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남한 전력시장에서 풍력발전점유의 전력가격수익 최적화

Optimizing the Electricity Price Revenue of Wind Power Generation Captures in the South Korean Electricity Market

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Abstract : How effectively a wind farm captures high market prices can greatly influence a wind farm's viability. This research identifies and creates an understanding of the effects that result in various capture prices (average revenue earned per unit of generation) that can be seen among different wind farms, in the current and future competitive SMP (System Marginal Price) market in South Korea. Through the use of a neural network to simulate changes in SMP caused by increased renewables, based on the Korea Institute of Energy Research's extensive wind resource database for South Korea, the variances in current and future capture prices are modelled and analyzed for both onshore and offshore wind power generation. Simulation results shows a spread in capture price of 5.5% for the year 2035 that depends on both a locations wind characteristics and the generations' correlation with other wind power generation. Wind characteristics include the generations' correlation with SMP price, diurnal profile shape, and capacity factor. The wind revenue cannibalization effect reduces the capture price obtained by wind power generation that is located close to a substantial amount of other wind power generation. In onshore locations wind characteristics can differ significantly/ Hence it is recommended that possible wind development sites have suitable diurnal profiles that effectively capture high SMP prices. Also, as increasing wind power capacity becomes installed in South Korea, it is recommended that wind power generation be located in regions far from the expected wind power generation 'hotspots' in the future. Hence, a suitable site along the east mountain ridges of South Korea is predicted to be extremely effective in attaining high SMP capture prices. Attention to these factors will increase the revenues obtained by wind power generation in a competitive electricity market.

Key Words : 계통한계가격(SMP; System Marginal Price), 전력시장(Electricity market), 풍력발전(Wind power generation), 풍력자원지도(Wind resource atlas)

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1. Introduction

When deciding the location to install new wind farms, it is important to look at any factor which will impact on the lifetime economics of the planned power generation to maximize the returns seen from such an investment. Although consideration is commonly given towards capacity factor, locational logistics etc. little thought towards how effectively a renewable plant will obtain revenue in the electricity market is given, due to the unknowns that surround this topic. Studies in various countries have shown that wind farms to not earn equally in an electricity market that adopts a competitive market structure with a spot market price (System Marginal Price; SMP)[(1),(2),(3)].

SMP price changes hourly, and is a single price that all generators get paid for electricity in South Korea for that hour. The price is set by the cost to run the most expensive generator on the power system during that hour. Renewable energy contributes a zero price to the economic dispatch of generators. This in effect will displace the most expensive generator on the system, hence reducing the SMP prices.

The benefits of renewable wind power generation to investors, grid operators, and society is not simply measured by the level of generation it achieves, but primarily how well it generates in the eyes of the electricity market, through increased revenues. Generation during times of high SMP prices is more valuable to the electricity system than generation during times of low SMP prices. A locations generation profile and how well it takes advantage of the SMP price is therefore an important consideration for wind generation. Future SMP prices will be lowered by the contribution of a zero bid price from renewable energy sources to the economic dispatch of generators, an effect dubbed as ‘renewable revenue cannibalization’. This and various other effects are important to recognize and quantify to ensure the optimization of renewable energy resources.

Little research has been attempted to explain the differences in capture price that can be seen among different wind farm revenues. Through the use of a neural network that will simulate changes in SMP prices, the variances in current and future capture prices will be modeled and analyzed. The knowledge that is uncovered in this research will reveal factors that should be considered in optimizing the revenue obtained from renewable wind generation.

2. Data and Methodology

2.1 Data

Wind time-series datasets produced by a mesoscale numerical weather prediction and correction using the meteorological mast measurements across South Korea are used. This wind data was produced by the Korea Institute of Energy Research (KIER). The data has an 1-hour time frame and represents a granularity of 3 km x 3 km. This data was used by KIER to produce a South Korean Wind Resource Atlas[4].

The wind resource assessment software Windographer™ is then used to convert this wind data into hypothetical wind power generation. This study simulates for a Nordex N100 2.5 MW turbine with a hub height of 80 m.

A neural network genetic algorithm is created using the artificial intelligence software NeuroShell Predictor™.

24-hour ahead forecasted electricity demand data for the year 2012 in South Korea and hourly SMP prices, generated by the Korean Power Exchange (KPX), is used in this study. This information was obtained from the Electric Power Statistics Information System (EPSIS), an online database managed by KPX[5].

A map obtained from the Korean Wind Power Journal (summer 2015) is used to forecast the future locational scenario of wind energy in South Korea.

2.2 Methodology

(1) Assumptions

A number of conditions are assumed as a part of this study.

It is assumed that the South Korean electricity market will remain a competitive market in which there is a variable price that varies according to generation conditions. Electricity market structures can change, however this fundamental principle should remain. This study does not consider any renewable incentive schemes.

Although solar power has not been considered, solar energy will have the same price effect as wind energy in lowering SMP prices.

It should be noted that the results are dependent on the unbiasedly chosen 3km x 3km locations wind profile. Since the wind profile over the South Korean peninsula is complex, these points do not fully represent the surrounding area. Therefore possible sites of interest should be individually investigated.

(2) Process

A number of steps are required to perform this experiment. Firstly, hypothetical wind generation is calculated for future possible wind farm sites. Since extra electricity generation impacts the SMP price, a neural network will be produced to determine the SMP price after hypothetical wind generation has been added to historical data to simulate future scenarios. Finally, economic equations will be applied to the model to determine the value of electricity generated by the various hypothetical generators.

(3) Hypothetical Generation

Wind data for a total of 110 locations was modeled. A majority of these points were chosen in an equally spaced grid format to view unbiasedly the results across all parts of South Korea.

Windographer is then used to simulate hourly generation data for a single Nordex N100 wind turbine. A single wind turbines' output can be scaled to represent multiple

N100 turbines at certain hypothetical locations without considering wake and other losses.

(4) Neural Network

All electricity generation has an impact on the SMP price. Therefore it is not logical to study the future interaction of SMP price with renewables without first modifying the SMP price to account for additional renewables.

A way to modify the historical SMP price to simulate the existence of renewable generation is required, hence a neural network employing an evolutionary algorithm is used to predict new SMP prices. This is a common method used to forecast SMP prices[(6),(7),(8)].

The input vectors to train and validate the neural network have the form presented in Eq. (1).

$$I_t = [L_t, F_t, D_t^{week}, H_t^{day}] \quad (1)$$

Where, I_t represents the input vector for period t, L_t represents the historical electrical load for the historical data point of period t, Ft represents the fuel price trend for the historical data point of period t, D_t^{week} represents the day of the week for the historical data point of period t, and H_t^{day} represents the hour of the day for the historical data point of period t.

The targets vector to train and validate the neural network has the form presented in Eq. (2).

$$T_t = [P_t] \quad (2)$$

Where, T_t represents the target vector for period t, and P_t represents the SMP price day for the historical data point of period t.

The model is trained and optimal weights are determined as shown in Table 1.

A calculated R-squared value of 0.937 and inspection indicates that an accurate model has been developed.

Table 1. Weighted importance of each neural network input

Input	Weight
Load (Demand)	40.3%
Fuel Price Trend	30.0%
Day of Week	22.8%
Time of Day	6.9%

(5) Model Generating New SMP Prices

The first step is to calculate the hourly total generation from the desired scaling of the total hypothetical generation. When this is compiled, the total renewable generation is subtracted from the forecasted demand. It is a viable proxy to subtract the total renewable energy from the electricity demand to determine the amount of generation that is to be met by price setting conventional generation, as outlined in Eq. (3).

$$\textit{Conventional Generation Requirement (MW)} = \textit{Demand} - \textit{Renewable Generation} \quad (3)$$

This new 'netted' demand is input into the

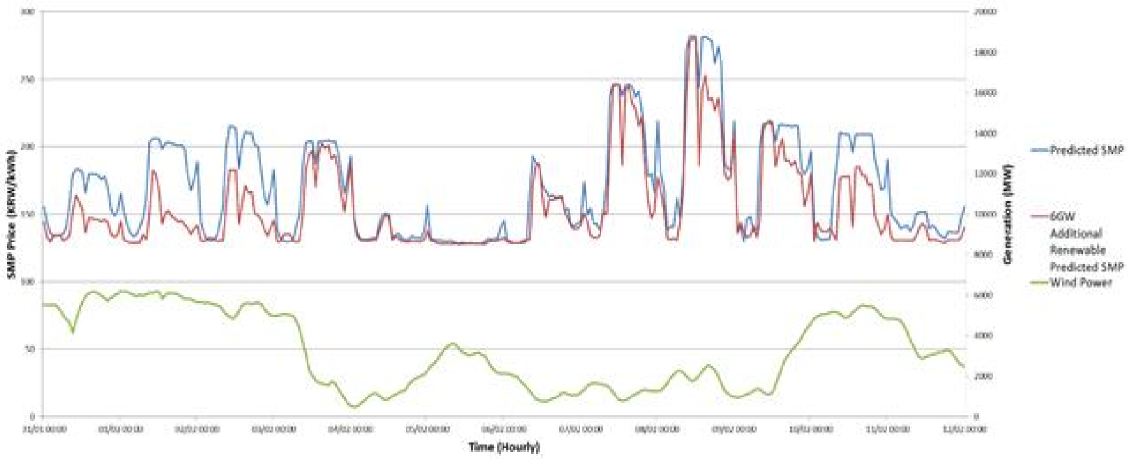

Fig. 1 Comparison of the predicted SMP versus 6 GW additional renewable predicted SMP

designed neural network and a new SMP price is generated that now accounts for the increased levels of renewable generation.

Fig. 1 shows the difference between the neural network's generated SMP prices before and after the introduction of 6 GW of additional renewable generation for a two week period. These results are in line with studies showing the expected changes in SMP prices with increased renewable penetration[(9),(10)].

(6) Revenue Analysis

The level of hourly revenue that a particular hypothetical wind turbine will make is calculated as shown in Eq. (4).

$$\begin{aligned} &\text{1 hour Revenue (KRW)} \\ &= \text{1 hour Generation (KWh)} \\ &\times \text{1 hour SMP Price (KRW/KWh)} \qquad (4) \end{aligned}$$

To determine the average price per unit of generation that this turbine produces is shown in Eq. (5).

$$\begin{aligned} &\text{Average Capture Price (KRW /KWh)} \\ &= \text{Sum of Revenue (KRW)} \\ &/ \text{ Sum of Generation (KWh)} \qquad (5) \end{aligned}$$

This figure can be expressed as a percentage of the TWA (Time-Weighted Average) price, which is an average of all hourly SMP prices in a year, using Eq. (6).

$$\begin{aligned} &\text{Average Capture Price (\%)} \\ &= \text{Average Capture Price (KRW/KWh)} \\ &/ \text{ Average SMP Price (KRW)} \qquad (6) \end{aligned}$$

3. Results

3.1 Wind Characteristics

To understand the differences that occur in capture prices among different locations, it is first important to understand the wind characteristics of South Korea.

Fig. 2 shows the correlation of wind speeds between different locations. With increased distance between sites, the correlation of wind speeds between the sites decreases. This implies that wind power output is likely to have a higher correlation within a geographically small area as opposed to a large area[11].

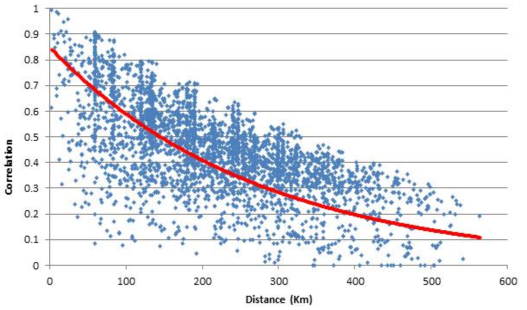

Fig. 2 Correlation of wind speed over distance in Korea

Fig. 3 shows South Korea's average diurnal generation over a year and also shows the average diurnal SMP price for the year 2012. There is an average correlation of -0.18 between wind speed and SMP. However, this varies greatly depending on location (-0.78 to 0.55).

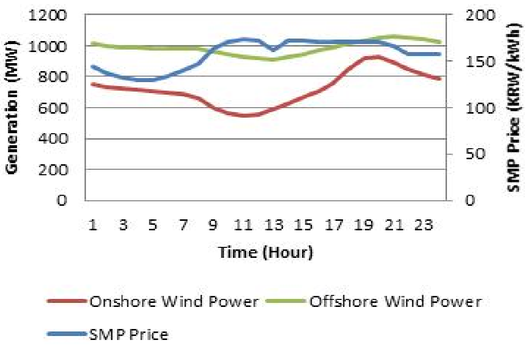

Fig. 3 Yearly average diurnal profile for offshore/onshore wind power and SMP in South Korea

Fig. 4 shows the correlation of average diurnal wind generation with average diurnal SMP price. It can be seen that offshore wind generation is generally negatively correlated and onshore varies.

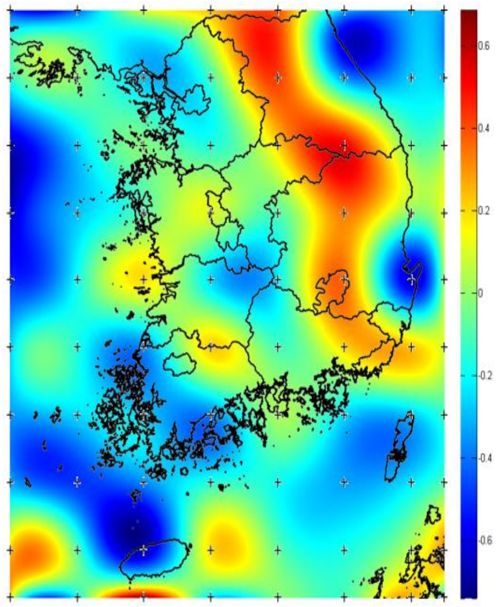

Fig. 4 Map of diurnal wind profile correlation to SMP price trend (wind speed correlation with SMP)

Fig. 5 shows the percentage increase between the minimum and the maximum of the average diurnal generation profile. It can be clearly seen that the percentage increase over sea (5%~45%) is very low in comparison with land (45%~180%). Upon deeper investigation, it is observed that this change occurs rapidly at the coastline.

Fig. 6 shows the capacity factors of the selected hypothetical generation locations. This is consistent with KIER's Wind Resource Atlas[4]. Any unexpected capacity factors are purely due to the unbiased choice of wind locations.

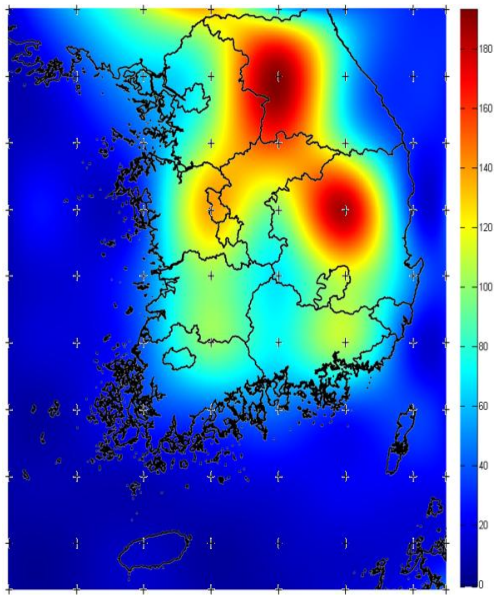

Fig. 5 Map of minimum to maximum percentage of diurnal shift increase (%)

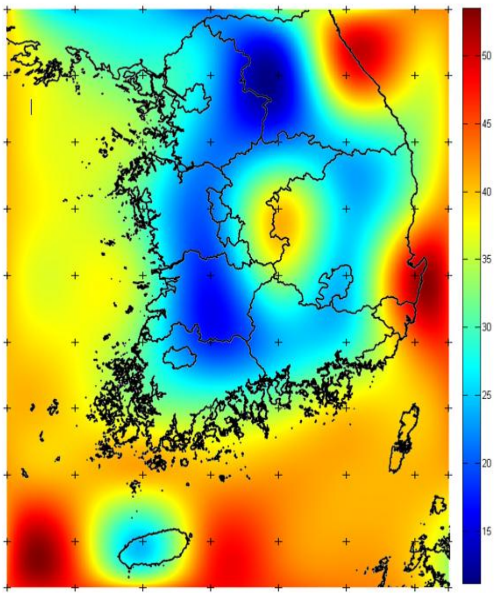

Fig. 6 Map of selected locations corresponding capacity factor(%)

3.2 Scenario Results

To view how SMP capture price may vary, two renewable generation scenarios have been simulated:

(1) No additional renewable generation

Fig. 7 shows the average capture price for renewable generation in different locations with no additional hypothetical generation added to the model(current renewable generation levels). It can be seen that capture prices for offshore locations are consistent with the TWA SMP price(TWA price average of all hourly SMP prices in a year). Capture prices for onshore locations vary significantly within a range of approximately 155~162 KRW/kWh.

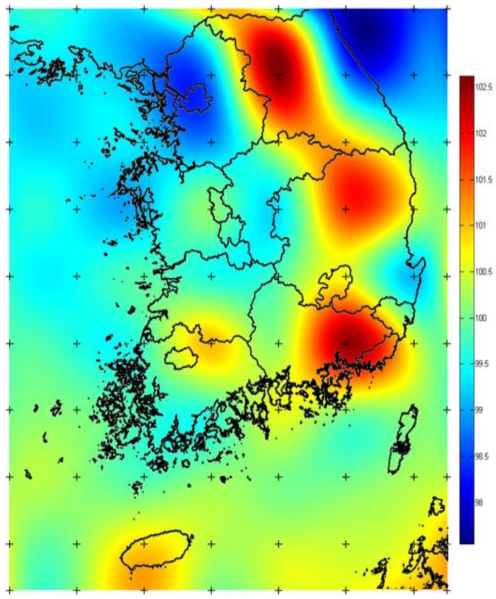

Fig. 7 Map of current wind generation capture prices in Korea (capture percentage of TWA price, %)

(2) Possible 2035 Renewable Generation Make-Up

The approximate locations of forecasted 2035 hypothetical wind generation in South Korea can be seen in Fig. 8.

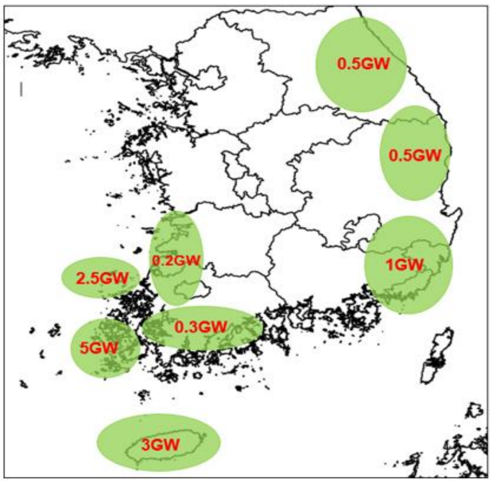

Fig. 8 Approximate location of 2035 hypothetical wind power generation capacity in South Korea (GW)

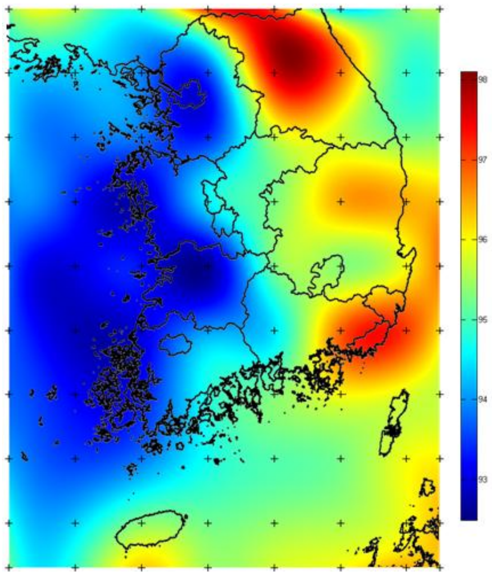

Fig. 9 Map of 2035 wind power generation capture prices in South Korea (capture percentage of original TWA price, %)

Fig. 9 shows the lowered capture prices compared with the TWA SMP price. Large drops in SMP price can be seen in the west with the largest drop in the south-west area of South Korea. The average fall in capture prices for 2035 with consideration only for wind generation is 20 KRW/kWh from current prices.

4. Discussion

4.1 Wind Characteristics

It has been discovered that a drop in average SMP price will indeed occur with increased renewable generation. The effects that cause these drops can be categorized into either system-wide effects or wind characteristics effects.

(1) System Wide Effects

As can be seen in Fig. 9 (2035 scenario), the overall drop in SMP prices is called the ‘wind revenue cannibalization’ effect. This effect describes the phenomenon whereby significant wind generation lowers the revenues achieved by wind farms. With high volumes of ‘free’ wind generation, prices are pushed downwards, hence wind generators capture lower prices. However, when there are low levels of wind generation, prices are high, therefore wind farms do not capture high prices efficiently as they in effect cannibalize their own revenue capture prices improve further east due to the decreased correlation with large levels of other wind power generation in South

Korea. The spikes and dips that oppose this trend are due to the selected sites specific wind characteristics.

Therefore, it is normally beneficial to install wind power generators as far as possible from existing and future generation.

(2) Wind Characteristics

A complex mix of a number of diurnal profile shape, minimum to maximum diurnal shift, wind speeds correlation with SMP price, and capacity factor cause variances in capture price.

Fig. 7 (current scenario) shows the contribution of a number of these factors to a sites capture price. The price spikes expressed in red are due to the sites high correlation with the average SMP diurnal profile as outlined in Fig. 3. As expected, the more correlated generation is with SMP price, the higher the average capture price should be. Although the correlation with SMP price is often negative offshore, the minimum to maximum diurnal shift is very low at these locations, therefore a negative correlation is not as significant as the wind profile of these locations is already relatively flat. Hence, it is deduced that a high minimum to maximum diurnal percentage shift will amplify the correlation or negative correlation of wind power generation with the SMP price. A high minimum to maximum diurnal increase should be aimed for if the sites wind speed is correlated with the SMP price, if it negatively correlates with SMP price then a site with a relatively flat diurnal profile is preferable.

In Fig. 9 (2035 scenario), the effect of the sites capacity factor on capture price now becomes significant. The largest reduction occurs in western regions due to the higher levels of generation placed at these locations in the model. However, when capacity factor of a wind turbine is low, the turbine will generate only when wind levels are significantly high. In this case, it can be inferred that there will be an increased level of activated wind generation in other locations when this particular turbine is activated, resulting in a lower SMP price, and vice versa for high capacity factor locations. This effect explains any unexpected variances that occur in the results.

(3) Significance of Results

Shcherbakova et al.[1] investigated the effect of increased wind penetration on the SMP in South Korea identifies a variance of 93.42~121.38 KRW/KWh among existing onshore wind farm revenues in South Korea. A number of other studies have identified the variance that occurs in other countries that employ an SMP market structure[2],[3]. This study uniquely attempts to create an understanding of these confirmed differences, and quantify future variances in capture price so that new wind farm developments may benefit from increased revenue per unit generation throughout its lifetime.

CAPEX and OPEX costs of a new wind development site do not vary due to a locations capture price. Therefore average capture price should be considered alongside CAPEX costs, OPEX costs, and capacity factor to determine the most profitable future wind farm site.

The results from this study can benefit the South Korean power industry in various ways. Primarily, renewable investors can make a more informed decision as to how to locate wind power to maximize profits. Also since this study promotes wind generation that captures higher SMP prices, electricity system operators will benefit from the supply of wind generation when it is greater desired. This study identifies a greater potential for wind installations at the eastern side of South Korea, a conclusion that is in line with government policy to increase installed wind capacity in these regions. Finally, electricity consumers will also feel value in this study through the promotion of higher capture prices per unit generation of renewable sources. This results in a reduction of SMP prices and hence reduces the overall cost of South Korean electricity generation. A lower cost of generation should induce lower consumer electricity prices.

5. Conclusion

The aim of this paper was to identify and determine the significance of any effects that cause a variance in average SMP prices captured by wind farms in different locations. Through the use of a neural network to model the impact of renewable generation on South Koreas SMP price and a database of wind profiles converted into hypothetical wind generation, the impact of different renewable scenarios was analyzed to pinpoint the reasons behind these observed variances in average capture price.

The system-wide renewable cannibalization effect has been determined as significant in the future lowering of electricity capture prices. It has been shown that areas surrounding high levels of wind generation will experience lower SMP prices on average. Thus it is recommended that new wind developments be located in regions far from the general trend of forecasted wind generation installations in South Korea. Thus the eastern and north-eastern regions of South Korea have been identified as areas that may exhibit superior future capture prices.

A locations specific wind profile has also been determined as important in evaluating a wind development potential for maximizing electricity generation revenue. In agreement with a separate study performed on existing wind farm revenues in South Korea(1), it is found that a higher correlation between a sites generation profile and the SMP price is beneficial in capturing a higher revenue per unit generation. It was also found that a high minimum to maximum diurnal percentage shift will amplify this correlation or negative correlation of power generation with the SMP price. Therefore, consideration of a sites diurnal profile is important when forecasting capture prices.

Wind generation is usually developed with no consideration towards the expected interactions between the planned generator and the electricity market, due to the relative uncertainty surrounding the forecast of an untested locations capture price. However, this study has successfully recognized the factors that require consideration in predicting a potential renewable sites current capture price, and capture price in a future with an increased renewable penetration in South Korea.

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