Transmission Network Expansion Planning for the Penetration of Renewable Energy Sources – Determining an Optimal Installed Capacity of Renewable Energy Sources

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Abstract – Due to global environmental regulations and policies with rapid advancement of renewable energy technologies, the development type of renewable energy sources (RES) in power systems is expanding from small-scale distributed generation to large-scale grid-connected systems. In the near future, it is expected that RES achieves grid parity which means the equilibrium point where the power cost of RES is equal to the power costs of conventional generators. However, although RES would achieve the grid parity, the cost related with development of large-scale RES is still a big burden. Furthermore, it is hard to determine a suitable capacity of RES because of their output characteristics affected by locations and weather effects. Therefore, to determine an optimal capacity for RES becomes an important decision-making problem. This study proposes a method for determining an optimal installed capacity of RES from the business viewpoint of an independent power plant (IPP). In order to verify the proposed method, we have performed case studies on real power system in Incheon and Shiheung areas, South Korea.

Keywords: Renewable energy source, Transmission network expansion planning, Optimal installed capacity, Individual power plant

1. Introduction

Due to deregulation, environmental reasons and technical improvements, renewable energy sources (RES) are increasingly penetrated and operated in power systems [1]. Energy policies such as a renewable portfolio standard (RPS), mandate utilities and other load serving entities procure a significant portion of their customers' electricity needs from RES [2-5]. Furthermore, these clean energy sources have become cost-competitive with conventional power systems [6, 7]. In some areas, the power cost of RES, including photovoltaic generation (PV) and wind turbine (WT), have already started to reach grid parity because these cost depend mainly on the area where the RES is located, while the power cost of conventional power such as coal-based power is depend on the fuel cost and it has shown a tendency to increase [8, 9]. For these reasons, the development of RES in power system is increasing, and the size is expanding from small-scale distribution systems to large-scale transmission systems.

The availability of RES varies over time, with location and with a kind of the used resource. The output of RES is intermittent and particularly hard to control compared to conventional power plants which are designed on a large scale for continuous operation and control the output [10]. Additionally, in most conventional power plants, changes in financing terms have had relatively little impact on power costs because the capital cost element in the power cost is small. On the other hand, the capital cost of RES forms the largest element of power cost. Governments have resolved these issues in order to promote the uptake of RES through a feed-in tariff, quota system, carbon tax and trading, and tax relief [11]. Nevertheless, renewable energy projects are still under some economic strains, especially for individual power plants (IPP). Therefore, IPP's stance on issues, such as determining an economic installed capacity of RES and location, has become more important.

Various studies for determining an optimal installed capacity of RES have introduced and provided methods. In [12], the objective function is to minimize the total cost involved in RES construction. In [13, 14], minimizing energy loss is considered as the objective function. Jianhui Wang et al. [15] proposes a method for solving a problem between individual generating companies' own decision and the independent system operator (ISO)'s market clearing problem. Gianni Celli et al. [16] presents an objective function in order to minimize the total cost on network upgrading, service interruptions, and energy purchased. However, most research is focused on the ISO's stance considering network conditions, constraints, and expenses. Therefore, determining size of RES in an IPP's stance has to be studied in order to voluntarily promote the

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uptake of RES. In this respect, this paper proposes a methodology to determine an optimal installed capacity of RES for profit maximization in IPPs, considering construction costs, interconnection costs, operation and maintenance costs, and the generation of revenue. The proposed method is applied to real power systems in South Korea in order to verify it.

2. Problem Formulation

The fixed cost for constructing a new power generation can be only considered for short term or temporary expenses. On the other hand, the variable benefit has to be considered during the warranty period of new power generation. It has to be considered as the present value of the variable benefits in the future. As a result, the investment plan of new power generation is evaluated based on the net present value (NPV), which is an indicator of how much value the investment of a new generation project adds to the IPP [17-20].

2.1 Objective function

In this paper, the optimal installed capacity of RES is determined by the maximized NPV that an IPP can obtain. This is determined by the maximized benefit with fixed costs and variable benefit. Accordingly, the objective function to select the optimal installed capacity of RES can be defined as follows:

Maximize:

$$NPV(g,k,P_{g,k}^{size}) = B(g,k,P_{g,k}^{size}) \cdot \frac{(1+r)^{N_g}-1}{r \cdot (1+r)^{N_g}} - C(g,k,P_{g,k}^{size})$$

(1)

$$\overline{P_{g,k}^{size}} = \left\{ P_{g,k}^{size} \middle| \underset{\forall P_{g,k}^{size}}{Max} \left(NPV(g,k,P_{g,k}^{size}) \right) \right\}$$

(2)

Subject to:

$$0 < P_{g,k}^{size} \le P_{g,k}^{size,max}$$

(3)

where Ng and r are the warranty period of RES g and the discount rate, respectively. The installed capacity of RES g located in k is $P_{g,k}^{size}$. The maximum installable capacity is based on the total land size, represented as $P_{g,k}^{size,max}$. C and B describe the fixed cost and annual benefit, respectively, upon all available installed capacity of RES. These variables will be covered in detail in the following paragraphs.

2.2 The fixed cost: C

The fixed cost in this paper is the initial cost for

construction and grid connection of the RES. This cost is a temporary expense, and can be described as the sum of the construction cost, C^{CT} and grid connection cost, C^{IC}. Therefore, it can be represented as follows:

$$C(g,k,P_{g,k}^{size}) = C^{CT}(g,k,P_{g,k}^{size}) + C^{IC}(g,k,P_{g,k}^{size})$$

(4)

2.3 The variable benefit: B

The annual variable benefit from the RES is based on operation of the RES. This benefit is calculated as the subtraction between annual power generation revenue, $R^{Gen.}$, and operation and maintenance (O&M) cost, $C^{O\&M}$. It can be described as follows:

$$B(g,k,P_{g,k}^{size}) = R^{Gen.}(g,k,P_{g,k}^{size}) - C^{O\&M}(g,k,P_{g,k}^{size})$$

(5)

3. Sizing Indices

The factors for determining an optimal installed capacity of RES are divided into income and expenses from the IPP's stance. In this paper, the capital cost of RES includes construction costs and grid connection costs as well as the O&M costs, and these costs are considered as expenses [21, 22]. On the other hands, power generation revenue from the RES is considered to be income.

3.1 Construction costs

While the exact construction costs of the RES could not be defined as a single form, they are broadly similar to the global estimate. Therefore, total construction cost could be estimated by the unit cost of construction per generation capacity. As such, the construction costs of RES could be defined as follows.

$$C^{CT}(g,k,P_{g,k}^{size}) = C_g^{CT} \cdot P_{g,k}^{size}$$

(6)

Here, C_g^{CT} is the unit construction cost per MW according to the types of generation source.

3.2 Interconnection costs

The interconnection costs of the RES in a network have led to the problem on the attribution of responsibilities between grid operators and generators. Different practices are separated to 3 approaches as Deep, Shallow and Super-Shallow based on the attribution of grid connection costs and grid reinforcement costs [23].

3.2.1 Deep charging approach

An approach where a renewable generation operator bears all of the connection costs for the grid connection line and the reinforced cost of the transmission system.

3.2.2 Shallow charging approach

An approach where a renewable generation operator bears the grid connection line cost, and the reinforced cost is borne by the transmission operator.

3.2.3 Super-Shallow charging approach

An approach where the transmission operator bears both the grid connection line cost and the reinforced cost of the transmission system.

In the case of Europe, the deep charging approach was generally used at initial stages of development. It was replaced by the shallow charging approach to bear grid connection costs by renewable generation operator, and has spread to the super-shallow approach at present [24]. South Korea is operating under the shallow charging approach. Therefore, this study assumes that the connection costs in IPP's stance are limited to the grid connection line cost. The connection cost of new power generation can deploy the formula for installed capacity and the distance to the connecting point as follows:

$$C^{IC}(g,k,P_{g,k}^{size}) = C^{IC}(P_{g,k}^{size}) \cdot d_k \qquad (7)$$

where, $C^{IC}(P_{g,k}^{size})$ is the unit grid connection cost per MW·km of power generation, g, and d_k represents the distance of the connection point of the transmission line to the new power generation facility. Generally, priority consideration for grid connection planning is given to the new power generation operator when the generation operator connects to the grid. The connection to either a substation of the shortest distance, or a nearby power generation facility or bus, must primarily be considered [25].

3.3 Operation and maintenance costs

In this paper, O&M costs includes labor cost, materials cost and repair & maintenance cost in order to operate and maintain the RES, which installed capacity is $P_{g,k}^{size}$. The annual cost for O&M of RES is defined as follows:

$$C^{O\&M}(g,k,P_{g,k}^{size}) = C_g^{O\&M} \cdot \int_{t=0}^{8760} P_{g,k}(t) \cdot dt \qquad (8)$$

where $C_g^{O\&M}$ means the unit cost of O&M per MWh generated from RES g. The output of RES g at time t is described by $P_{g,k}(t)$.

3.4 Generation revenue

The revenue from power generation means profit which is obtained by the sale of electric power, and it is determined by the amount of power and the power sale price of delivery time.

The formula below describes the power generation equations for PV and WT:

$$P_{g,k}(t)\big|_{PV} = \begin{cases} \dfrac{\eta_g}{W_g} \cdot G_k^{2}(t) \cdot P_{g,k}^{size} & 0 < G_k(t) \le W_g \\ \eta_g \cdot G_k(t) \cdot P_{g,k}^{size} & G_k(t) > W_g \end{cases} \qquad (9)$$

$$P_{g,k}(t)\big|_{WT} = \begin{cases} 0 & 0 < V_k(t) \le V_{ci} \\ \{a_g + b_g \cdot V_k(t) + c_g \cdot V_k^{2}(t)\} \cdot P_{g,k}^{size} & V_{ci} < V_k(t) \le V_r \\ P_{g,k}^{size} & V_r < V_k(t) \le V_{co} \\ 0 & V_{co} < V_k(t) \end{cases}$$
$$(10)$$

The output of RES g differs according to the grid connection point k. Furthermore, the output of PV is affected by weather conditions and characteristics of PV system. W_g is the irradiation point, where further increases in irradiation produce relatively small change in efficiency. $G_k(t)$ and η_g is irradiation and the corresponding efficiency via W_g, respectively. On the other hand, the output of WT can be calculated using wind velocity, $V_k(t)$ and the constant output coefficients, a_g, b_g and c_g. Therefore, there are limitations to control and forecast the output of these types of power generation. In other words, the RES may produce less than the amount anticipated by power generation operators during special circumstances, and electrical power from the RES might be larger than the capacity of the grid connection line at other times. As a result, the actual power from RES to the grid should be limited by the transmission transfer capability, and it is represented as follows:

$$P_{g,k}^{output}(t) = Min\left(P_{g,k}(t), P_{g,k}^{IC}\right) \qquad (11)$$

This equation confirms that the actual power from the RES to the grid is determined as the smaller amount between the output power of RES g at time t, $P_{g,k}(t)$ and the total transfer capability (TTC) of the interconnection line, $P_{g,k}^{IC}$.

The revenue from annual power sales of the RES is defined as the actual supply of power and the power sale price based on each time as follows [26]:

$$R^{Gen.}(g,k,P_{g,k}^{size}) = \int_{t=0}^{8760} \pi(t) \cdot P_{g,k}^{output}(t) \cdot dt \qquad (12)$$

where $\pi(t)$ is the power sale price at time t.

4. Flow Chart for Determining an Optimal Installed Capacity of RES

Finally, the process for determining an optimal installed capacity of RES is described in Fig. 1.
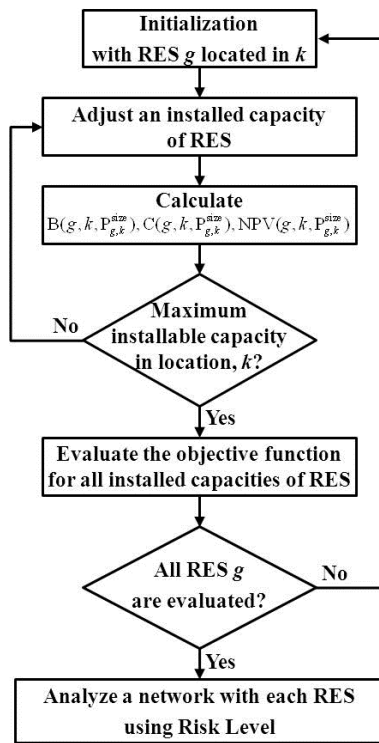After determining the installed capacity of RES in a

Fig. 1. Flow chart for determining an optimal installed capacity of RES

network, the effects derived from this RES are evaluated by the risk level which will be proposed in our future work.

5. Case Study

Actual grid data of Incheon and Shiheung in South Korea have been applied to the case study for high-voltage

transmission lines in the range of 154kV to 345kV. The map for the objective grid is in Fig. 2.

G2, G3 and G4 are power generators for actual grid, and G1 and G5 are the existing power generators on the power system. No additional RES are in this system. A PV and WT are interconnected into case study system in Case 1 and Case 2, respectively. The location of RES in each case is presented on the following map:

The PV in Case 1 is installed nearby Hwaseong Lake, and it is interconnected at Bus No.12. The wind farm in Case 2 is installed at offshore of Mokdeok Island, and it is interconnected at Bus No.1.

Fig. 3. The location of the RES in each case

Fig. 2. Case study system

Table 1. The power sale price

Time Zone [hour]	Price [$/MWh]
0-6, 22-24	100
6-12, 17-22	200
12-17	500

All system data and grid constraints are based on the real data in KEPCO (Korea Electric Power Corporation). It is assumed that the power sale price, $\pi(t)$ is defined differently according to 3 different time zones in order to calculate the practical revenue of RES, $R^{Gen.}(g, k, P_{g,k}^{size})$.

The optimal installed capacity of RES is calculated by Matlab 7.0.4.

5.1 Case 1: Photovoltaic generation

The output from PV system is in general based on temperature and irradiation. In this case study, the output of PV is calculated using irradiation only in order to simplify the calculation process. For calculating an output of PV in the Case 1, the irradiation data measured at the area of Hwaseong Lake during 2010 were used.

It is assumed that the area for photovoltaic power generation is 988 acres (4km²) and the model of the PV module is S-Energy 285PC8, which data are presented in the following table:

In cases of PV systems, they usually use approximately 40% of the total land size for electrical energy production. Therefore, the maximum installable capacity is limited to 230MW at Case 1.

ACSR240*1 line/2 lines, ACSR330*1 line and ACSR410*1 line are postulated in regard to the feasible lines for interconnecting the PV. The distance for interconnection is 25km, and the interconnection costs by each line for this system are as follows:
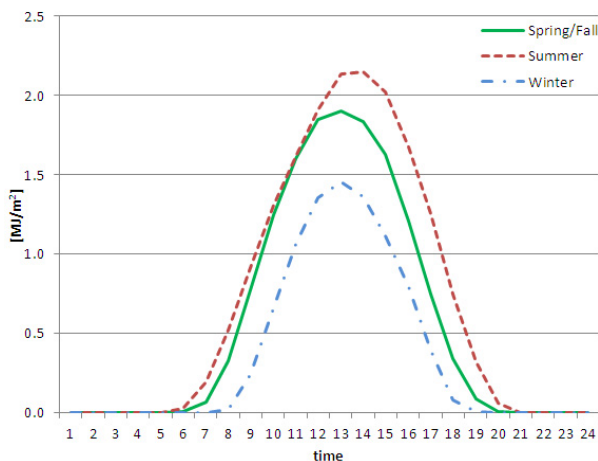

Fig. 4. Case 1: daily average irradiation

Table 2. Case 1: data of the PV module

Output [W]	Module Size [mm]	Warranty [year]
285	1985*999*50	20

Table 3. Case 1: interconnection costs of feasible transmission lines

Transmission line model	TTC [MW]	Interconnection costs per km [million$/km]	The total interconnection costs [million$]
ACSR240*1	142	0.3432	8.58
ACSR320*1	172	0.3432	8.58
ACSR410*1	200	0.4092	10.23
ACSR240*2	284	0.52	13.00

The unit construction cost (C_g^{CT}) and O&M cost ($C_g^{O\&M}$) of the PV are 9.6 million$/MW, 12.8 $/MWh [11].

An optimal installed capacity of a PV is determined by NPV analysis on each interconnection line model and the results are shown in Fig. 5.

The Installable Capacity Zone which means the maximum available capacity at the limited land size for the PV in Case 1, is 230MW. The solid line represents the daily variable benefit of PV power generation and O&M cost, and the dotted line shows NPV based on a 3% discount rate for 20 years as the warranty period of the PV. In the cases of ACSR240*1 line and ACSR330*1 line for an interconnection line between the PV and the existing grid, 185MW and 224MW are the optimal capacities, respectively, because NPV is the highest at that point. In the case of ACSR410*1 line and ACSR240*2 lines for the interconnection, 260MW and 369MW are the optimal capacities, respectively. However, these capacities exceed the "Installable Capacity Zone" based on the limited land size, and thus 230MW is the optimal capacity in the cases of ACSR410*1 line and ACSR240*2 lines.

Table 4 shows the results of the optimal capacity for PV. In case 1, ACSR410*1 line is determined as an interconnection line for PV system and the optimal installed capacity of the PV is 230MW, where it has as much NPV as possible.

5.2 Case 2: Wind farm

The WT captures the wind's kinetic energy in a rotor, and the power extracted by the rotor blades is affected by wind velocity, rotor swept area and air density varied with pressure and temperature [27]. This case study calculates the output of the WT based on wind velocity. In the Case 2, the following wind velocity data acquired by KMA during 2010 near Mokdeok Island were used.

It is assumed that the maximum installable capacity is 1GW for offshore wind power generation in case 2. A Vestas V90-3.0MW is applied as the model of offshore WT,

Table 4. Case 1: optimal capacity of the PV by NPV analysis

Interconnection line model	max NPV analysis	
	Capacity of PV[MW]	NPV [million$]
ACSR240*1 line	185	275.48
ACSR320*1 line	224	335.52
ACSR410*1 line	260	390.18
ACSR240*2 lines	369	555.65

(a) ACSR240*1 line

(b) ACSR330*1 line
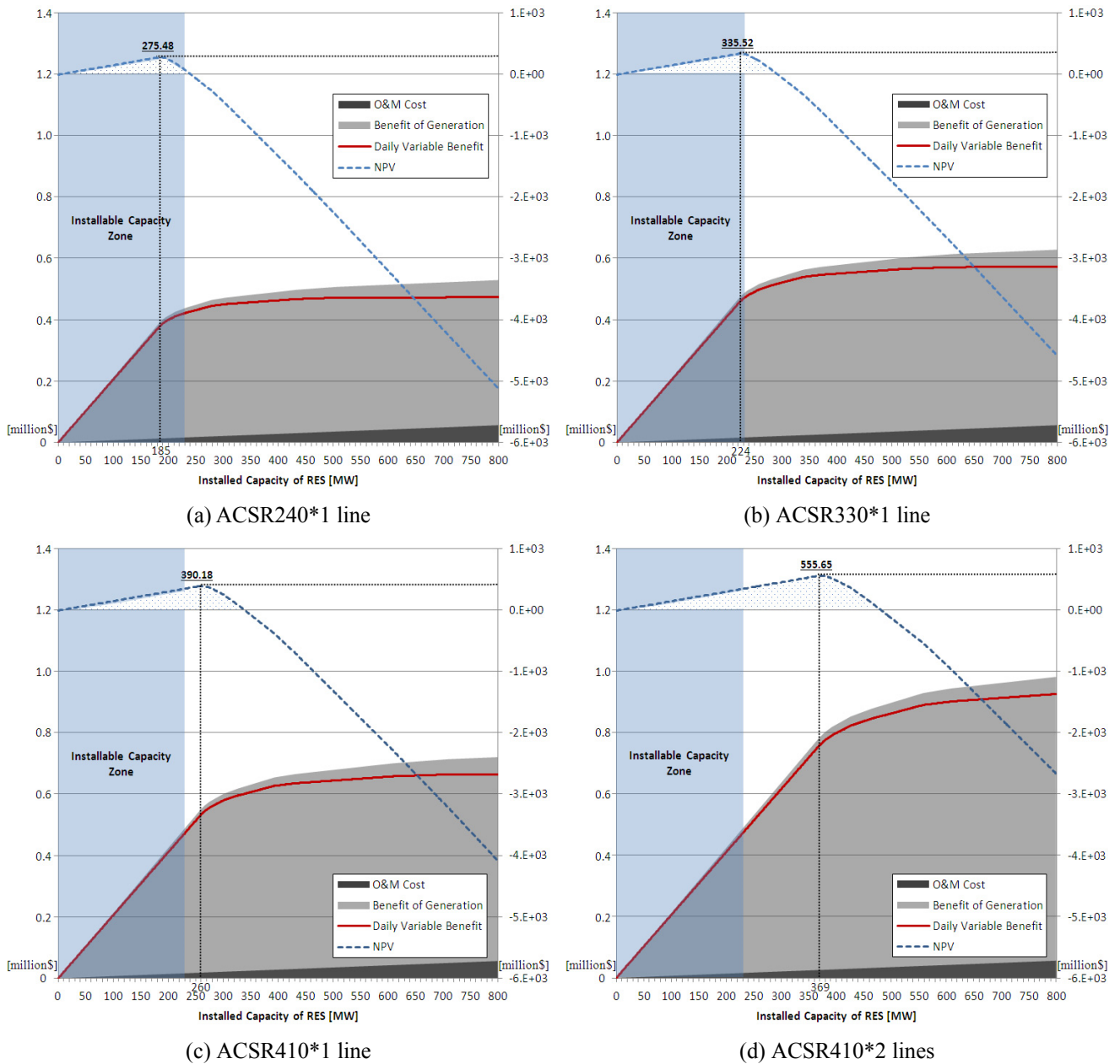

(c) ACSR410*1 line

(d) ACSR410*2 lines

Fig. 5. Case 1: NPV analysis of installed capacities of PV

Table 5. Case 2: data of the WT

Output [MW]	Cut-in speed [m/s]	Nominal speed [m/s]	Cut-out speed [m/s]	Warranty [year]
3	4	15	25	15

Table 6. Case 2: the interconnection cost of HVDC

Transmission line model	TTC [MW]	Interconnection cost per km [million$/km]	The total interconnection cost [million$]
HVDC*2 lines	150*2	4	74

which data are presented in the following Table 5:

The advantage of high-voltage direct current (HVDC) is the ability to transmit huge amounts of power with lower losses, especially in undersea cables where high capacitance causes additional AC loss. Therefore, HVDC is used for the interconnection line between the offshore wind power generation and an inland transmission network. The actual data of HVDC between Jeju Island and Haenam in

South Korea is applied to Case 2 [28-30]. The following table represents TTC, the unit grid connection cost and interconnection cost of HVDC for 18.5km interconnection between the wind farm and Bus No.1, which is the nearest existing network from the wind farm.

The daily benefit of wind farm generation, O&M cost and daily variable benefit are calculated in regards to an
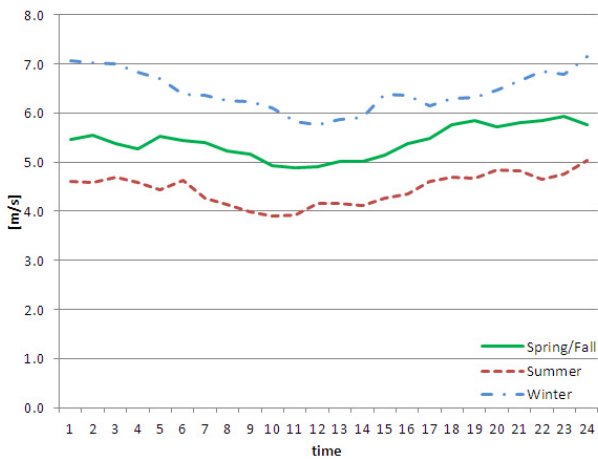
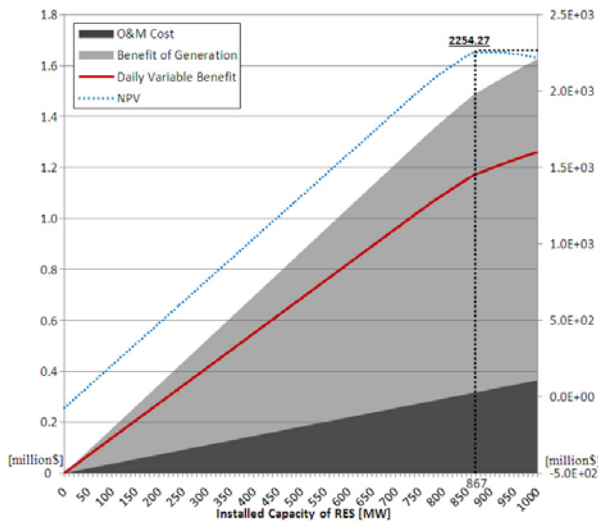**Fig. 6.** Case 2: daily average wind velocity

Fig. 7. Case 2: NPV analysis of installed capacities of a wind farm

Table 7. Case 2: the optimal capacity of the wind farm by NPV analysis

Interconnection line model	max NPV analysis	
	Capacity of PV[MW]	NPV [million$]
HVDC	867	2254.27

installed capacity of wind farm, and then NPV is analyzed by the fixed cost and the annual benefit. These results are represented in Fig. 7.

The solid line represents the daily variable benefit by benefit of WT power generation and O&M cost, and the dotted line shows NPV based on 3% discount rate for 15 years as the warranty period of WT.

As a result, in case of HVDC*2 lines for the interconnection line between the wind farm and the existing grid, installing 867MW for the wind power generation makes the highest value as NPV, 2254.27 million$. In here, the quantity of WT is 289 units for the 867MW offshore wind farm.

6. Conclusion

This paper proposes the method for determining an optimal installed capacity of RES from an economic perspective. In order to verify the proposed method in this paper, data sets from real power systems in Incheon and Shiheung, South Korea are applied to case studies.

This study will be helpful in determining the capacity, from a business viewpoint of IPP, and can encourage voluntarily participation in installing RES.

This paper is limited to pre-TNEP step. In our future work, the effects derived from RES installation will be evaluated by a proposed method called risk level. Furthermore, the optimal network planning using this risk level assessment will be also proposed in Part II.

Acknowledgements

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