MAXIMUM LIMIT OF CO2 REDUCTIONS BY WINDMILLS IN THE ELECTRICITY AND HEAT SUPPLY SYSTEM : ANALYSIS IN HOKKAIDO REGION IN JAPAN

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Overview

The large-scale provision of windmills is a key to reduce CO_2 emissions because of its large global potential and relatively low power generation cost among renewable energy sources. However, the large-scale installation of windmills will cause the increase of excess power loss, and such inefficiency prevents the promotion of wind power by increasing power supply cost. The utilization of windmills can be effective by utilizing the excess power output. According to earlier studies, battery storage (Rasmussen, Andresen, and Greiner, 2012) and heat conversion (Pensini et al., 2014) can contribute to the effective use of variable renewable powers such as wind and solar power, but combined effect of these measures 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 can be reduced by installing the onshore wind power. The effectiveness of windmill usage is measured by the CO_2 reduction per installed capacity, and the maximum limit of CO_2 reduction is discussed based on the effectiveness of windmills usage. The battery storage and electric heating are focused as the measures against demand-supply mismatches, and their effects on the effectiveness of CO_2 reduction by windmills are investigated.

Methodology

In this study, 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.

When there is no limit to the total CO_2 emissions from electricity and heat supply system, the electricity demand assumed to be satisfied with 10% of hydropower and 90% of gas generated power, and all the heat demand assumed to be satisfied with the heating oil. This energy mix is called "base energy mix" hereafter. When the limitation of total CO_2 emissions is externally given, gas generated power is substituted by wind power. As the larger amount of CO_2 is reduced, the waste of excess power increases and the effectiveness of windmills usage decrease. As the 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 (ΔCO_2) against the theoretically maximum CO_2 reduction as

$$\mathrm{CECF} = \Delta CO_2/(f_e * C_w * 8760) \qquad (1)$$

Where ΔCO_2 is defined as the CO_2 reduction from the base energy mix; C_w is the minimum required capacity of windmills to achieve ΔCO_2; f_e is the CO_2 emission factors of gas generated power.

The electricity and heat supply system model developed for this study estimates the maximum CECF of windmills to achieve the certain level of CO_2 reduction from the base energy mix. The CO_2 reduction target was externally given, and required capacity of windmills and operation patterns of power sources to maximize the CECF were estimated by the model. The hourly electricity and heat demand must be satisfied. The four analytical conditions were given as shown in Table 1. In Case 1, all the excess power needs to be wasted. In the cases 2and 3, battery storage and electric heating are separately utilized, and in the case 4, both of them can be utilized. For all of these cases, the maximum limit of total CO_2 emissions was decreased from the base emission in 0.5 Mt steps; in other words, the ΔCO_2 is increased in 0.5 Mt steps. From the relationship between ΔCO_2 and CECF, the maximum limit of ΔCO_2 that would be possible with high CECF is discussed.

Table 1 Availability of battery storage and electric heating in the four cases.

	Case 1	Case 2	Case 3	Case 4
Battery storage	*n/a*	*available*	*n/a*	*available*
Electric heating	*n/a*	*n/a*	*available*	*available*

Results

Fig.1 shows the annual CECFs of windmills versus CO_2 reduction from the base energy mix (ΔCO_2) in cases 1–3. In the cases 2 and 3, no limitation is set to battery storage capacity and output of electric heating. This study regards the usage of windmills effective when CECF of windmills is equal to or larger than 30%. In all the cases, CECFs do not change until ΔCO_2 reaches to 4.0 Mt (million ton), and begin to decrease thereafter. In the Case 1, the maximum limit of ΔCO_2 that would be possible with effective use of windmills is 6.0 Mt. In the cases 2 and 3, the CECFs become higher than Case 1 when ΔCO_2 exceeds 4.0 Mt. The maximum limits of ΔCO_2 increase to 8.0 and 7.5 Mt, respectively. However, even when battery storage and elecric heating are installed without the limitation of storage capacity and rated output, CECFs gradually decreases as ΔCO_2 increases. The results indicate that a part of excess power is wasted despite the measures against excess power output can be installed as much as required. 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.

Fig.2 shows the annual CECF of windmills versus battery storage capacity and rated output of electric heating in Case 4. ΔCO_2 is 9.0 Mt. The horizontal and vertical axes correspond to battery storage capacity and rated output of electric heating 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. The curve between the green and purple areas indicates a set of combinations of battery storage capacity and rated output of electric heating which can achieve the 30% of CECFs. The results show that the 9.0 Mt of CO_2 reduction is possible with 30% or higher CECF by combining battery storage and electric heating. Such a large amount of CO_2 reduction decreases the CECF to lower than 30% in cases s 1–3 as shown in Fig.1. However, in Case 4 (Fig.2), the combinations of battery storage and electric heating, such as 10 hours of battery storage capacity and 0.7 of electric heating, or 30 hours of battery storage capacity and 0.3 of electric heating, can achieve such a higher CO_2 reduction target without ineffectiveness of windmills usage.

Conclusions

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 CO_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_2 emissions by wind power.

References

Pensini, A., C. N. Rasmussen, and W. Kempton (2014): “Economic analysis of using excess renewable electricity to displace heating fuels”, Applied Energy, No.131, pp.530–543.

Rasmussen, M. G., G. B. Andresen, and M. Greiner (2012): “Storage and balancing synergies in a fully or highly renewable pan-European power system”, Energy Policy, vol.51, pp.642–651.

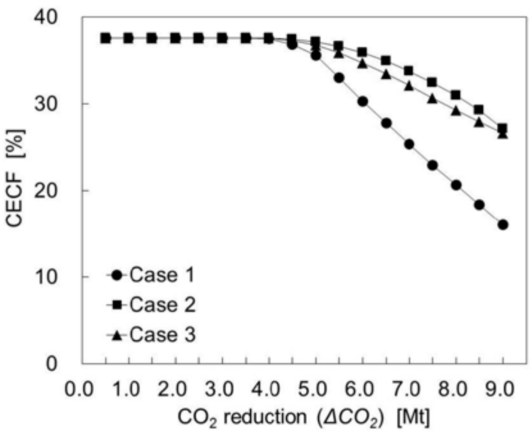

Fig.1 The annual CECFs of windmills versus CO_2 reduction from the base energy mix in cases 1–3.

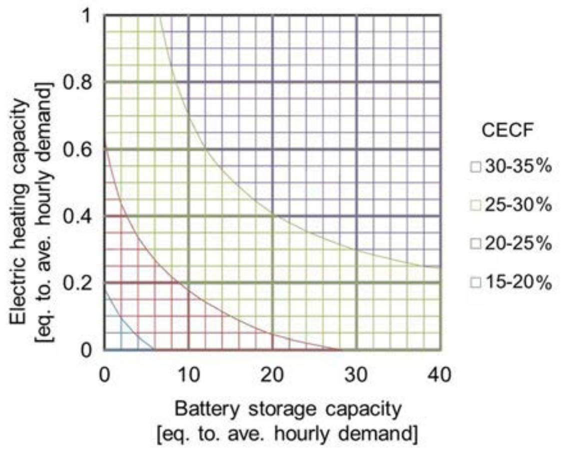

Fig.2 The CECF of windmills against the installed capacity of battery and electric heating in Case 4 when ΔCO_2 is 9.0 Mt.