Maximum Limit of CO₂ Reductions by Windmills in the Electricity and Heat Supply System: Analysis in Hokkaido Region in Japan

by

Kengo Suzuki*, Daishi Tenjimbayashi, Yutaka Tabe, Takemi Chikahisa,

*Assistant professor, Division of Energy and Environmental Systems, Graduate School of Engineering, Hokkaido University, North 13, West 8, Kita-ku, Sapporo, Hokkaido, 060-8628, Japan

Phone: +81-11-706-6334/Fax: +81-11-706-6333/Email: kengosuzuki@eng.hokudai.ac.jp

Abstract

The large-scale provision of windmills is a key to reduce the CO₂ emissions, and the utilization of excess power output by battery storage and electric heating can contribute to the effective use of windmills. This study targets the electricity and heat supply system of Hokkaido, the largest and northernmost prefecture in Japan, and investigates how much percentages of CO₂ emissions can be reduced by installing the onshore wind power with the effective use of windmills. As the index of effectiveness of windmills usage, the carbon-based effective capacity factor was defined as the rate of actual CO₂ reduction by windmills against the theoretically maximum CO₂ reduction. The electricity and heat supply system model is developed for the study. When there is no limitation to the CO₂ emissions, the electricity demand is assumed to be satisfied with 10% of hydropower and 90% of gas generated power, and all the heat demand assumed to be satisfied with heating oil (base energy mix). The results show that the 6.0 Mt of CO₂, about 55% of total CO₂ emissions from power grid in the base energy mix, is reduced with the effective use of windmills. Battery storage and electric heating can raise the effectiveness of windmills usage, but a part of excess power is wasted as the CO₂ reduction target becomes higher. The combined use of battery storage and electric heating can realize more effective use of excess power of windmills than their separate use. The 9.0 Mt of CO₂, 82% of the emissions from electricity grid and 54% of the total emissions from electricity and heat supply system in the base energy mix, can be reduced with the effective use of windmills. These results suggest the importance of the integrated operation of electricity and heat supply system.

1 Introduction

Globally, the large part of electricity and heat is produced by burning fossil fuels. For the mitigation of global warming, the electricity and heat supply system need to be decarbonized. For the power supply system, the large-scale provision of wind power facilities is a key to reduce the CO₂ emissions because of its large global potential and relatively low power generation cost among renewable energy sources. However, the excess installation of windmills will present demand-supply mismatches in the power grid. When power output is in excess of demand, some of the windmills need to be disconnected from the grid to avoid excess power input. Such inefficiency presented by the disconnection of windmills increases the cost of power generation, and prevents the promotion of wind power.

The usage of windmills can become effective by utilizing the excess power output. The earlier studies showed that battery storage can balance the demand and supply when a large part of the electricity demand is covered by wind and solar power, but the effect of storage capacity unit sizes on the balancing decreases when the total storage capacity increases (Rasmussen, Andresen, and Greiner, 2012; Tsuchiya, 2012). The heat conversion of excess power can also contribute to demand-supply balancing, and simultaneously, can reduce the CO₂ emissions from the heat supply system. Pensini et al. (2014) analyzed the use of excess renewable power to displace the heating fuels in buildings, and found that
the heating with excess renewable power can be more economical than conventional fuel-burning system, and concluded that the integration of the electric power system with the heating system makes high renewable penetration scenarios more economically competitive. As these studies showed, both the battery storage and heat conversion can contribute to the effective use of windmills, but the combined effect of these technologies to utilize the excess power output have not been investigated.

This study targets the electricity and heat supply system of Hokkaido, the largest and northernmost prefecture in Japan, and investigates how much percentages of CO$_2$ emissions is reduced by installing the onshore wind power in the future. The effectiveness of windmills usage is measured by the CO$_2$ reduction per installed capacity, and the maximum limit of CO$_2$ reduction is determined based on the effectiveness of windmills usage. The battery storage and electric heating are focused as the measures against demand-supply mismatches. By using the power and heat supply system model, the maximum limit of CO$_2$ reduction is discussed when the excess power output cannot be utilized. Then, the effects of battery storage and electric heating on the effectiveness of CO$_2$ reduction by windmills are investigated.

2 Methodology

2.1 Analytical Target and Methodology

Hokkaido, the target region for this study, is the largest and the northernmost prefecture in Japan, and its low population density and cold climate are more similar to northern European countries than other regions of Japan. Hokkaido has a large potential for onshore wind power, 132 GW, about half of the total potential of Japan (MOE, 2014), with its good wind power generation conditions. The electricity and heat demand in Hokkaido are larger in winter and are positively correlated with the seasonal patterns of wind power output. For heat demand, the heating oil consumption in household is very large in Hokkaido, covering 12% of the total final energy consumption (METI, 2010). Overall, considering self-sufficiency and lowering CO$_2$ emissions, wind power can be considered as a main power source for future energy mix in Hokkaido.

In this study, the electricity and heat supply system of the future Hokkaido is modeled as follows. The grid electricity demand in Hokkaido is assumed to be satisfied with wind power, hydropower, gas generated power, and battery supplied energy. The heat demand is assumed to be satisfied with the heating oil and excess power of wind power. For the heat demand, only the boiling and space heating demand in the household is targeted in this study. The amount of annual hydropower generation was fixed by the reason explained in 2.3.

When there is no limit to total CO$_2$ emissions from electricity and heat supply system, the electricity demand is satisfied with hydropower and gas generated power, and the heat demand is satisfied with the heating oil. This energy mix is called “base energy mix” hereafter. Under the base energy mix, CO$_2$ emission from electricity supply system is emitted by gas generated power, and that from heat supply system is emitted by burning heating oil. When the limitation of total CO$_2$ emissions from electricity and heat supply system is externally given, gas generated power begin to be substituted by wind power. As the larger amount of CO$_2$ becomes to be reduced compared with the base emission case, the larger capacities of windmills need to be installed and the demand-supply matching in power grid becomes difficult. Such mismatches increase the waste of excess power and prevent the effective use of windmills.

As an index of the effectiveness of windmills usage, the carbon-based effective capacity factor (CECF) was defined as the rate of actual CO$_2$ reduction by the electricity generated by windmills ($\Delta$CO$_2$) against the theoretically maximum CO$_2$ reduction as

$$\text{CECF} = \frac{\Delta CO_2}{(f_e \times C_w \times 8760)} \quad (1)$$

where $\Delta CO_2$ is defined as the CO$_2$ reduction from the base energy mix; $C_w$ is the minimum required capacity of windmills to achieve $\Delta CO_2$; $f_e$ is the CO$_2$ emission factor of gas generated power. The denominator of equation (1) indicates the amount of CO$_2$ reduction when all windmills are operated at the maximum rate over a year and all the generated power by windmills is used to substitute the gas generated power.
Because the total CO₂ emissions from electricity and heat supply system is reduced by substituting the gas generated power and heating oil by the zero-emission power from windmills, \( \Delta CO_2 \) satisfies

\[
\Delta CO_2 = f_e * E_e + f_h * e_h * E_h
\]

(2)

where \( E_e \) and \( E_h \) are the electricity generated by windmills and used to satisfy the electricity and heat demand over the analysis period; \( e_h \) is the efficiency of converting electricity to heat; and \( f_h \) is the CO₂ emission factor of heating oil. When all the electricity generated by windmills is used to substitute the gas generated power \((E_h = 0)\), the CECF is written as \( E_e / (C_w * 8760) \), and is equal to capacity factor (CF) which is defined as the rate of the actual electricity generated to the maximum generation at rated output. And the CECF decreases when a part of electricity is converted to heat because the emission factor of heating oil is smaller than that of gas generated power \((f_h < f_e)\). The CECF also decreases when a part of excess power is wasted. In this study, \( f_e, f_h, \) and \( e_h \) were set to 0.342 Mt-CO₂ /TWh, 0.244 Mt-CO₂ /TWh, and 0.9 respectively. “Mt” indicates “million ton” in this study.

The electricity and heat supply system model developed for this study estimates the maximum CECF of windmills to achieve the certain level of CO₂ reduction. The CO₂ reduction target was externally given, and required capacity of windmills and operation patterns of power sources were estimated by the model. The objective function of the model can be represented by

\[
\text{Maximize } \text{CECF}
\]

(3)

The hourly electricity demand must satisfy:

\[
\sum_i (u_i(t) * C_i) + G_{gas}(t) + H_{water}(t) - B_{in}(t) + B_{out}(t) - E_h(t) \geq D_e(t)
\]

(4)

where \( u_i(t) \) is the rate of output of the wind power installed at location \( i \); \( G_{gas}(t) \) and \( H_{water}(t) \) are the output of the gas generated power and hydropower; the \( B_{in}(t) \) and \( B_{out}(t) \) are the energy volumes charged and discharged to and from battery storage; and \( D_e(t) \) is the electricity demand in hour \( t \).

Note that the maximization of CECF is equal to the minimization of required windmills capacities, and the model actually calculates the minimum required windmills capacities to make the optimization model linear. This model targets the demand-supply matching at hourly or longer durations, and not the stability of electric power in the second or minute scales. Also, restrictions on the power grid capacity and transmission losses were not considered.

To investigate the effect of battery storage and electric heating on the CECF of windmills, the four analytical conditions were given as shown in Table 1. In all cases, the flexible operation of hydropower and gas generated power can be used to alleviate demand-supply mismatches, and the windmills locations are diversified to a variety of locations with different uncorrelated wind patterns to smooth their total output. In Case 1, no other measures are available and all the excess power needs to be wasted. In Case 2, battery storage can be installed to balance the demand and supply of electricity. In Case 3, excess power can be converted to heat to substitute the heating oil. In Case 4, both the battery storage and electric heating can be installed. For all of the four cases, the maximum limit of total CO₂ emissions was decreased from the value for base energy mix in 0.5 Mt steps; in other words, \( \Delta CO_2 \) is increased in 0.5 Mt steps. From the relationship between \( \Delta CO_2 \) and CECF, the maximum limit of CO₂ reduction that would be possible with effective use of windmills is discussed.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backup power</td>
<td>available</td>
<td>available</td>
<td>available</td>
<td>available</td>
</tr>
<tr>
<td>Diversification of windmills locations</td>
<td>available</td>
<td>available</td>
<td>available</td>
<td>available</td>
</tr>
<tr>
<td>Battery storage</td>
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<td>available</td>
<td>n/a</td>
<td>available</td>
</tr>
<tr>
<td>Electric heating</td>
<td>n/a</td>
<td>n/a</td>
<td>available</td>
<td>available</td>
</tr>
</tbody>
</table>
2.2 Hourly patterns of electricity and heat demand and wind solar power output

For the electricity demand, the hourly demand data of the electricity grid in Hokkaido in 2012 (HEPCO, 2012) was used. The annual electricity demand was 35.6 TWh, and the average hourly demand was 4.05 GW. For the heat demand, the annual total heat demand in the residential sector can be estimated as 21.7 TWh (METI, 2012), but the hourly demand pattern of whole the Hokkaido cannot be obtained. Then, the hourly pattern of single residence (FES, 2014) is used to approximate the pattern of whole the Hokkaido. Because this hourly pattern is obtained for only one day per month, the same pattern is repeated in each month. From the settings of demands, CO₂ emission factors, and the efficiency of electric heating, annual CO₂ emissions from electricity and heat supply system under the base energy mix are 11.0 Mt (=35.6*0.342) and 5.9 Mt (=21.7*0.244/0.9). Hourly output patterns of wind power were estimated from the meteorological data for 2012 (JWA, 2012). Wind speed and air temperature data were converted to rates of power output by using the typical power curve of a 2MW class windmill (Carrillo et al.,2013; Suzuki et al., 2014). The 8 locations with good wind conditions (W1–W8) were selected as candidates for power source diversification as shown in Fig.1.

![Fig.1 Locations for wind power generation.](image)

Table 2 shows the annual and seasonal CFs (Capacity Factors) of wind power sources. The winter includes the months from January to March and October to December, and the summer is the period from April to September. The windmills output is high in winter and low in summer at all locations, and the CF in W1, located at the northernmost point in Hokkaido, is much higher than in the other locations. The monthly changes in the electricity demand, heat demand, and the CF of wind power are shown in Fig.2. The monthly electricity and heat demands are normalized by their annual demand. For wind power, only the W1 pattern is shown as all the locations have similar seasonal variations. The electricity and heat demand is larger in winter than in summer because of the cold climate, and the heat demand has the larger seasonal difference than the electricity demand. The wind power output is positively correlated with the demand. Table 3 shows the Spearman's rank correlation coefficients among the hourly output patterns of wind power sources. The correlation coefficient varies from 1 to −1, with 1 and −1 perfectly positive and negative correlations, and zero a complete lack of correlation between two data series. The pairs of neighboring locations, such as W1 and W4 or W2 and W8, have higher correlations.

Table 2 Annual and seasonal capacity factors (CF) in the eight locations shown in Fig.1 [%]. The winter includes January to March and October to December, and the summer is for April to September.

<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
<th>W5</th>
<th>W6</th>
<th>W7</th>
<th>W8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>37.6</td>
<td>27.8</td>
<td>27.5</td>
<td>27.5</td>
<td>25.4</td>
<td>24.4</td>
<td>23.4</td>
<td>23.2</td>
</tr>
<tr>
<td>Winter</td>
<td>51.2</td>
<td>40.8</td>
<td>36.6</td>
<td>33.4</td>
<td>37.6</td>
<td>34.8</td>
<td>35.1</td>
<td>40.4</td>
</tr>
<tr>
<td>Summer</td>
<td>24.0</td>
<td>14.7</td>
<td>18.5</td>
<td>21.7</td>
<td>13.1</td>
<td>14.0</td>
<td>11.7</td>
<td>6.0</td>
</tr>
</tbody>
</table>
The correlation coefficients are 1 to –1; 1 and –1 indicate perfect positive and negative correlation and zero shows a complete lack of correlation between two data series.

<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
<th>W5</th>
<th>W6</th>
<th>W7</th>
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<tbody>
<tr>
<td>W1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>0.41</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3</td>
<td>0.37</td>
<td>0.26</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>W4</td>
<td>0.57</td>
<td>0.25</td>
<td>0.42</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5</td>
<td>0.49</td>
<td>0.52</td>
<td>0.13</td>
<td>0.13</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W6</td>
<td>0.42</td>
<td>0.79</td>
<td>0.24</td>
<td>0.20</td>
<td>0.58</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W7</td>
<td>0.51</td>
<td>0.57</td>
<td>0.17</td>
<td>0.13</td>
<td>0.77</td>
<td>0.66</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>W8</td>
<td>0.49</td>
<td>0.76</td>
<td>0.25</td>
<td>0.20</td>
<td>0.58</td>
<td>0.72</td>
<td>0.64</td>
<td>1</td>
</tr>
</tbody>
</table>

2.3 Settings of power sources

The hydropower assumed to be flexibly operated as a backup power source because of the potential for quick start-up and shutdown. The share of hydropower in the annual electricity demand was fixed at 10% based on the present situation as there is assumed to be no further development of large-scale hydropower plants in Hokkaido. In the model, the operation of hydropower is restricted by the reservoir capacity (HC), the generator capacity (HG), and the water inflow to the power plants (H_{in}(t)) were obtained from statistic data. The time series changes in stored water (H_i(t)) can be represented as

\[ H_i(t) - H_i(t-1) = H_{in}(t) - H_{out}(t). \] \hspace{1cm} (5)

The water inflow and stored water are described as units of energy assuming that the amount of water required for a unit of electricity production is constant. The stored water cannot exceed the reservoir capacity (0 \(\leq\) H_{in}(t) \(\leq\) HC), and the power output cannot exceed the generator capacity (0 \(\leq\) H_{out}(t) \(\leq\) HG). When the reservoir is full, hydropower must be generated even when the wind power output exceeds the electricity demand. The estimated monthly changes in water inflow to hydropower reservoirs per hour are shown in Table 4 (METI, 2013a). The water inflows are assumed to be constant throughout a month because of data limitations. The water inflow is higher in spring and till summer than it is in winter because of a seasonal fluctuation arising from snow-melting and rainfalls. The reservoir and generator capacities (HC and HG) are estimated as 14.3 GWh and 1.28 GW (METI, 2013b; ECDH, 1986).
Table 4  Water inflow into hydropower reservoirs per hour by month [MW].

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water inflow</td>
<td>280</td>
<td>246</td>
<td>270</td>
<td>491</td>
<td>669</td>
<td>578</td>
<td>608</td>
<td>460</td>
<td>343</td>
<td>355</td>
<td>317</td>
<td>249</td>
</tr>
</tbody>
</table>

In the model, the operation of the battery storage is restricted by the battery storage capacity (BC), the maximum rate of the battery charge/discharge (BR), the self-discharge rate (Ls), and the charge/discharge efficiency (Eio) of battery power. The hourly change in the battery stored electricity (Br(t)) can be represented as

\[ Br(t) - (1-Ls) \times Br(t-1) = Eio \times Br(t) - B_{out}(t) / Eio. \]  

(6)

The amount of stored electricity cannot exceed the storage capacity (0 \( \leq Br(t) \leq BC \)). The maximum energy volume that can be charged/discharged per hour is the product of the storage capacity and the maximum charge/discharge rate (0 \( \leq Eio \times Br(t), B_{out}(t) \leq BR \times BC \)). This study assumes that all battery storage is in NaS (sodium-sulfur) batteries, and the BR, Ls, and Eio were set to 0.167, 0.01/hour, and 0.92 based on (Zakeri and Syri, 2015). The BC was also externally given value, and was varied within a certain range.

For the conversion of electricity to heat, the heat storage is not considered in this study, and the excess power cannot be converted to heat at the time period of no heat demand:

\[ e_h \times E_h(t) \leq D_h(t) \]  

(7)

where \( D_h(t) \) is the heat demand in hour \( t \).

3  Results

3.1 Effectiveness of windmills usage without excess power output utilization

In the Case 1, neither battery storage nor electric heating are installed, and all the excess power is wasted. Fig.3 shows the required capacity of windmills plotted against the CO2 reduction from the base energy mix (ΔCO2) in Case 1. Because the share of hydropower in the annual electricity demand is fixed at 10%, the electricity demand is satisfied with 10% of hydropower and 90% of gas generated power, and all the heat demand is satisfied with the heating oil in the base energy mix. The detail of total installed capacity at each location (W1–W5) is also shown. The required capacity of windmills increases almost proportional to ΔCO2 until the reduction amount reaches to 4.0 Mt, 36% of total CO2 emissions from grid electricity. However, as the larger amount of CO2 emissions is reduced, the required capacity increases at the higher rate. For windmills locations, almost all windmills are concentrated at W1, the location with the best wind condition, when ΔCO2 is relatively low, but gradually distributed to other locations when the larger CO2 emissions need to be reduced.

Fig.4 shows annual wind power generation versus ΔCO2 in Case 1. The differences in painting patterns of the bars indicate the usage and loss of generated power. “Direct use” means a part of electricity directly used to satisfy grid electricity demand without using battery storage. “Excess loss” means an amount of wasted power by demand-supply mismatches. As ΔCO2 increases, the larger part of electricity demand needs to be satisfied with windmills, and the power supply from windmills increases proportional to the reduction amount. Until ΔCO2 reaches to 4.0 Mt, all power output from windmills can be used to satisfy the electricity demand. But the excess loss begins to increase as the amount of CO2 reduction exceeds 4.0 Mt, and the share of excess loss in the total generation increases as ΔCO2 increases.
Fig.3: Required installed capacity of windmills at the stated amount of CO$_2$ reduction compared with the base energy mix ($\Delta$CO$_2$) in Case 1. Under the base energy mix condition, the electricity demand is satisfied with 10% of hydropower and 90% of gas generated power, and all the heat demand is satisfied with the heating oil. The differences in painting patterns of the bars indicate the differences in windmills locations.

Fig.4: Annual wind power generation versus $\Delta$CO$_2$ in Case 1. The differences in painting patterns of the bars indicate the usage and loss of generated power.

Fig.5 shows the annual CF and CECF of windmills versus $\Delta$CO$_2$ in Case 1. Until $\Delta$CO$_2$ reaches to 5.0 Mt, the CF is 37.6% because all the windmills are concentrated at W1 as shown in Fig.3. Thereafter, the CF decreases as $\Delta$CO$_2$ increases because windmills are diversely installed to other locations. The CECF is equal to the CF until $\Delta$CO$_2$ reaches to 4.0 Mt because all power output from windmills is used to satisfy the electricity demand as shown in Fig.4. Thereafter, the CECF becomes lower than the CF because a part of windmills output begin to be wasted by the demand-supply mismatches.

The CECF indicates the effectiveness of CO$_2$ reductions by windmills, and the lower CECF is similar to the higher CO$_2$ emission reduction cost. To discuss the maximum limit of CO$_2$ reduction that would be possible with effective use of windmills, the enough level of CECF needs to be determined. In Japan, the CF of typical offshore windmills is 30%. Then, if all the electricity produced is used to satisfy the demand without waste, the CECF of offshore windmills becomes 30%. Usually, the CFs of onshore windmills, targets of this study, are smaller than offshore windmills, and if the CECF of onshore windmills can be equal to that of offshore windmills, it appear to be regarded as the effective use of onshore windmills. Then, this study regards the usage of onshore windmills effective when CECF of windmills is equal to or larger than 30%. In the Case 1, the maximum limit of CO$_2$ reduction that would be possible with effective use of
windmills is 6.0 Mt, about 55% of total CO₂ emission from electricity grid.

Fig.5: Annual capacity factor (CF) and carbon-based effective capacity factor (CECF) of windmills versus ΔCO₂ in Case 1.

Fig.6 (a) and (b) show typical operational patterns for the power sources and electricity demand in Case 1 when ΔCO₂ is 4.0 and 7.0 Mt. The horizontal axes correspond to the 744 hours from January 1st to 31st. The black line shows the electricity demand, and the differences in coloring patterns of areas indicate the different power sources. In Fig.6 (a), the windmills capacity, the height of the green area, is 3.55GW, and is lower than annual average hourly electricity demand, 4.05GW. Then, the windmills output does not exceed the demand, and all the generated electricity can be used to satisfy the electricity demand. In Fig.6 (b), the windmills capacity is increased to 9.19 GW: more than doubled compared with (a). The excess power is wasted when the windmills operate at high rate, such as the period from 30 to 120 hours. In (b), the output pattern of windmills is more even; the large output deterioration, such as the period from 150-200 hours, is compensated. Such a leveling of output pattern is caused by the geographical diversification of windmills locations shown in Fig.3. Such an output smoothing appears to contribute to reduce the excess loss, but its effect on CECF is limited because all the excess power needs to be wasted. For the further reduction of CO₂ emissions, measures to utilize the excess power need to be adopted.

Fig.6: Typical operation patterns for the power sources in Case 1. The amount of CO₂ reduction is (a) 4.0 Mt, (b) 6.0 Mt. The horizontal axes correspond to the 744 hours in January 1st to 31st. The black line shows the electricity demand, and the differences in patterns of the areas indicate the different power sources.
3.2 Considering battery storage and electric heating

In Case 2, battery storage is considered as a measure against excess power loss. Fig.7 shows the annual CF and CECF of windmills versus ΔCO₂ in Case 2. No limitation is set to the battery storage capacity, BC. Compared with Case 1 (Fig.5), both the CF and CECF are increased when ΔCO₂ exceeds 4.0 Mt. Especially, the CF keeps the 37.6% until the amount of CO₂ reduction reaches to 9.0 Mt. The result indicates that all the windmills are concentrated on location W1. The leveling of windmills appears not to be required in this case because the surplus electricity can be utilized via battery storage. The CECF is also higher than Case 1, but begins to decrease when ΔCO₂ exceeds 5.0 Mt despite battery storage can be installed as much as required. Under the conditions of this study, the CECF is higher than 30% until the amount of CO₂ reduction reaches to 8.0 Mt.

![Graph: CF and CECF of windmills versus ΔCO₂ in Case 2.](image)

Fig.7: CF and CECF of windmills versus ΔCO₂ in Case 2.

Fig.8 shows annual wind power generation versus ΔCO₂ in Case 2. Here, the gas generated power can be substituted not only by the direct use of windmills output but also by the discharge from battery storage. Then, the sum of “Direct use” and “Discharge” in Case 2 (Fig.8) is equal to “Direct use” in Case 1 (Fig.4). As ΔCO₂ increases, the amount of discharge, power supply via battery storage, also increases. When ΔCO₂ exceeds 4.0 Mt, the total wind power generation is smaller than Case 1 because the excess power can be effectively used. However, the self-discharge loss also increases as the power supply via battery increases, and a part of generated power cannot be utilized. This is the cause of CECF decrease in Fig.7. As the larger amount of excess power needs to be charged and discharged, the larger amount of electricity needs to be stored for a longer period, and the self-discharge loss increases.

![Graph: Annual wind power generation versus ΔCO₂ in Case 2.](image)

Fig.8: Annual wind power generation versus ΔCO₂ in Case 2.
In Case 3, electric heating is considered as a measure against excess power loss and as a substitution of burning heating oil. Fig.9 shows the annual CF and CECF of windmills versus \( \Delta CO_2 \) in Case 3. No limitation is set to the output of electric heating. The CF and CECF are increased compared with Case 1 when \( \Delta CO_2 \) exceeds 4.0 Mt, and this trend is similar to Case2. The higher CF indicates that almost all the windmills are concentrated on location W1. The CECF is also higher than Case 1, but the decrease of CECF cannot be prevented when \( \Delta CO_2 \) exceeds 5.0 Mt despite there is no limitation to the output of electric heating. Under the conditions of this study, the CECF is higher than 30% until \( \Delta CO_2 \) reaches to 7.5 Mt.

![Fig.9: CF and CECF of windmills versus \( \Delta CO_2 \) in Case3.](image)

Fig.10 shows annual wind power generation versus \( \Delta CO_2 \) in Case 3. The electric heating begins to be installed when \( \Delta CO_2 \) exceeds 4.0 Mt, and as \( \Delta CO_2 \) increases, the amount of electricity converted to heat also increases. The total wind power generation is smaller than Case 1 because a part of excess power can be used to reduce the CO\(_2\) emissions from heat supply system. However, the larger amount of electricity is required to reduce the same amount of CO\(_2\) emissions than Case 1 because the heat use of electricity can reduce only the smaller amount of CO\(_2\) emissions compared with its direct use. And a part of electricity is wasted as excess loss because the amount of heat conversion is restricted by heat demand pattern (equation (7)).

![Fig.10: Annual wind power generation versus \( \Delta CO_2 \) in Case3.](image)

The results shown in Fig.7-10 were obtained under the conditions that battery storage capacity and the rated output of electric heating were regarded as infinite. Actually, the optimal capacity of battery storage and rated output of electric heating were determined as follows.
heating appear to be determined by the cost and benefit of their installation. Fig.11 (a) and (b) shows the annual CECFs of windmills versus the capacity of battery storage and the rated output of electric heating in cases 2 and 3; the horizontal axes are normalized by the average hourly electricity demand. Three curves in these figures correspond to the different $\Delta CO_2$. The values of leftmost plots are equal to those in Case 1 shown in Fig.4. As these figures show, the effect of adding a unit of capacity gradually decreases as the total capacities increase, and close to zero when the capacity exceeds a certain level. As $\Delta CO_2$ becomes higher, the gradients of CECF decrease more slowly against the increase of the capacities, indicating that the larger capacity of battery storage and electric heating can be effectively used. In Case 2, when $\Delta CO_2$ is 8.0 Mt, CECF is increased from 20.6% (Fig.5) to 31.0% (Fig.7) by installing battery storage without limitation. And the CECF can be increased to 26.2% by installing the battery storage capacity equal to 10 hours of average hourly electricity demand (Fig.11 (a)). The result indicates that about a half of effect of infinite battery storage capacity on CECF can be obtained by installing only 10 hours capacity ($(0.262-0.206) / (0.310-0.206) = 0.54$). By the same calculation, about a half of the effect of infinite electric heating capacity on CECF can be obtained by installing only 0.2 hours of electric heating capacity.

The results of this section indicate that both the battery storage and electric heating can raise the effectiveness of windmills usage by utilizing excess power. And even when these measures against demand-supply mismatches are installed without limitation, a part of excess power is wasted, and the effectiveness of windmills decreases as the $CO_2$ reduction target becomes higher. For battery storage, this ineffectiveness is caused by the increase of self-discharge because the larger amount of electricity becomes to be stored for a longer period. For electric heating, the ineffectiveness is caused by the lower carbon emission factor of heat use and lack of heat demand. Because the cause of ineffectiveness is different between battery storage and electric heating, their combined use may realize the further effective usage of windmills. Another finding is that the effect of adding a unit of battery storage and electric heating capacity gradually decreases as their total capacities increase. The installation of their capacity should not exceed a certain level because the effect of adding a unit capacity becomes almost zero thereafter.

Fig.11: Annual CECFs of windmills versus (a) battery storage capacity (Case 2) and (b) electric heating capacity (Case 3). Three curves in these figures correspond to the different $\Delta CO_2$.

### 3.3 Combined use of battery storage and electric heating

In Case 4, the combined use of battery storage and electric heating is enabled. Fig.12 shows the annual CECFs of windmills versus battery storage capacity and rated output of electric heating in Case 4. $\Delta CO_2$ is (a) 8.0 Mt and (b) 9.0 Mt. The horizontal and vertical axes correspond to battery storage capacity and rated output of electric heating, and they are normalized by the average hourly demand. The colors of graph areas indicate the ranges of annual CECFs of windmills against every combination of battery storage and electric heating capacity. For example, if a combination of
battery storage capacity and output rate of electric heating is plotted in the purple area, the combination result in the CECF of between 30% and 35%. Then, curves between the green and purple areas indicate a set of combinations of battery storage capacity and rated output of electric heating which can achieve the 30% of CECFs. For example, in (a), 30% of CECF can be achieved by 30 hours of battery storage without electric heating, and can also be achieved by 10 hours of battery storage capacity and 0.2 of electric heating. The results indicate that the combined use of electric heating largely reduces the required battery storage capacity. As shown in Fig.11(a), the 30 hours of battery storage is not effective because the effect of adding a unit of capacity, the gradient of a curve in the figure, have already decreased. However, 12 hours of battery storage capacity and 0.2 of electric heating output appear to be effective because the gradients of curves in Fig.11 (a) and (b) are relatively large. Then, by combining these two measures against excess power, their installed facilities become to be used more effectively. And by the combination of these measures, the 9.0 Mt of CO₂ reduction is possible with 30% or higher CECF as shown in Fig.12 (b). Such a large amount of CO₂ reduction decreases the CECF to lower than 30% in cases 2 and 3 as shown in Fig.7 and Fig.9. However, in Case 4 (Fig.12(b)), the combinations of battery storage and electric heating, such as 10 hours of battery storage capacity and 0.7 of electric heating, or the 30 hours of battery storage capacity and 0.3 of electric heating, can achieve such a higher CO₂ reduction target without ineffectiveness of windmills usage. The 9.0 Mt of CO₂ corresponds to 82% of the emissions from electricity grid and 54% of the total emissions from electricity and heat supply system. The results indicate that the combined use of battery storage and electric heating can realize more effective usage of excess power of windmills than their separate usage.

Fig.12: annual CECFs of windmills versus battery storage capacity and rated output of electric heating in Case 4. ΔCO₂ is (a) 8.0 Mt and (b) 9.0 Mt.

Fig.13 (a)–(c) show typical operational patterns for the power sources and electricity demand when ΔCO₂ is 9.0 Mt in (a) Case 2, (b) Case 3, and (c) Case 4 with 10 hours of battery storage capacity and 0.7 of electric heating output. The horizontal axes correspond to the 744 hours from January 1st to 31st. The black line shows the electricity demand, and the differences in coloring patterns of areas indicate the different power sources. In Case 2 (Fig.13 (a)), all the excess power is charged to battery, and stored for a long time before discharged. For example, the accumulated power charge during the period of 30 to 120 hours is larger than the accumulated lack of wind power supply during the period of 150 to 180 hours and 210 to 230 hours. Then, the charged power needs to be stored for a long period, and the self-discharge loss increases. In Case 3 (Fig.13 (b)), a part of excess power cannot be converted to heat, such as in the period of 30 to 120 hour, because of the lack of heat demand. In Case 4 (Fig.13 (c)), the use of excess power is switched by the situations. When the period of power excess is short, such as 140 to 150 hours and 200 to 210 hours, all the excess power is charged to battery storage, and discharged at the subsequent period of windmills power deterioration. And when the period of
power excess is long, such as 30 to 120 hours, the excess power is mainly converted to heat to avoid the large self-discharge loss. By such a combination of battery storage and electric heating, the higher CECF can be achieved in Case 4 compared with cases 2 and 3.

Fig.13: Typical operational patterns for the power sources and electricity demand when ΔCO2 is 9.0 Mt in (a) Case 2, (b) Case 3, and (c) Case 4 with 10 hours of battery storage capacity and 0.7 of electric heating output. The horizontal axis corresponds to the 744 hours from January 1st to 31st. The black line shows the electricity demand, and the differences in coloring patterns of areas indicate the different power sources. “h.conv” indicates the conversion of electricity to heat.

In conclusion, both the battery and electric heating can contribute to the effective CO2 reduction by windmills, and the combined use of these two measures result in the more effective CO2 reduction than their separate use. Under the settings of this study, the maximum limit of CO2 reduction with the effective use of windmills is 6.0 Mt when all the excess power of windmills is wasted. But when the combined use of battery storage and electric heating is available, 9.0 Mt of CO2 can be reduced with the effective use of windmills. Various combinations of battery storage and electric heating facilities are possible to achieve the same amount of CO2 emissions with the same CECF. The cost analysis is required to determine the best mix of these two measures, and is the next step of this study.
4. Conclusions

This study targets the electricity and heat supply system of Hokkaido, and investigated the maximum limit of CO\textsubscript{2} reduction that would be possible with effective use of windmills. The main conclusions are as follows;

(1) As the CO\textsubscript{2} reduction target increases, the larger part of electricity demands needs to be satisfied with windmills. As a result, the windmills are diversely installed to several locations to level their total output. However, the windmills diversification is not enough to compensate the excess power. Under the conditions of this study, the maximum limit of CO\textsubscript{2} reduction is 6.0 Mt, corresponds to 55% of emissions from power grid in the energy mix without wind power.

(2) Both the battery storage and electric heating can raise the effectiveness of windmills usage by utilizing excess power. However, even when these measures are installed without limitation, a part of excess power is wasted as the CO\textsubscript{2} reduction target becomes higher. The cause of ineffectiveness is different between battery storage and electric heating; the increase of self-discharge for battery, and the lower carbon emission factor and lack of heat demand for electric heating. And the effect of adding a unit of battery storage and electric heating capacity gradually decreases as their total capacities increase.

(3) The combined usage of battery storage and electric heating can realize more effective usage of excess power of windmills than their separate usage. The excess power is preferentially charged to battery when the period of power excess is short, and is preferentially converted to heat when the period of power excess continues for a long period to avoid the self-discharge loss. Under the conditions of this study, The 9.0 Mt of CO\textsubscript{2} emissions, corresponding to 82% of the emissions from electricity grid and 54% of the total emissions from electricity and heat supply system, can be reduced without ineffective use of windmills. These results suggest that the integrated operation of electricity and heat supply system is important to effectively reduce the CO\textsubscript{2} emissions by wind power.

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