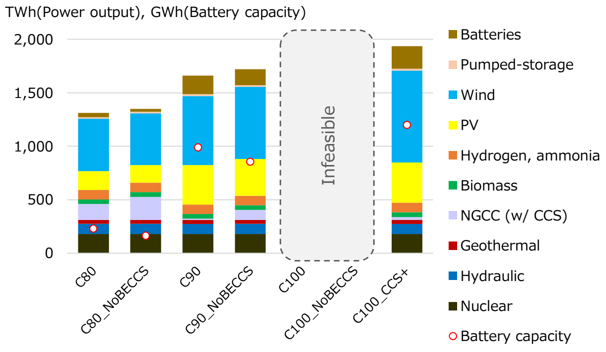


Figure 1 Power output and battery introduction (2050)

For 80% CO_2 reduction scenarios, the share of natural gas-fired thermal power with CCS (NGCC) will exceed 10% (16% for the NoBECCS scenario), and, along with biomass thermal power and ammonia-fired thermal power, decarbonized thermal power with adjustment capability will account for approximately 25% of the output in 2050 (**Figure 1**). Meanwhile, coal-fired thermal power with CCS, despite having low generation costs, will not be selected from the perspective of using the limited storage potential efficiently, since it has a small output relative to the amount of CO_2 collected. Since even a small amount of uncollected CO_2 emissions will become impermissible as CO_2 reduction requirements become stricter, the output of NGCC with CCS will start to decrease and VRE power sources will increase instead. For the at least 90% reduction scenarios, the share of VRE power will surpass 60%, making it necessary to introduce a massive battery capacity of approx. 1000 GWh for adjusting power supply and demand because of limited thermal power operation. However, since it is possible to collect 100% of CO_2 from thermal power if costs permit, further analysis should be conducted regarding the pace of increase in this cost and its impact on the operation of thermal power with CCS in the context of large-scale decarbonization.

In all scenarios, biomass thermal power will be used to the limit of fuel supply availability. For other decarbonized thermal power sources, ammonia power will also be developed to the limit of fuel supply availability, while hydrogen will not be consumed for generation but will be used instead for FCV and FT synthesis in the final demand sector, thus reducing CO_2 in that sector (**Figure 2**). Hydrogen has a relatively high fuel cost, which hinders its widespread use in the power sector where it must compete with other power sources. However, its use will be economically rational in the final demand sector where the means for large-scale CO_2 reduction are limited. Note that hydrogen production by electrolysis will hardly be introduced since losses associated with conversion to hydrogen must be avoided as electricity demand rises driven by the need to accelerate electrification in the final demand sector.

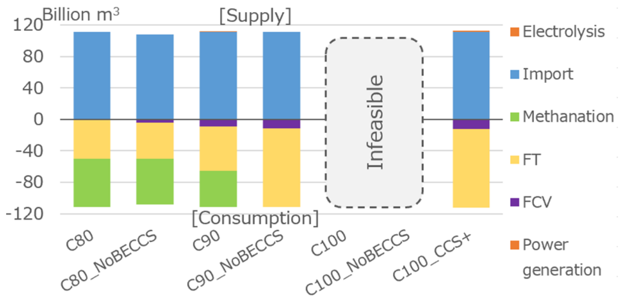
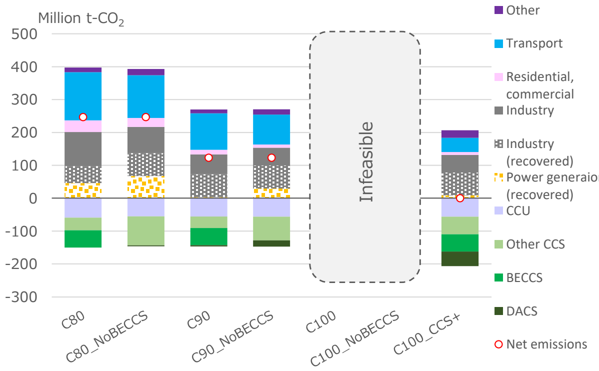
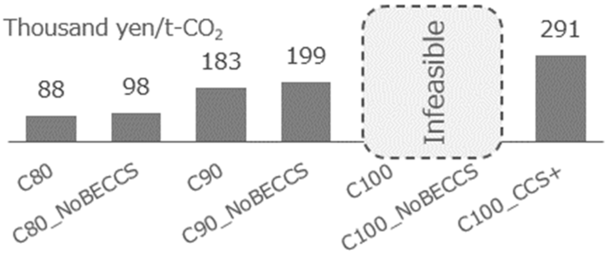


Figure 2 Supply-demand balance of hydrogen



(a) CO_2 balance



(b) CO_2 marginal abatement cost

Figure 3 CO_2 balance and marginal abatement cost (2050)

4.2 CO_2 balance and marginal abatement cost

The CO_2 balance and marginal CO_2 abatement cost in 2050 are shown for each scenario in **Figure 3**. In all scenarios, industry and transport are the key CO_2 emitter sectors, suggesting the relative difficulty of decarbonizing those sectors. In contrast, the residential and commercial sector, which is relatively easy to electrify, will be electrified nearly 100% and will account for a very small portion of CO_2 emissions.

CO_2 emissions will decrease even in hard-to-decarbonize sectors through electrification and energy conservation as the CO_2 reduction target rises, but there are limits. To overcome these limits, it is necessary to introduce negative emission technologies such as BECCS and DACS. If available, BECCS will reduce CO_2 by a net 50 million tonnes even for the reduction target of 80%. It is suggested, however, that this reduction can be achieved without negative emission technologies for the 80% reduction scenarios, since the introduction of DACS will be limited even if BECCS is not available. However, these technologies will be indispensable for reduction rates of over 90%. Without BECCS, achieving a 90% reduction involves reducing approx. 20 million tonnes of CO_2 in net terms using DACS, which is relatively more costly. For the 100% reduction scenarios, the amount of net CO_2 reduction from these technologies will amount to almost 100 million tonnes.

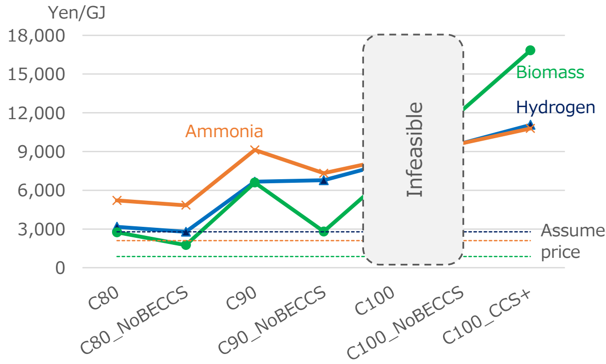


Figure 4 Implicit value of each decarbonized energy in 2050 (Assumed prices + shadow prices on limited supplies)

The amount of CO_2 used for CCU will be around 55 million tonnes for all scenarios, the primary purpose being decarbonizing the transport sector through FT synthesis. The amount used for CCU will be the same for all scenarios presumably because of limits in the availability of hydrogen.

It has been suggested that large-scale decarbonization of energy systems, including achieving carbon neutrality, is technically possible by introducing negative emission technologies, but this would inevitably impose a heavy economic burden. The marginal CO_2 abatement cost in 2050 would be almost 100,000 yen/t-CO_2 for the 80% reduction scenarios, almost 200,000 yen/tonne for 90% reduction, and almost 300,000 yen/tonne for 100% reduction. The results for the 80% and 90% scenarios suggest that using BECCS has a marginal cost reduction effect of approximately 10,000–15,000 yen/tonne and that the effect grows with the CO_2 reduction rate. This point is also suggested by the shadow prices associated with the restrictions in the amount of biomass fuel imports. **Figure 4** indicates the implicit value of imported hydrogen, imported ammonia, and imported biomass in 2050, calculated based on the shadow prices of the energies associated with the limits in their supply and their set import prices. The value of imported biomass is lower than that of ammonia for CO_2 reduction rates of 80% and 90% due to the low generation efficiency of biomass thermal power. However, since negative emission technologies will be indispensable for achieving carbon neutrality, if BECCS is available, the potential value of imported biomass will be about 55% higher than that of hydrogen and ammonia for the same scenarios.

5. Conclusion

This paper discussed the extent to which BECCS and other negative emission technologies would be introduced to reduce CO_2 by 80–100% by 2050 in Japan and their impact on the alleviation of CO_2 abatement cost, using an energy system optimization model which incorporates a high-temporal-resolution power sector. The results showed that introducing BECCS would reduce the marginal CO_2 abatement cost by approximately 10,000 yen/tonne in the 80% reduction scenario. It was suggested that negative emission technologies such as BECCS and DACS are indispensable for achieving reduction rates of 90% and higher. To achieve carbon neutrality, around 150 million tonnes of CO_2 must be stored, in addition to around 100 million tonnes of negative emissions using negative emission technologies. Accordingly, the value of biomass energy used for BECCS will exceed those of hydrogen and ammonia. The tasks going forward include considering biomass gas GTCC generation, studying the import price of biomass and the amount available for import, verifying CO_2 storage potential in and outside Japan, and analyzing the impact of high CO_2 abatement cost on the economy.

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