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# Site selection of offshore wind farms around the Korean Peninsula through economic evaluation

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ABSTRACT

We have conducted a feasibility study on the development of offshore wind farms around the Korean Peninsula as part of the national plan. This study deals with the selection of the optimal site for an offshore wind farm. We set rating indices in order to select an optimal site of the candidate coasts, which include the expected B/C (benefit to cost) ratio, the possible installation capacity of the wind farm, the convenience of grid connection, and so on, for each candidate site. The expected B/C ratio is described as the benefit from the annual energy production compared to the costs that correspond to the construction of the turbine foundation, and the grid connection between the offshore wind farm and the substation on land. It can be found from the evaluation that the construction costs associated with the substructure and grid connection are crucial in determining the location of the first offshore wind farm in Korea. Consequently, we could select a top site among the candidate sites to be implemented as the first national project of offshore wind farm development.



## 1. Introduction

Recently, development of offshore wind farms in Korea has become widely understood as being essential to achieve the national target for the renewable energy. As part of the national plan, the front running project for the offshore wind farm development that is dedicated to investigating the possible resources based on the economy, considering current technological status, is being performed. So far, studies on the development of wind turbines, such as the design of turbine blades and the development of onshore wind farms, have been mainly performed in Korea. Studies in the field of offshore wind farms, such as assessments of offshore wind resources and possible sites, have not been widely performed. On the other hand, various studies and projects in offshore wind farms have been conducted in advanced countries. Manwell et al. (2002) [1] analyzed wind speed and power density for the assessment of offshore wind resources offshore New England by using measurement data. Bishop and Miller (2007) [2] studied the visual assessment of offshore wind turbines by considering the influence of distance, contrast, movement and social variables. Dhanju et al. (2008) [3] proposed a method for assessing electricity production and the value of wind resources, specifically for the offshore environment. Dvorak et al. (2010) [4] created a wind resource assessment for offshore California and classified this region by its coastal transmission access, water depth, and wind turbine development potential, etc. Korea has established the groundwork for an analysis of wind resources by preparing a national wind map with the numerical simulation of Kim et al. (2006) [5]. Oh et al. (2012) [6] reviewed the possibility of wind power development by calculating the usage rate of wind turbines at sea with such a national wind map. In this study, the feasibility of wind power development was reviewed by calculating the benefit ratio against the cost for offshore wind power development around South Korea, in consideration of the depth of water and the distance from the shoreline and substations, as well as the wind resources analyzed previously. An optimal candidate site for the development of Korea's first large-sized offshore wind farm was then selected.

## 2. Offshore site conditions

### 2.1. Consideration factors for site selection

The feasibility of wind power development is dependent on wind resources and, especially, constructability offshore. Therefore, wind resources are the most important factor as the standard for site selection. Sea environment factors such as sea depth and soil condition are also important. The length of the transmission line is also an important factor because the cost for undersea cable installation has an enormous influence on economic feasibility.

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Table 1 shows the factors with an influence on the feasibility of wind power development. Site selection can be conducted through an evaluation of those factors.

### 2.2. Wind resources

Wind power is proportional to the cube of wind speed. A minor change of wind speed causes a considerable change in wind power generation, so it needs to be estimated precisely.

The national wind resource map developed by the Korea Institute of Energy Research (KIER) has been used to assess wind resources [5]. Fig. 1 shows the average wind speed distribution for 3 years (2005–2007), at a resolution of 3 km × 3 km. Looking into the regional differences in offshore wind distribution, wind speed is greater in the East and South Seas than in the West Sea, and is especially the greatest in the Southern East Sea region and areas around Jeju Island.

### 2.3. Sea depth

In the case of offshore wind power development, water depth considerably affects the economics of the wind power project when establishing the offshore foundation. Foundation type is dependent on the water depth and soil conditions, etc. Stationary foundations such as monopole, jacket, tripod and gravity structure are proven technologies and applicable within 50 m of depth immediately. Floating foundations under development will be required in deeper sea areas. Currently, areas within 20 m of depth are considered as priority development sites. Fig. 2 shows the contour map of sea depth around the Korean Peninsula. It can be seen that shallow areas are widely distributed in the West Sea and parts of the South Sea, whereas very deep sea areas abound in the East Sea and the areas around Jeju Island, which have good wind resources.

### 2.4. Distance from the coastline

Distance from land must be considered in terms of the environmental impact of wind turbines, such as visuals, noise and electric impact. So far, there are no regulations about visual impact from offshore wind turbines, but they may provoke civil complaints. Therefore, areas over 10 km from land were not subject to a visual impact assessment. Distance from the coastline of the Korean Peninsula is shown in Fig. 3.

**Table 1**
Consideration factors for site selection of offshore wind farms.

| Classification | Factor | Detailed factor |
|---|---|---|
| Wind state | Wind resources | Wind speed, wind power density |
| | Weather, typhoon | Return period and maximum wind speed |
| Sea state | Wave | Wave height and period |
| | Tide and current | Tidal range and current velocity |
| | Sea depth, soil conditions | Bathymetry and depth, geological stratum and features |
| | Earthquakes | Possibility, activity, magnitude |
| Environment | Protection area of the environment, passage route of birds | Exclusion of protection area, route of birds, habitats of rare species' |
| Condition of location | Distance from coastline, harbor, substation | Required minimum or maximum distance from coastline, harbor, substation |
| Misc. | Existing sea uses | Exclusion of fishery, national park, military areas |

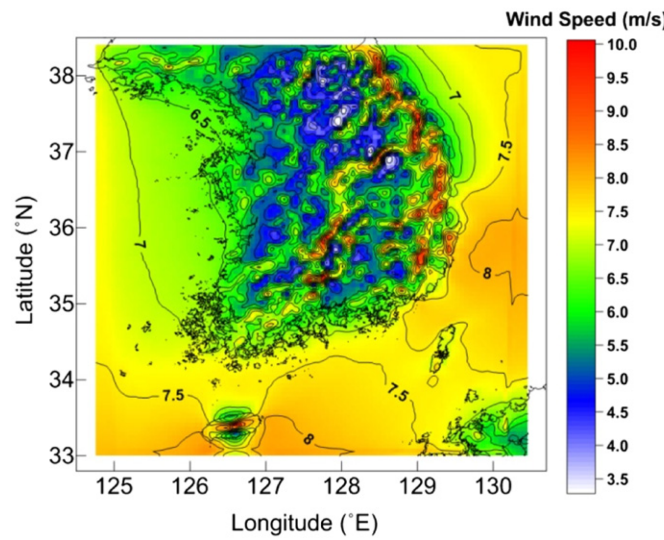


**Fig. 1.** Average wind speed by KIER wind map (El. 80 m).

### 2.5. Distance from existing substations

Distance from existing substations of land also considerably affects the economics of the project, because the cost of cable construction is dependent on the distance from substations. In order to consider the distance from substations as a constraint for site selection, the shortest distance from all existing substations of land has been estimated as shown in Fig. 4.

## 3. Site selection

The economic feasibility of each site was evaluated to select a preferred site for wind power development, in consideration of the abovementioned offshore site conditions. The resolution of the wind resource map used is 3 km, and economic feasibility was compared by dividing the entire offshore area around the Korean

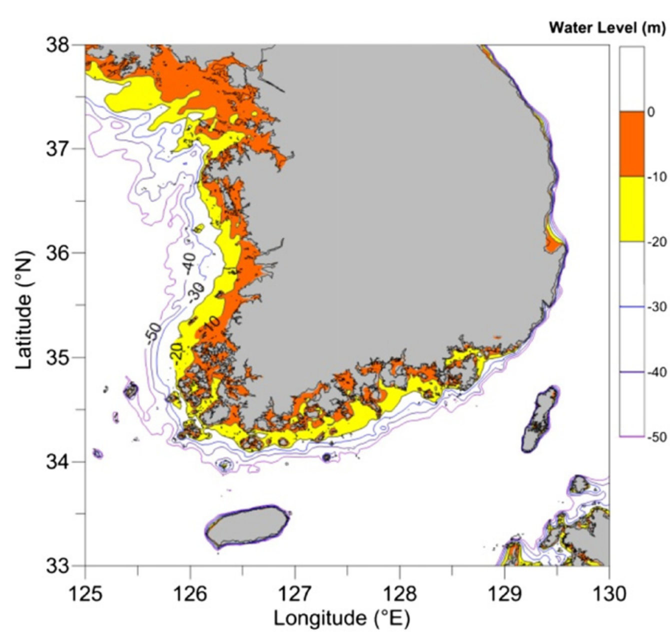


**Fig. 2.** Bathymetry of sea.

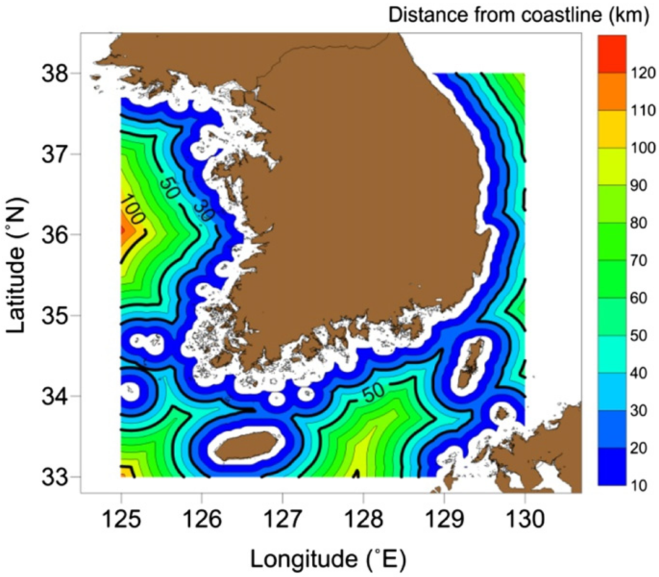


**Fig. 3.** Distance from coastline.

Peninsula into a grid pattern of 3 km × 3 km, and calculating the cost-benefit figures at each grid cell.

### 3.1. Benefit estimation

For the calculation of generation capacity, a 3 MW turbine was considered for offshore wind power, with the power curve as shown in Fig. 5. The dimensions of the turbine include a hub height of 80 m and a rotor diameter (RD) of 91.2 m. The criteria for arranging wind turbines at each grid cell was assumed to be with a total of 25 turbines (5 lines × 5 rows) arranged at a distance of 8RD. In addition, the annual energy production (AEP) was calculated by using the scale and shape parameters of Weibull distribution at each cell, as shown in Fig. 6 (Oh et al. (2012) [6]'s calculation using the KIER wind map [5]). The yearly generation profit was calculated by multiplying the annual energy production

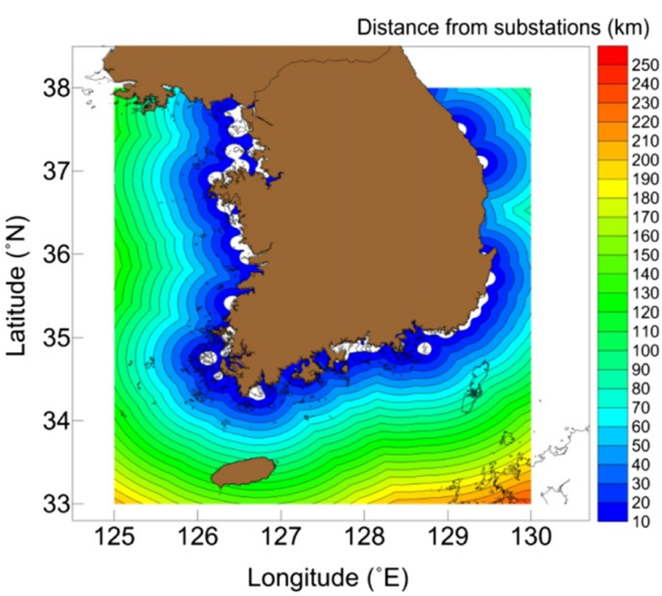


**Fig. 4.** Distance from substations.

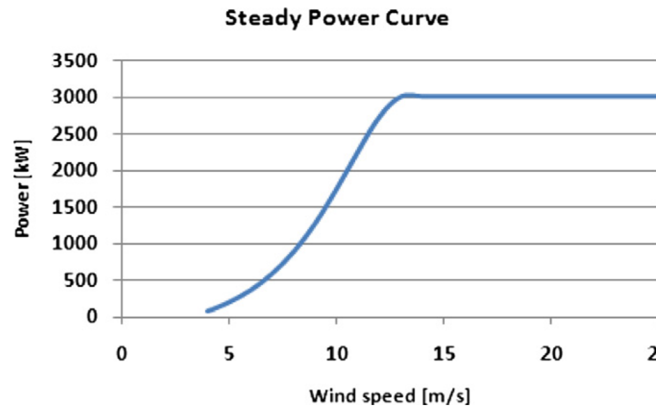


**Fig. 5.** Power curve of reference wind turbine.

by the generation cost of 194 won/kWh, in consideration of a farm loss of 10%.

### 3.2. Cost estimation

With regard to development costs, the total cost amounting to the sum of the cost of each item was calculated with reference to the guidelines for calculating investment cost as suggested by Dicorato et al. (2011) [7]. The suggested cost of the calculation formula is based on euro, and in this study, the total cost was converted into won based on a 1563.5 won/euro exchange rate.

#### 3.2.1. Turbine cost

Dicorato et al. (2011) [7] suggested the turbine cost calculation formula for 2 MW–5 MW turbines as below Eq. (1). This formula has been derived from real project of offshore wind farm in Europe. This study estimates 3 MW turbine cost by Eq. (1).

$$c_{WT} = 2.95 \cdot 10^3 \cdot \ln(P_{WT}) - 375.2[\text{k€}] \quad (1)$$

where $P_{WT}$ is the rated power [MW] of a single wind turbine. Transport and installation costs have to be added to costs expressed by Eq. (1). This value corresponds to 10% of turbine commercial cost.

#### 3.2.2. Foundation cost

Foundation cost is composed of manufacturing cost and transport and installation cost. Dicorato et al. (2011) also suggested three formulas for the monopile foundation costs. In this study, the following costing formula was used because this formula shows best agreement with the actual cost of five constructed offshore wind farms among three formulas, and the available range where the formula can be applied was limited to below 20 m in depth. Of course, monopile can be embedded over 20 m in depth. But the costs for installation of monopile increase rapidly over 20 m in depth and Eq. (2) has the linear dependence with water depth.

$$c_f = 320 P_{WT}(1 + 0.02(D - 8))\left(1 + 0.8 \cdot 10^{-6}\left(h\left(\frac{d}{2}\right)^2 - 10^5\right)\right)\left[\text{k€}/\text{turbine}\right] \quad (2)$$

where $D$ (m) represents sea depth, $h$ (m) is hub height and $d$ (m) is rotor diameter. An increase of 50% of manufacturing costs of foundation $c_f$ is assumed in order to consider transport and installation.

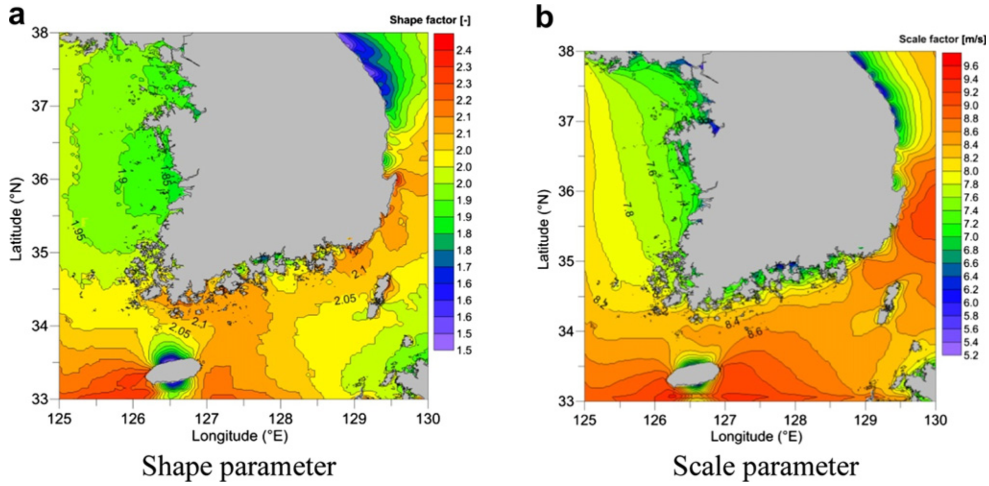


**Fig. 6.** Distribution of Weibull parameters for offshore wind (a) Shape parameter (b) Scale parameter.

*3.2.3. Electric system – collection system cost*

The collection system cost for the installation of the total 20 km was calculated by considering the wind farm layout as shown in Fig. 7. The cost was considered the same at every grid cell, and the mean value shown in the guidelines was considered. Cable production cost, transport & installation costs were considered as 396 k€/km and 365 k€ per km, respectively.

*3.2.4. Electric system – integration system cost*

First, MV/HV transformer cost was calculated by the following formula:

$$c_{TR} = 42.688 A_{TR}^{0.7513} [\text{k€}] \tag{3}$$

where $A_{TR}$ is the rated power of transformer [MVA].

MV switchgear cost, busbar system cost, and HV switchgear cost were measured as 70 k€, 2650 k€, and 920 k€, respectively. Diesel generator cost was calculated by the following formula:

$$c_{DG} = 21.242 + 2.069 n_{WT} P_{WT} [\text{k€}] \tag{4}$$

where $n_{WT}$ is the number of turbines in the offshore wind farm. Finally, the cost of the offshore substation platform was calculated by using the following formula:

$$c_{SS,f} = 2534 + 88.7 n_{WT} P_{WT} [\text{k€}] \tag{5}$$

Integration system cost is the sum of these previously mentioned costs. The same value was applied to every cell.

*3.2.5. Electric system – transmission system cost*

HV transmission system is a transmission line connecting from an offshore substation to a land substation, and is composed of undersea cables and some land cables. In this study, the cost for undersea cable installation was calculated in consideration of the minimum distance from the substations located on the coastline to the grid cells of each site. The transmission system cost of each grid cell was calculated at the level of 150% of the suggested cost, in light of present domestic affairs, while the guidelines showed 670 k€/km as production cost and 720 k€/km as installation cost with regard to 630 $mm^2$ 150 kV undersea cables. As our investigation, there was a big difference between the costs suggested by the domestic manufacture and suggested by the guidelines with regard to experiences in Europe. Therefore the level of 150% was decided as the expected cost referring to the domestic manufacturer's suggestion.

*3.2.6. Grid interface cost*

Regulation device costs were not included here, but 75 k€/turbine was considered for SCADA/EMS system cost.

*3.2.7. Project development cost*

Project development cost is often estimated as a percentage of the total investment. In this study, 46.8 k€/MW (shown as the mean value) was considered.

### 3.3. Estimation and comparison of the B/C ratio

The B/C ratio was calculated to compare the economic feasibility of development by grid cell, in consideration of the present value of annual development profit and the present value of total cost, within the total operating period, and through applying a formula for the calculation of levelized generation cost as following Eq. (6);

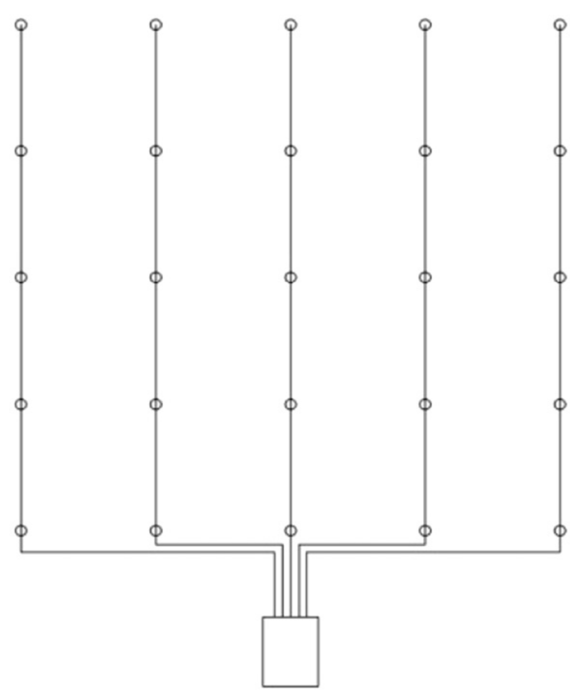

**Fig. 7.** Reference wind farm layout.

**Table 2**
Criteria for the analysis of economic feasibility.

| Index | Value |
|---|---|
| Total operating period, $(n - t_c)$ | 20 years |
| Construction period, $t_c$ | 3 years |
| Depreciation period, $t_d$ | 20 years |
| Operations and maintenance rate, $r_m$ | 1.97% |
| Inflation rate, $r_{\inf}$ | 3% |
| Discount rate, $r_d$ | 7% |
| Borrowing interest rate, $r_i$ | 5% |
| Borrowing capital rate, $r_c$ | 75% |
| Repayment period, $t_{re}$ | 10 years |
| Tax rate, $r_t$ | 22% |

$$\text{B/C ratio} = \sum\nolimits_{t=1}^{n} \frac{E_t}{(1+r_d)^t} \Big/ \sum\nolimits_{t=1}^{n} \frac{I_t + M_t + T_t}{(1+r_d)^t} \quad (6)$$

where, $n$ is a life time of wind farm, $t$ is the operating period (year), $r_d$ is a discount rate, $E_t$ is the profit from electricity generation in the year $t$, $I_t$ is the investment expenditures in the year $t$ and estimated as following Eq. (7);

$$I_t = \left\{ \begin{array}{ll} I_i \times \frac{100 - r_c}{100 \times 3} & \text{for} t = 0 \sim 2\text{year} \left(t_c\right) \\ I_i \times \frac{r_c}{100 \times 10} + \frac{r_i}{100}\left[I_i \times \frac{r_c}{100} - \frac{I_i \times r_c/100}{t_{re}}(t - (t-1))\right] & \text{for} t = 3 \sim 12\text{year}\left(t_{re}\right) \\ 0 & \text{for} t = 13 \sim 22\text{year} \end{array} \right\} \quad (7)$$

where $I_i$ is the initial investment, $r_c$ is a borrowing capital rate, $r_i$ is a borrowing interest rate, $t_c$ is the construction period, $t_{re}$ is the repayment period. $M_t$ is the operations and maintenance expenditures in the year $t$ and estimated as following Eq. (8);

$$M_t = I_i \times \frac{r_m}{100} \times \left(\frac{100 + r_{\inf}}{100}\right)^t \quad (8)$$

where $r_m$ is an operations and maintenance rate, $r_{\inf}$ is an inflation rate. $T_t$ is a corporation tax in the year $t$. Factors such as the initial investment cost, debt, interest cost, discount rate, and yearly generation profit were considered for the calculation. The criteria as shown in Table 2 were applied in this study. For the selection of the most preferred development site, the targets for the calculation of economic feasibility were limited to a distance of over 10 km from the coastline, and within 20 m in depth, as mentioned before. The calculation results are as shown in Fig. 8. The results are initial estimates for relative comparison, given present domestic affairs were not sufficiently reflected in cost calculations and the features of each site were not properly considered. In practical site evaluation, however, grid connectivity and usage conditions of the area should be reviewed in detail. During the development of farms, in addition, the increase in efficiency through the selection of suitable turbines or optimal arrangement may bring about higher economic feasibility, and any increase in investment cost may lead to a drop in economic feasibility.

Looking into the distribution of each target area with regard to the calculation results of economic feasibility (Fig. 8), economic feasibility is mostly insufficient. Compared to the turbines considered in this study, however, many machines with greatly improved usage rates are being launched of late. The improvement of economic feasibility, including the design of cost-effective foundation types suitable for appropriate sites other than monopile, is always feasible. Looking into the distribution of the calculation results of economic feasibility for the selection of the optimal site at the present stage, the areas satisfying the constraints, a distance of over 10 km from the coastline and below 20 m in depth, are mostly on the west coast and some of the areas along the south coast. These areas were divided into three parts depending on location characteristics, (the mid-west coast, the south west coast, and the south coast). The number of cells in each area and the average B/C ratio were compared as shown in Table 3. As for Area I located in the mid-west coast, it has a great number of cells because it is widely spread throughout an area of low depth. However, economic feasibility is very low, because there is a long distance to grid connectivity in long-distance areas. If development starts from short-distance cells, economic feasibility will be secured and large-scale development will be feasible in the area. However, the cells available for development may be very limited in number, in the event of a confrontation between the two Koreas. Area II covers the area from the mid-west coast through the south coast. There is an area of low depth beside the coastline. Economic feasibility is relatively good, so it is expected that most development will be promoted in this area. Area III has an intricate coastline. Its area of a low depth is not wide, so there are only a small number of appropriate cells. It has relatively good wind resources, promising positive economic feasibility and bright prospects for development. It is judged that Area II will be first developed in consideration of the capacity of possible development and economic feasibility. This area was subdivided for comparison as shown in Fig. 9 and Table 4. In addition, the western areas of Area III, shown as having the highest economic feasibility for a small size, were also compared.

As shown in Fig. 9, Area II is largely divided into five sites because of islands. Among the five areas, Areas II-2 and II-4 are relatively good in terms of development conditions. It is expected that Area III-1 will be developed first because it has relatively good economic feasibility levels, even though it is a moderately small area. Area II-2 and Area II-4 may, however, be selected as preferred development sites in consideration of large-scale extension possibilities. Between both areas, Area II-4 may be selected as the most preferred candidate site because it includes cells with a B/C ratio over 1, according to the present calculation criteria.

### 3.4. First candidate site

Area II-4, the most preferred development site, stretches over Buan-gun in Jeollabuk-do and Yeonggwang-gun in Jeollanam-do. There is an area of low depth below 20 m spreading beside the coastline. The area is relatively close to the point connected to the land substation, so it has better development conditions than other areas. Looking into usage conditions of sea, this area is the most preferred development site, because it is in a no-oil tanker

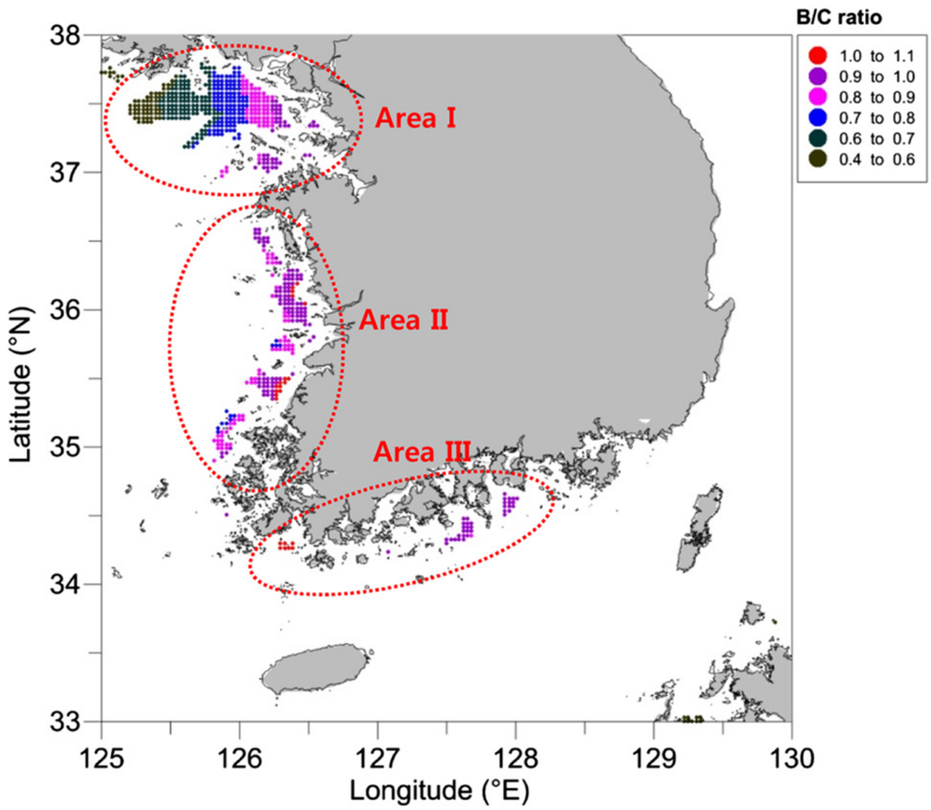


**Fig. 8.** Distribution of target area and B/C ratio.

**Table 3**
Number of cells by area and average B/C ratio.

| Area | Number of cell | Average of B/C ratio |
|---|---|---|
| I | 416 | 0.73 |
| II | 189 | 0.91 |
| III | 54 | 0.86 |
| Total | 659 | 0.79 |

navigation zone, has no large ship navigation routes, and is not being used as an ocean park or a fishery. As shown in Fig. 10, four cells (A–D), by distance, were selected to compare geographical characteristics, wind characteristics, and economic feasibility, as outlined in Table 5. Present value, also known as present discounted value, is the value on a given date of a payment or series of payments made at other times. In this study, all the benefit and cost from a B/C ratio was calculated as the present value in the wind farm operating year $t$ by the Eq. (6) ~ Eq. (8). Looking into the characteristics by cell, there are no significant differences in development profit, because there are no major differences in the

**Table 4**
Number of cells at each area of the south west coast and average B/C ratio.

| Area | Number of cell | Average of B/C ratio |
|---|---|---|
| II-1 | 22 | 0.91 |
| II-2 | 71 | 0.94 |
| II-3 | 20 | 0.83 |
| II-4 | 41 | 0.96 |
| II-5 | 35 | 0.84 |
| Total | 189 | 0.91 |
| III-1 | 7 | 1.04 |

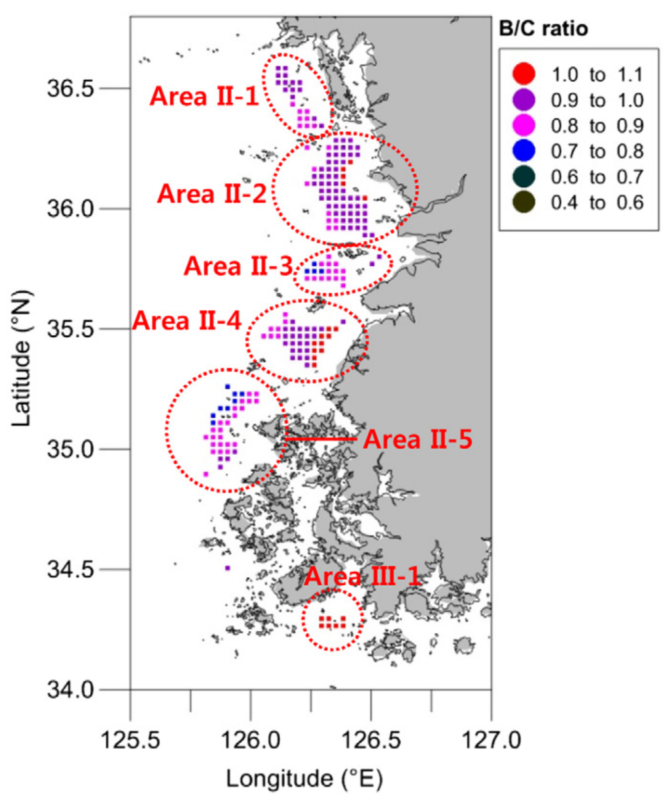


**Fig. 9.** Distribution of B/C ratio on the south west coast.

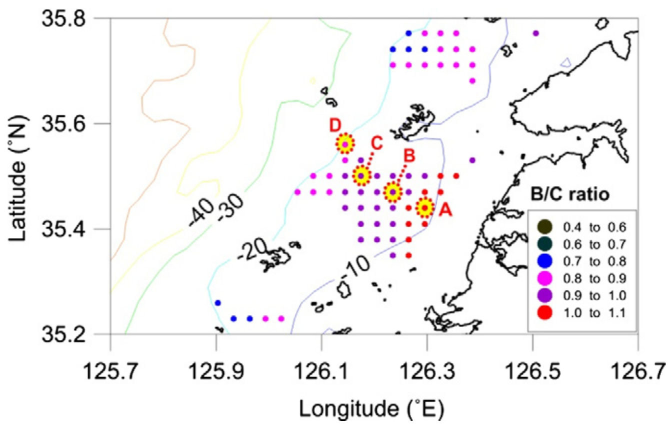


**Fig. 10.** Distribution of B/C ratio of Area II-4.

**Table 5**
Comparison of the calculation results among each cell of Area II-4.

| Factor | A | B | C | D |
|---|---|---|---|---|
| Longitude [°E] | 126.2952 | 126.2349 | 126.1747 | 126.1446 |
| Latitude [°N] | 35.4398 | 35.4699 | 35.5000 | 35.5602 |
| Depth of water [m] | 10.99 | 12.91 | 15.46 | 19.57 |
| Minimum distance from land [km] | 11.44 | 13.69 | 12.97 | 11.42 |
| Minimum distance from substation [km] | 11.96 | 18.22 | 24.55 | 30.19 |
| Wind speed [m/s] | 6.66 | 6.71 | 6.74 | 6.74 |
| Density of wind energy [W/m$^2$] | 362.19 | 370.38 | 377.62 | 380.16 |
| AEP [MWh]/1WT | 7094.98 | 7211.70 | 7291.42 | 7295.77 |
| Capacity factor of turbines (%) | 27.00 | 27.44 | 27.75 | 27.76 |
| Profit from power generation over 20 years/75 MW (k₩) | 619,392, 170 | 629,581, 334 | 636,540, 772 | 636,920, 293 |
| Profit from power generation over 20 years/75 MW (present value, k₩) | 286,568, 673 | 291,282, 803 | 294,502, 664 | 294,678, 254 |
| Turbine cost/1 MW (k₩) | 1,642,862 | 1,642,862 | 1,642,862 | 1,642,862 |
| Foundation cost/1 MW (k₩) | 837,763 | 868,213 | 908,442 | 973,392 |
| Collection system (k₩) | 23,796,470 | 23,796,470 | 23,796,470 | 23,796,470 |
| Integration system (k₩) | 23,479,036 | 23,479,036 | 23,479,036 | 23,479,036 |
| Transmission system (k₩) | 38,988,374 | 59,395,332 | 80,030,484 | 98,416,306 |
| SCADA/EMS (k₩) | 2,931,563 | 2,931,563 | 2,931,563 | 2,931,563 |
| Project development (k₩) | 5,487,885 | 5,487,885 | 5,487,885 | 5,487,885 |
| Total cost (k₩) | 280,730,203 | 303,420,891 | 327,073,234 | 350,330,311 |
| Total cost (present value, k₩) | 279,384,628 | 299,478,716 | 320,195,964 | 340,163,721 |
| B/C Ratio | 1.03 | 0.97 | 0.92 | 0.87 |

distribution of wind resources. Economic feasibility is more influenced by the cost of undersea cables for connection to the land grid than the cost of foundations influenced by sea depth. This area may be considered the most preferred candidate site because it has good conditions for connecting undersea cables, influencing economic feasibility, but the improvement of the rate of use of machinery through the selection of the optimal wind turbine and an in-depth review of the design of efficient undersea cables and offshore substations should be conducted for the successful development of a wind farm, because wind resources are not particularly good.

## 4. Conclusions

To evaluate the feasibility of offshore wind power development around the Korean Peninsula (South Korea) and select appropriate sites, economic feasibility of the development project was compared for the entire coast. Profit calculation was conducted by using a numerical wind map and the total development cost was calculated using a cost calculation formula corresponding to sea depth and the distance from undersea cables. The criteria for target sites were limited to below 20 m in depth, in consideration of the available range of the calculation formula, and were limited to over 10 km in distance from the coastline, in consideration of usage conditions of coasts and environmental concerns. As a result, the preferred target sites were mostly distributed in the West Sea, and some sites were distributed in the South Sea. As a result of the economic feasibility calculations, the sites with excellent economic feasibility are greatly influenced by the distance undersea cables must travel and the technology enabling the capacity factors of turbines to be improved. Cost savings for undersea cables are required for the successful development of offshore wind power development, because wind resources are not quite as good in these areas, by and large. Looking into the results of calculating the economic feasibility by area to select a candidate site, in addition, it is expected that the West Sea will be developed on a larger scale, because there are gradual areas of low depth, and site development will start centering around the area where land grid connection is easy. In this study, it is determined that the area stretching over Buan-gun in Jeollabuk-do and Yeonggwang-gun in Jeollanam-do is most advantageous in terms of possible farm development size and economic feasibility. It is expected that Korea's first government-led offshore wind farm will be developed here.

## Acknowledgments

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