Methodology of New Effective Installed Reserve Rate considering Wind Turbine Generators

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Contents

1. Introduction

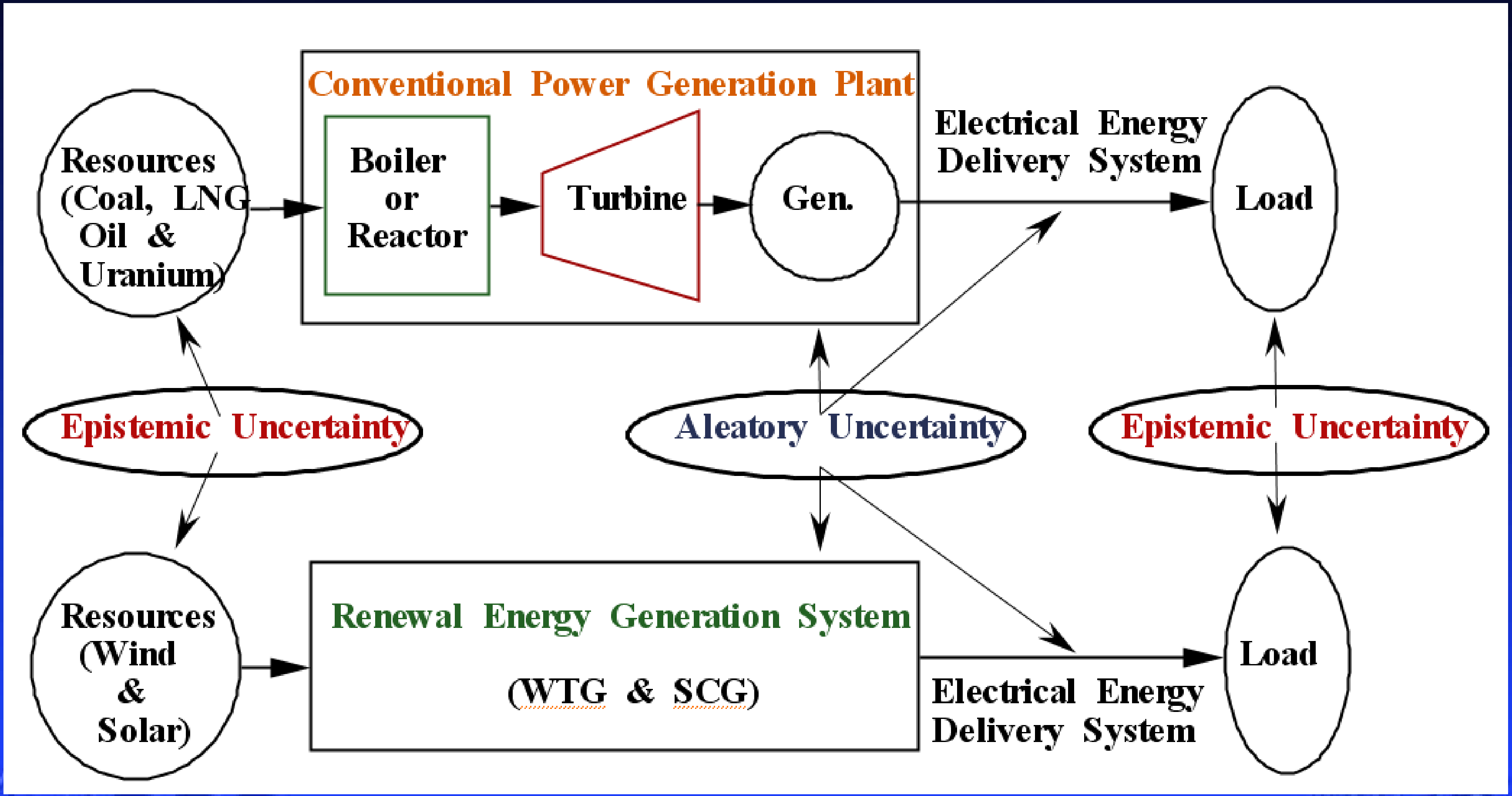
Location of REG(Renewable Energy Generator) is distributed because the successful operation of the REG depends on their renewable resource supply very strongly.

Resources and power control of REG are difficult relatively than the conventional generators as like as the nuclear, coal, LNG, etc. power plants.

Outage of renewable energy resource may give the same effect with forced outage of conventional generators to demand in viewpoint of reliability.

➢ **Aleatory uncertainty: Outage of Unit (Ex, Outage of Generator, Lines..)**
➢ **Epistemic uncertainty: Uncertainty of Information (Ex, Forecast of Load, Supply of Resources)**

[3]: Roy Billinton and Dange Huang, "Aleatory and Epistemic Uncertainty Considerations in Power System Reliability Evaluation", PMAPS, May 25-29, 2008.].



- **“How should the REG with high uncertainty level be handled and solved in order to operate successful system and make a reasonable planning?”**
- **This paper proposes a new effective installed reserve rate in order to evaluate reliability of power system considering renewable generators, which include uncertainty of resource supply. It is called EIRR(effective installed reserve rate) in this paper.**
- **It is developed with considering capacity credit based on ELCC(Effective Load Carrying Capability) by using LOLE reliability criterion. The proposed method is applied to Jeju system in South Korea.**

Two Methods for Evaluating the Capacity Credit

- One uses ELCC in viewpoint of reliability as previous comments.

- Anther uses capacity factor in view point of economics.

The ELCC is used in this paper because it is focused on development of reliability new index rather than economics viewpoint.

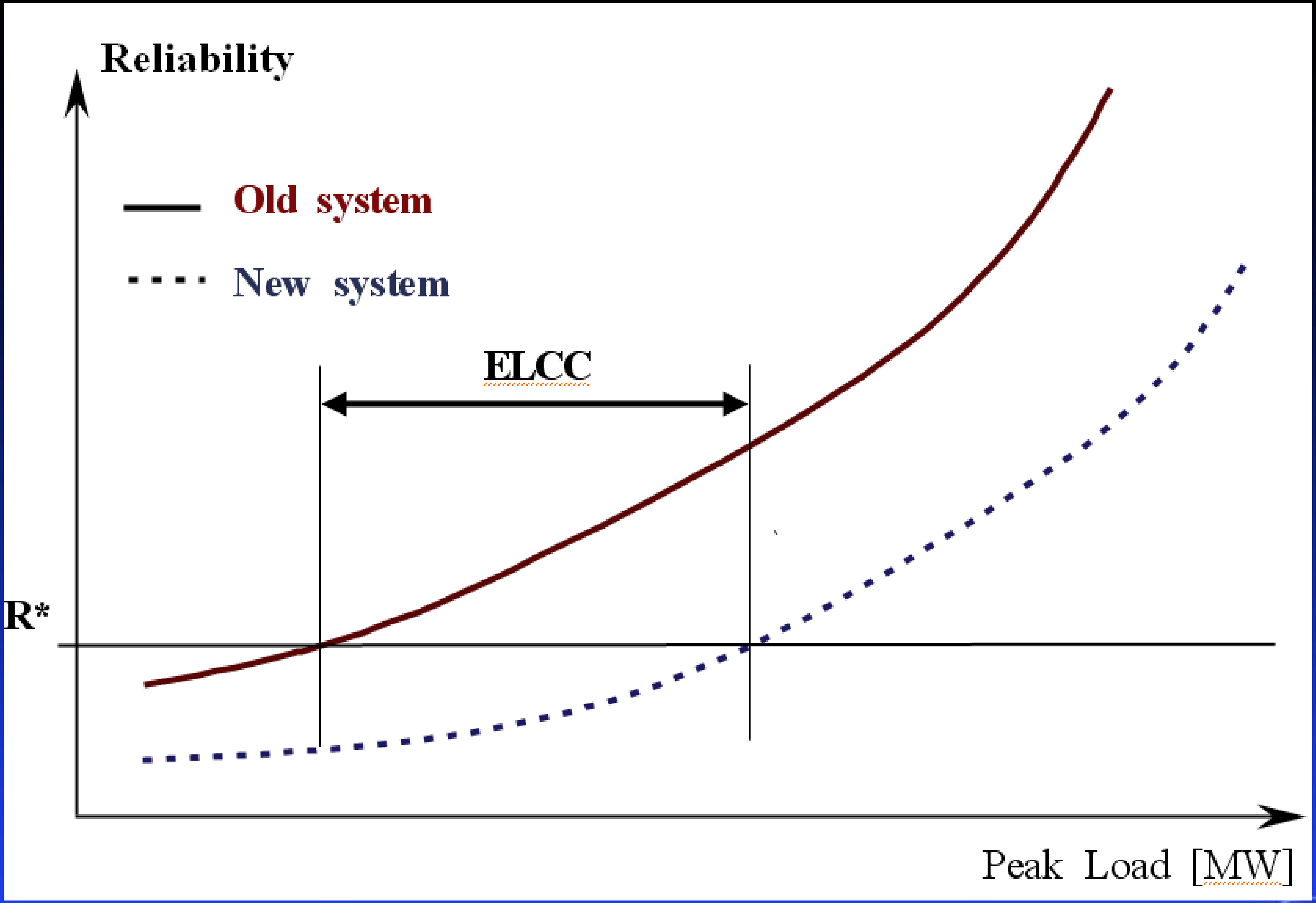
2. Effective Load Carrying Capability(ELCC)

ELCC?
"How much does a new generator cover future load with considering uncertainty of the generator?"[5].

Answer) It is defined as difference of increasing system loads between before and after the new generator penetration in looking for same target risk level.

How much is the actual reliability contribution of new generator?
It is one of the actual contribution assessment methods

[5] L. L. Garver, "Effective load carrying capability of generating units," IEEE Transactions on Power Apparatus and Systems, vol. PAS-85, no. 8, 1966, pp. 910-919.


Reliability
Old system
New system
ELCC
R*
Peak Load [MW]

$$\sum_{i=1}^{n} P(X_E > C_E - L_i) \cdot t_i = \sum_{i=1}^{n} P(X_P > (C_E + C_A) - (L_i + \Delta L)) \cdot t_i$$

$$\text{Capacity Credit } (\mu) = \frac{\Delta L}{C_A} \times 100 \ [\%]$$

ΔL is the extra load that can be served by the additional generation
X_E : random variable of outage capacity pdf before adding WTG
X_p : random variable of **outge capacity pdf after adding WTG**
C_E : the capacity before adding WTG
C_A : the added generator's capacity

3. Effective Installed Reserve Rate

$$IRR = g(C_i, L_p) = \frac{\sum C_i - L_p}{L_p} \times 100 \text{ [\%]}$$

$$EIRR = g(C_k, \mu_k, L_p)$$

$$= \frac{\left(\sum_{k \in GC} C_{Ck} + \sum_{k \in GR} C_{Rk} \times \mu_k - L_p\right)}{L_p} \times 100$$

C_{Ck}: k^{th} capacity of conventional generator [MW]
C_{Rk}: k^{th} capacity of renewable energy [MW]
μ: capacity credit
GC: conventional generators group
GR: renewable generators group

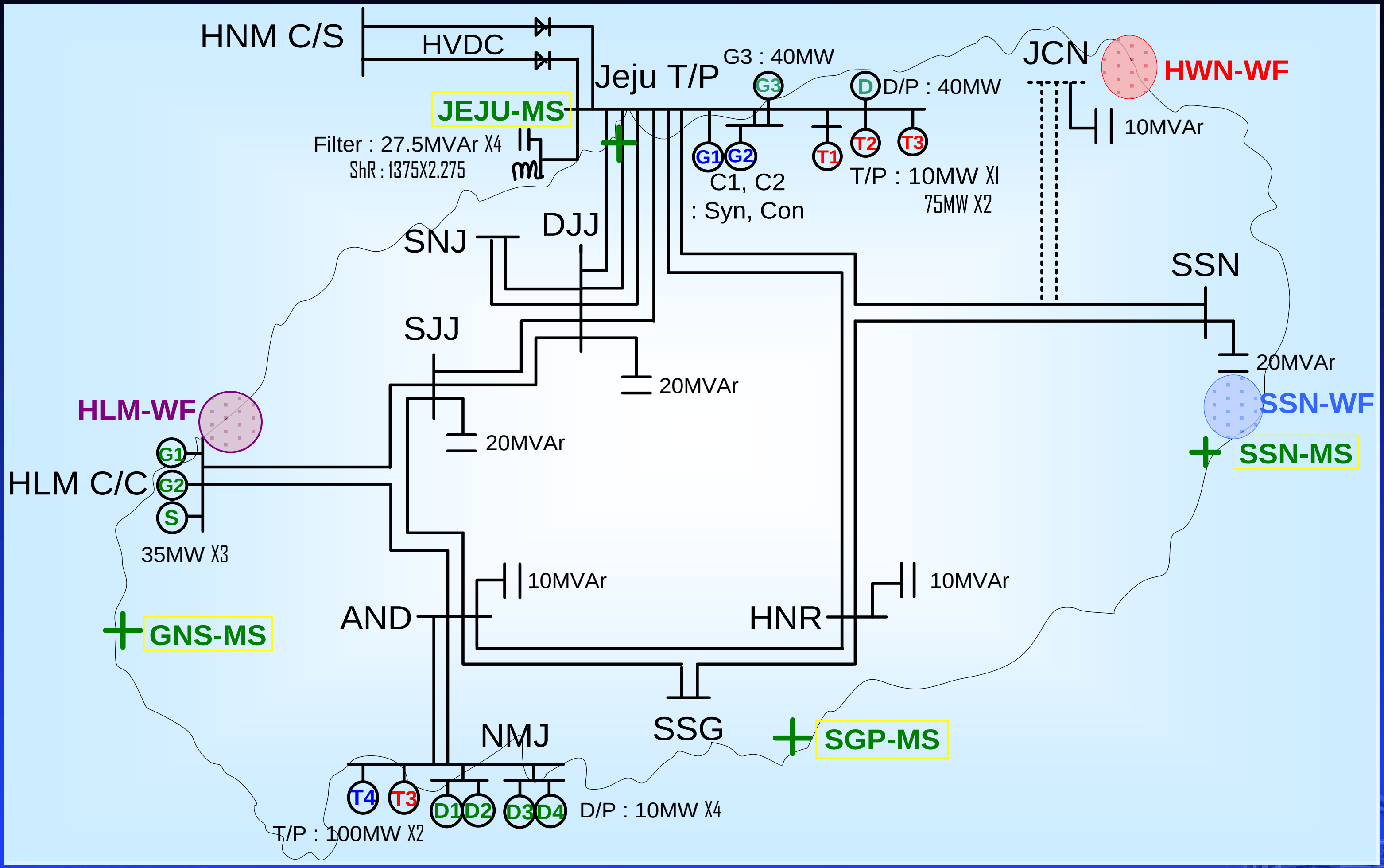
For example:

The present install capacity is 550MW and peak load is 500MW. Assume that new WTG of the capacity 100MW is penetrated.

- ✓ **The conventional install reserve rate yields IRR=30%. (= 150x100/500[%])**
- ✓ **But, ELCC range of 100MW of WTG has from 20~30MW and so the percent capacity credit is 20~30%. It is more reasonable, therefore, that the actual effective installed reserve rate should be assessed 14~16%.**

4. Case Studies

A map of Jeju Island



- **Model system**

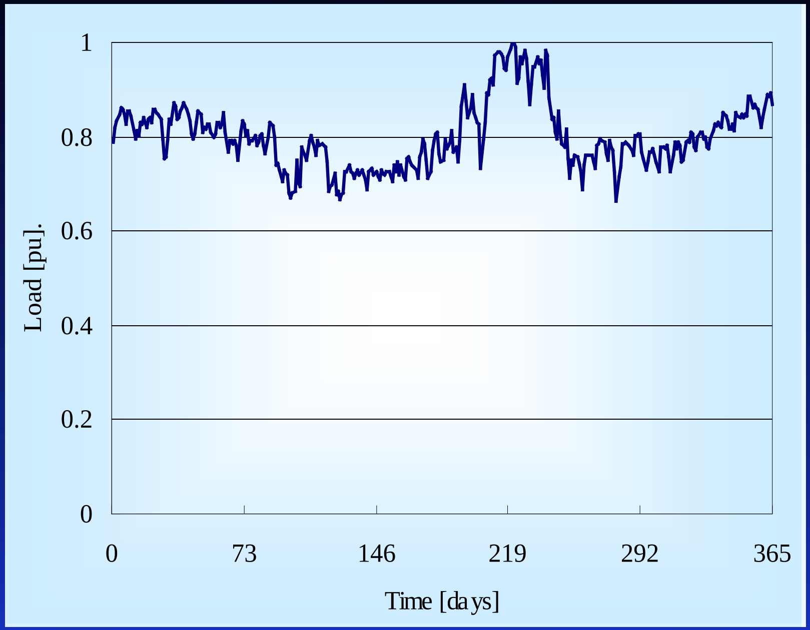
Total capacity is 945MW.

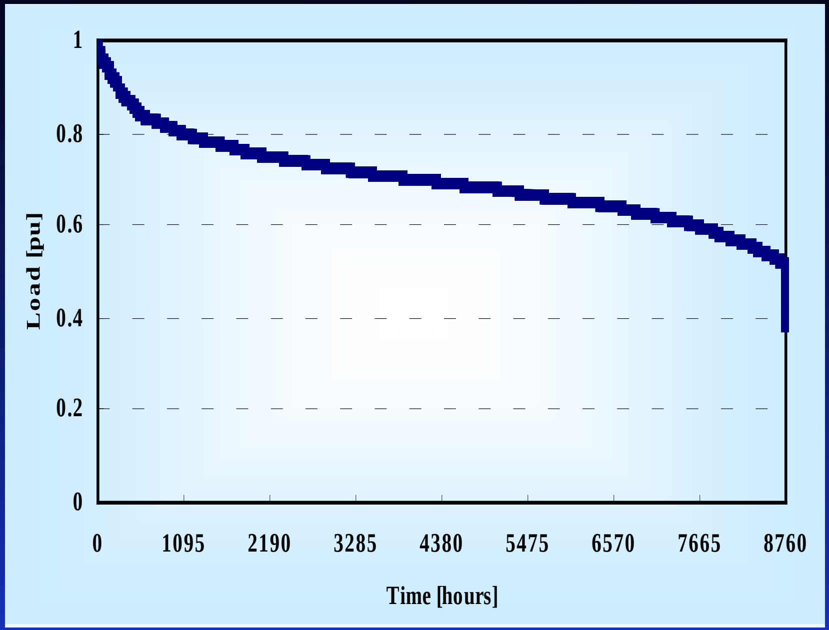
The capacity of conventional generators is 845MW

The capacity of wind turbine generators is 100MW

$$IRR = \frac{(945-681)}{681} \times 100 = 38.77\ [\%]$$

	Name	Type	Capacity [MW]	Num	α [Gcal/ MW^2h]	β [Gcal/ MWh]	γ [Gcal /hr]	Fuel cost [$/ Gcal]	FOR
1	HWN1	WTG	50	1	-	-	-	-	-
2	SSN2	WTG	30	1	-	-	-	-	-
3	HLM3	WTG	20	1	-	-	-	-	-
4*	HVDC	DC	75/150*	2	0.004	1.512	45.207	43.3	0.010/ 0.028*
5	NMJ3	T/P	100	2	0.004	1.512	45.207	43.3	0.012
6	JJU1	T/P	10	1	0.062	2.100	5.971	43.599	0.015
7	JJU2	T/P	75	2	0.003	1.832	30.231	43.599	0.012
8	HLM1	G/T	35	2	0.004	2.401	20.32	77.909	0.013
9	HLM1	S/T	35	1	0.004	2.401	20.32	77.909	0.013
10	JJU3	D/P	40	1	0.025	0.364	28.484	43.599	0.018
11	NMJ1	D/P	10	4	0.006	1.999	1.36	43.3	0.018
Total			945	18	-	-	-	-	-

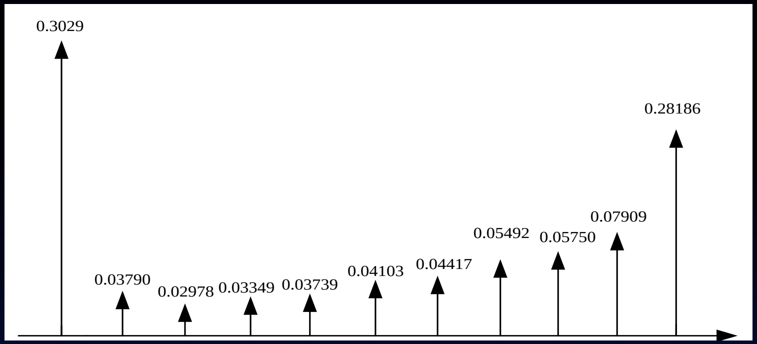




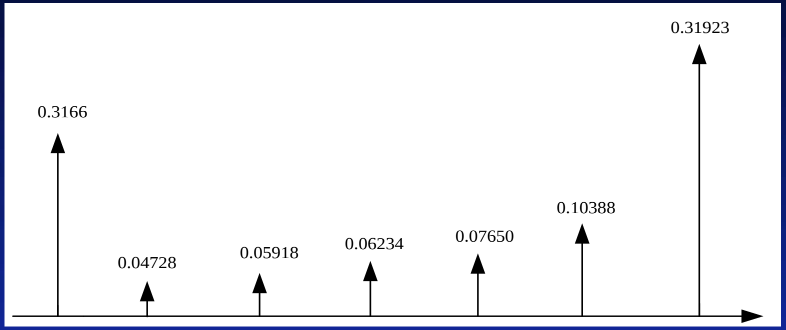
- **Daily peak load variation curve**
- **Daily peak load duration curve**

The data of each WF

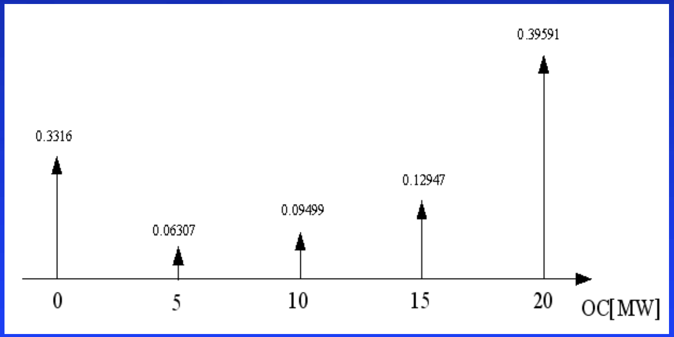
WF Name	HLM-WF	SSN-WF	HWN-WF
WTG capacity	20MW	30MW	50MW
Cut-in speed(V_{ci})	5m/sec	5m/sec	5m/sec
Rated speed(V_R)	14m/sec	15m/sec	16m/sec
Cut-out speed(V_{co})	25m/sec	25m/sec	25m/sec
Wind speed range	0~35	0~40	0~45
Mean wind speed	6.4	7.6	8.5
Standard deviation	9	10	11



(a) Outage capacity density function(f_{o1}) of WTG at HWN-WF



(b) Outage capacity density function (*fo2*) of WTG at SSN-WF

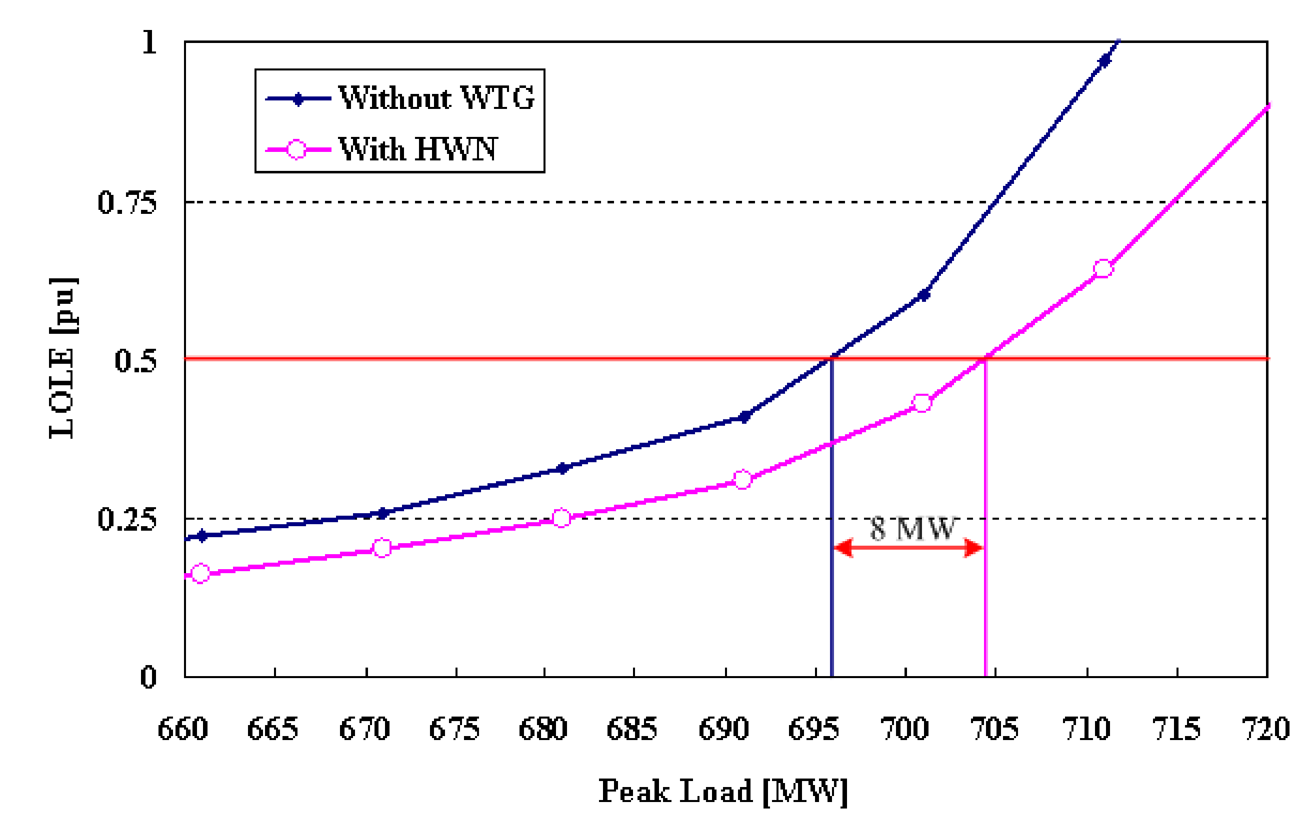


(c) Outage capacity density function(*fo3*) of WTG at HLM-WF

Results

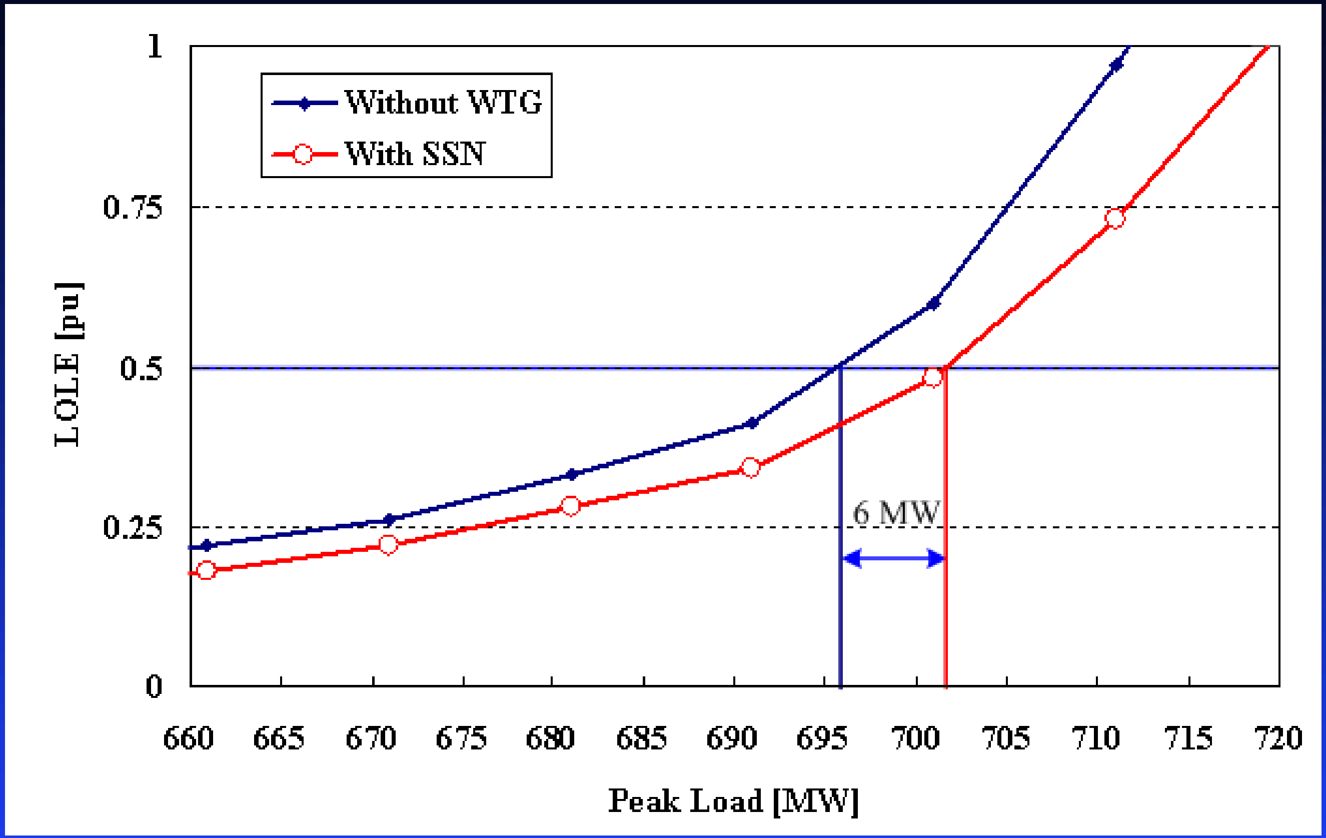
	Without WTG	With WTG
LOLE [days/year]	0.33	0.19
EENS [MWD/year]	12.88	7.01
EIR [pu]	0.99994	0.99996

ELCC of HWN



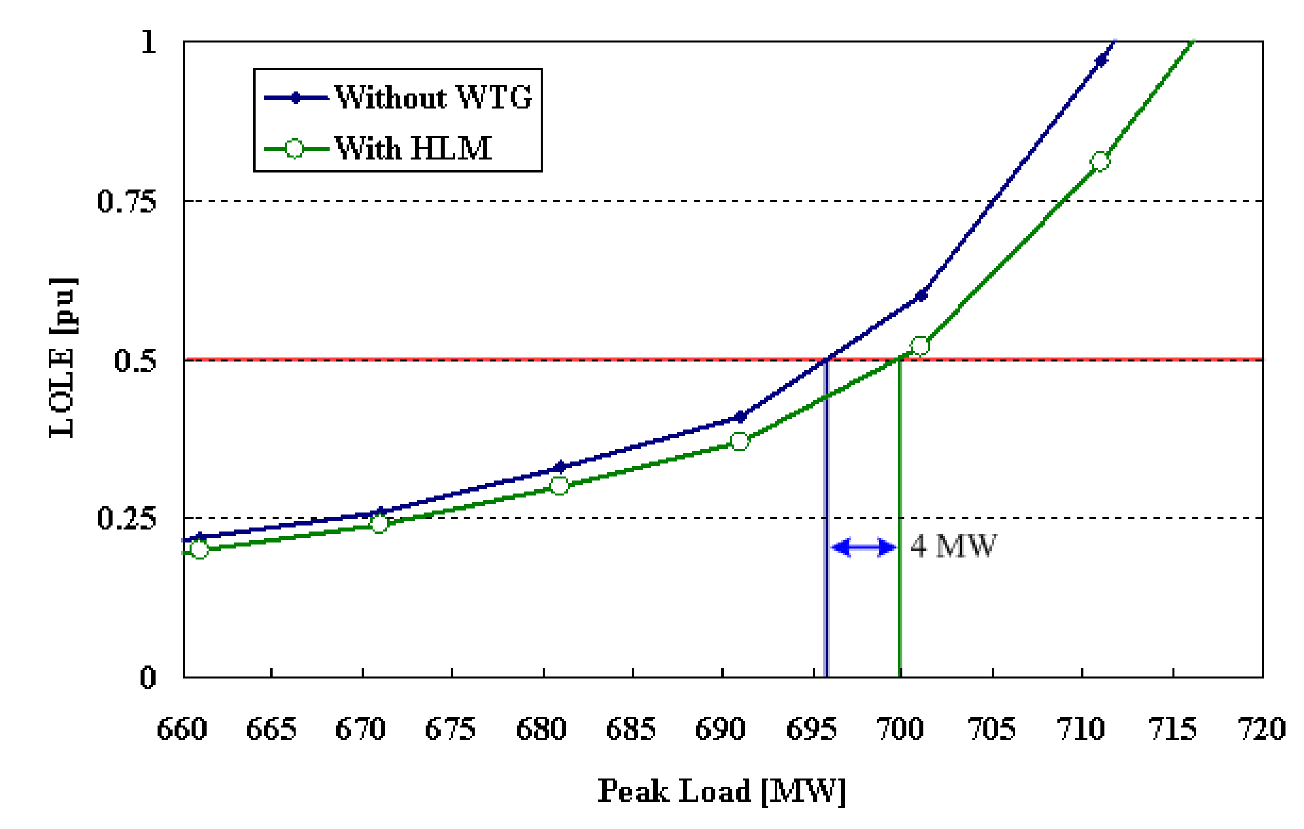
Without WTG
With HWN
8 MW
LOLE [pu]
1
0.75
0.5
0.25
0
660
665
670
675
680
685
690
695
700
705
710
715
720
Peak Load [MW]

ELCC of SSN



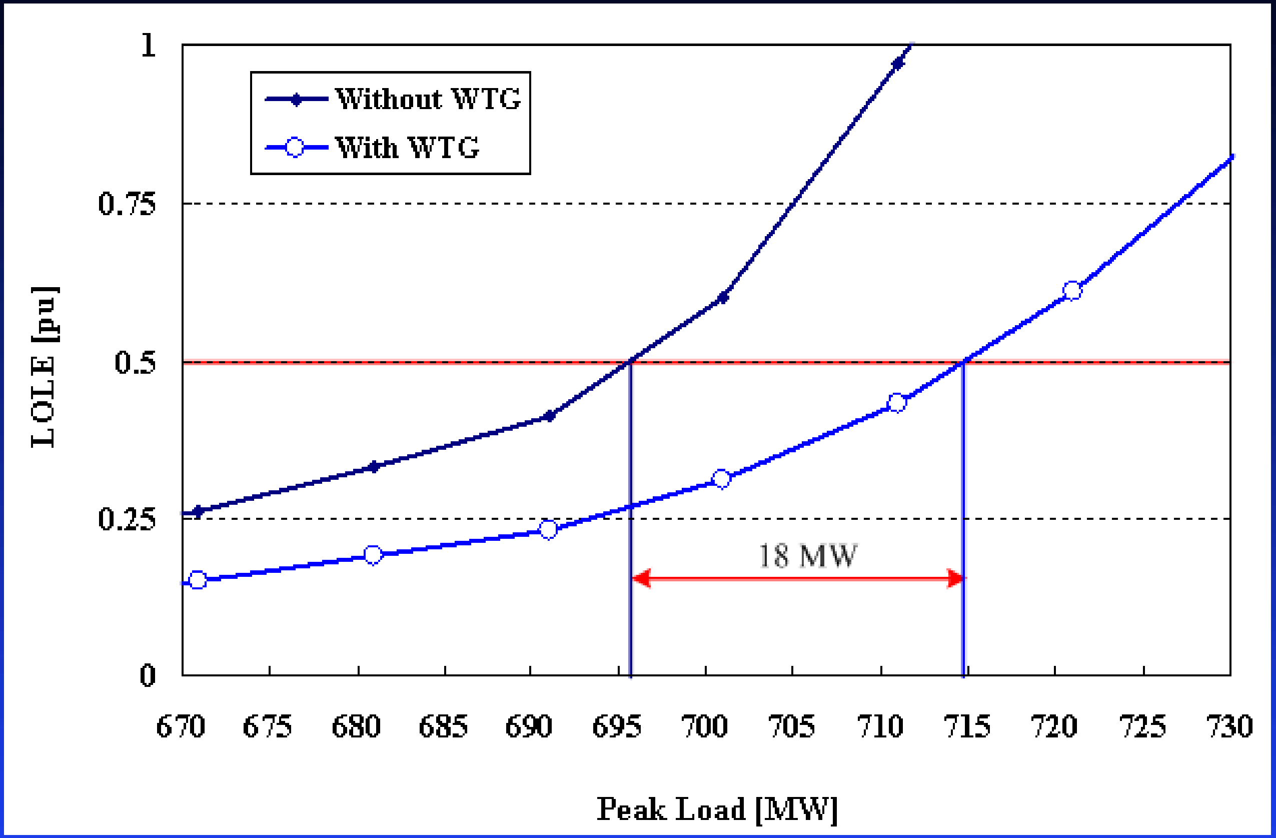
Without WTG
With SSN
LOLE [pu]
1
0.75
0.5
0.25
0
6 MW
660
665
670
675
680
685
690
695
700
705
710
715
720
Peak Load [MW]

ELCC of HLM



Without WTG
With HLM
1
0.75
0.5
0.25
0
LOLE [pu]
4 MW
660 665 670 675 680 685 690 695 700 705 710 715 720
Peak Load [MW]

ELCC of all WTG



ELCC and Capacity credits of WTG farms

WTG-WF	capccity [MW]	ELCC [MW]	Capacity Credit [%]	μ [pu]
HWN	50	8	16	0.16
SSN	30	6	20	0.2
HLM	20	4	20	0.2
total	100	18	18.67*	
All WTG	100	18	18	0.18

$$EIRR = \frac{(845 + 50 \times 0.16 + 30 \times 0.2 + 20 \times 0.2 - 681)}{681} \times 100 = 26.73 [\%]$$

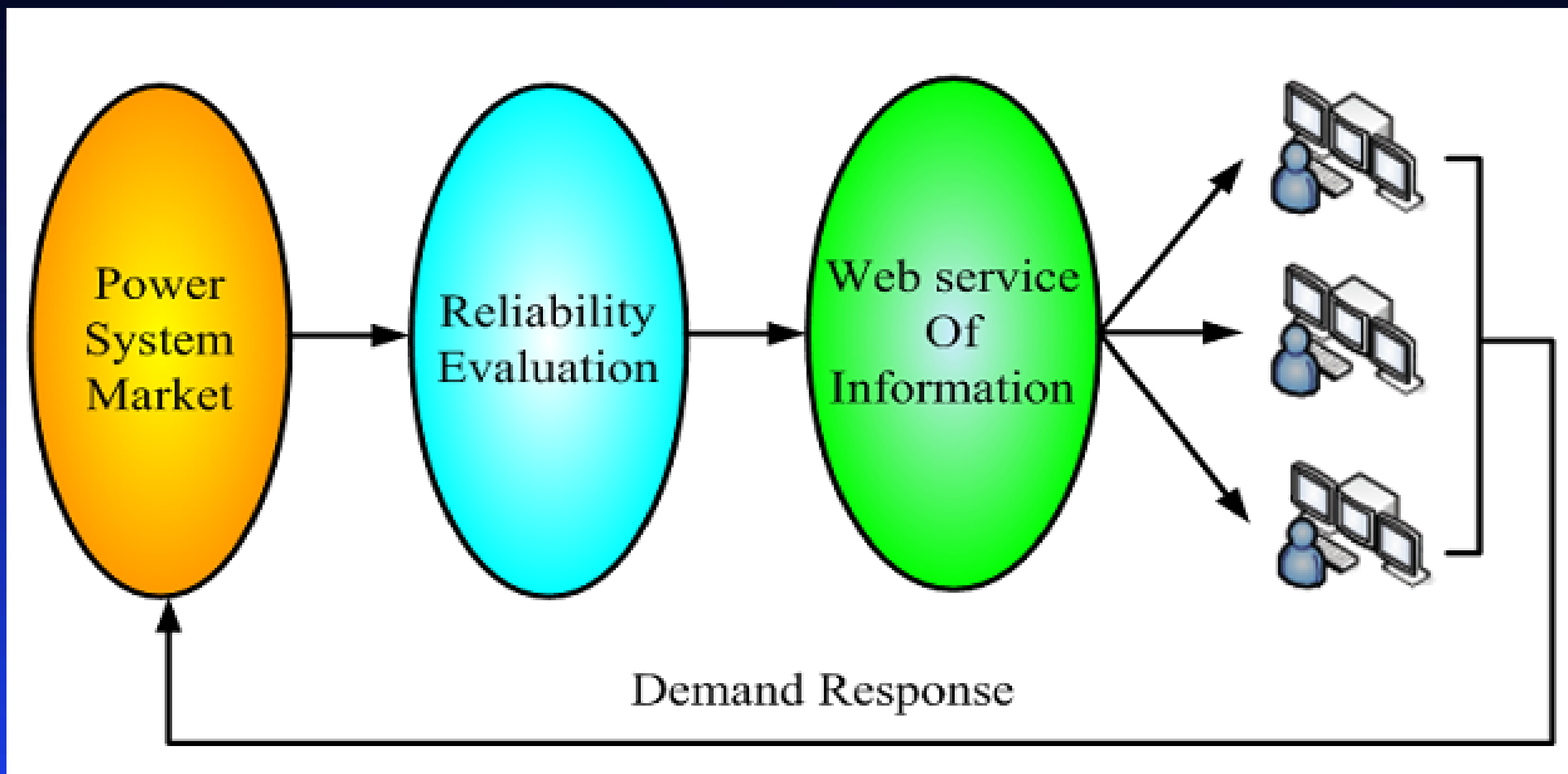
$$EIRR_{ALL} = \frac{(845 + 100 \times 0.18 - 681)}{681} \times 100 = 26.73 [\%]$$

$$IRR = \frac{(945 - 681)}{681} \times 100 = 38.77 \ [\%]$$

$$IRR - EIRR = 38.77 - 26.73 = 12.04 \ [\%]$$

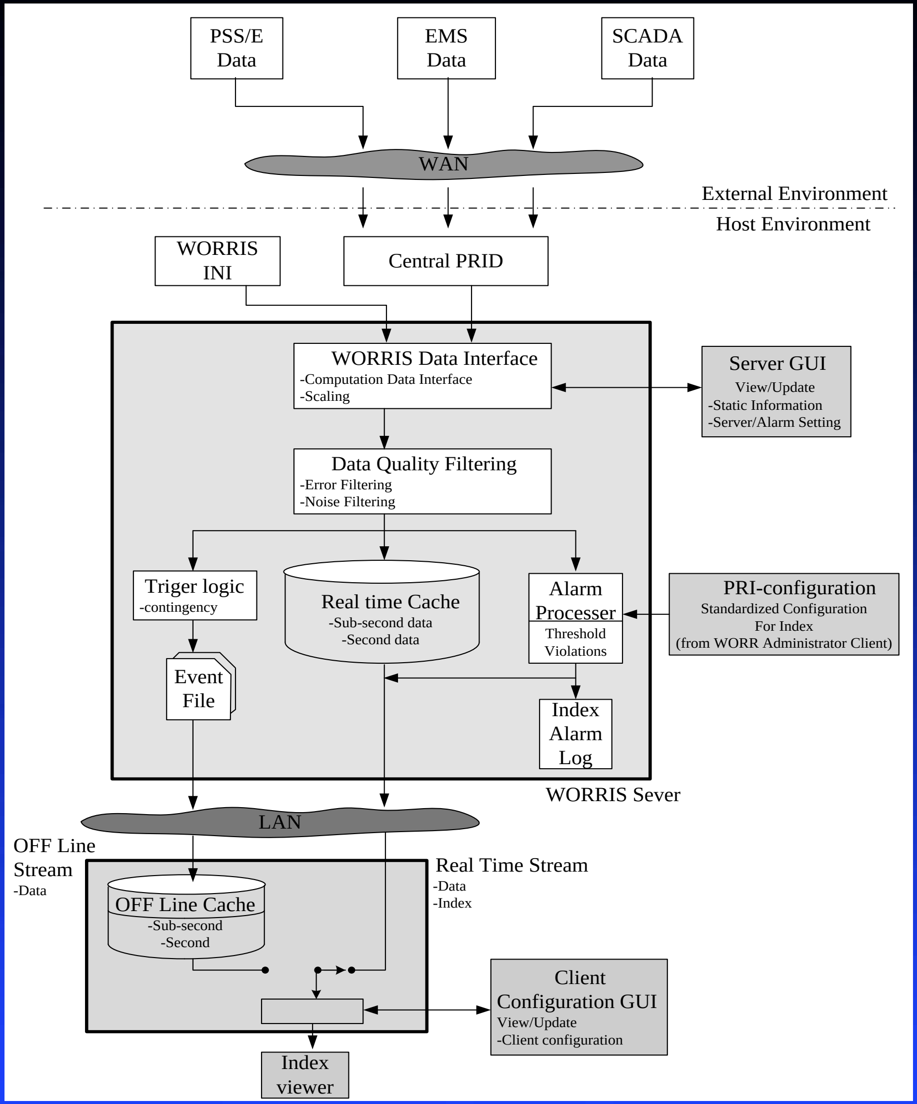
The comparison of the conventional installed reserve rate and the proposed effective installed reserve rate

	Total installed capacity [MW]	Installed reserve rate[%]
IRR	945	38.77
EIRR	945	26.73
$EIRR_{ALL}$	945	26.73


Power
System
Market
Reliability
Evaluation
Web service
Of
Information
Demand Response

WORRIS(Web based Online Realtime Reliability Information System) Version 1.0

http://worris.gsnu.ac.kr/



5. Conclusions

This paper proposes a new effective installed reserve rate in order to evaluate actual reliability contribution level of renewable generators penetrated rapidly in power system in recent.

EIRR(effective installed reserve rate) was proposed newly in order to assess actual installed reserve contribution.

It is developed with considering capacity credit based on ELCC(Effective Load Carrying Capability) by using LOLE reliability criterion.

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Thank you for your kind attention

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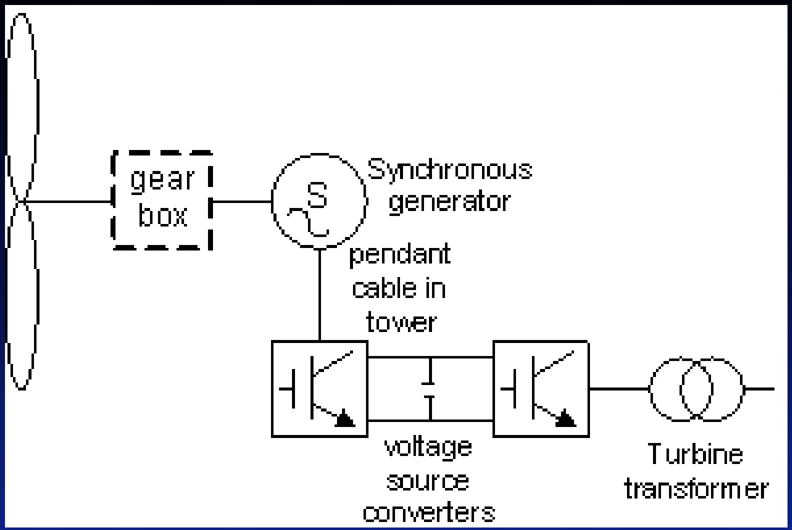
Appendix

Reliability Evaluation of Power System considering a Wind turbine generator

1. Power of Typical WTG



❖ Typical WTG

$$P = \frac{1}{2}\rho A V^3 C_p$$

Where, P is power [W].

C_p is power coefficient.

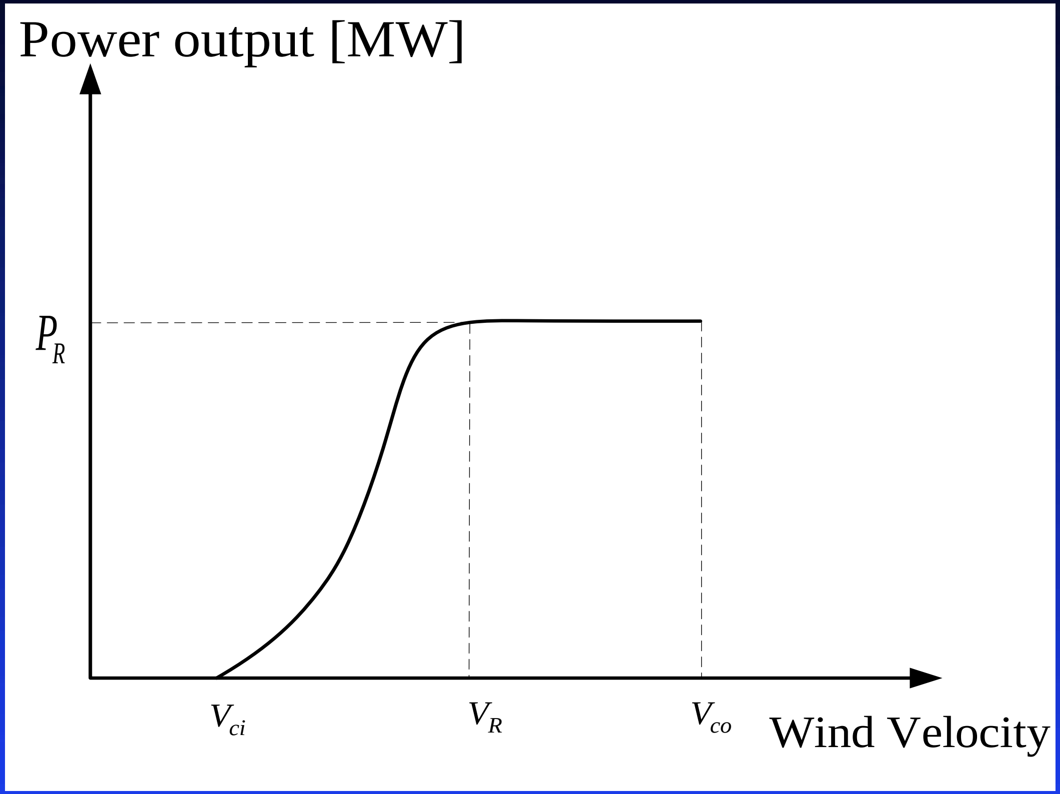
ρ is air density (1.225 kg/m^3).

V is wind velocity (m/sec).

A is swept area of rotor disc (m^2).

32

2. Power Output Model of WTG



Where,
V_{ci}: The cut-in speed [m/sec]
V_R: The rated speed [m/sec]
V_{co}: The cut-out speed [m/sec]
P_R: The rated power [MW]

❖Power output model of wind turbine generators

The following Equation is the mathematical expression for the power output. The power generated P_i(i=1,…,N_b) corresponding to a given speed SW_{bi} (i=1,…,N_b) can therefore be obtained.

$$P_i=0,\ 0\leq SW_{bi}<V_{ci}\ ,\ SW_{bi}>V_{co}$$
$$=P_R(A+B\text{x}SW_{bi}+C\text{x}SW_{bi}^{2}),\ V_{ci}\leq SW_{bi}<V_R$$
$$=P_R,\ V_R\leq SW_{bi}\leq V_c$$

Where,

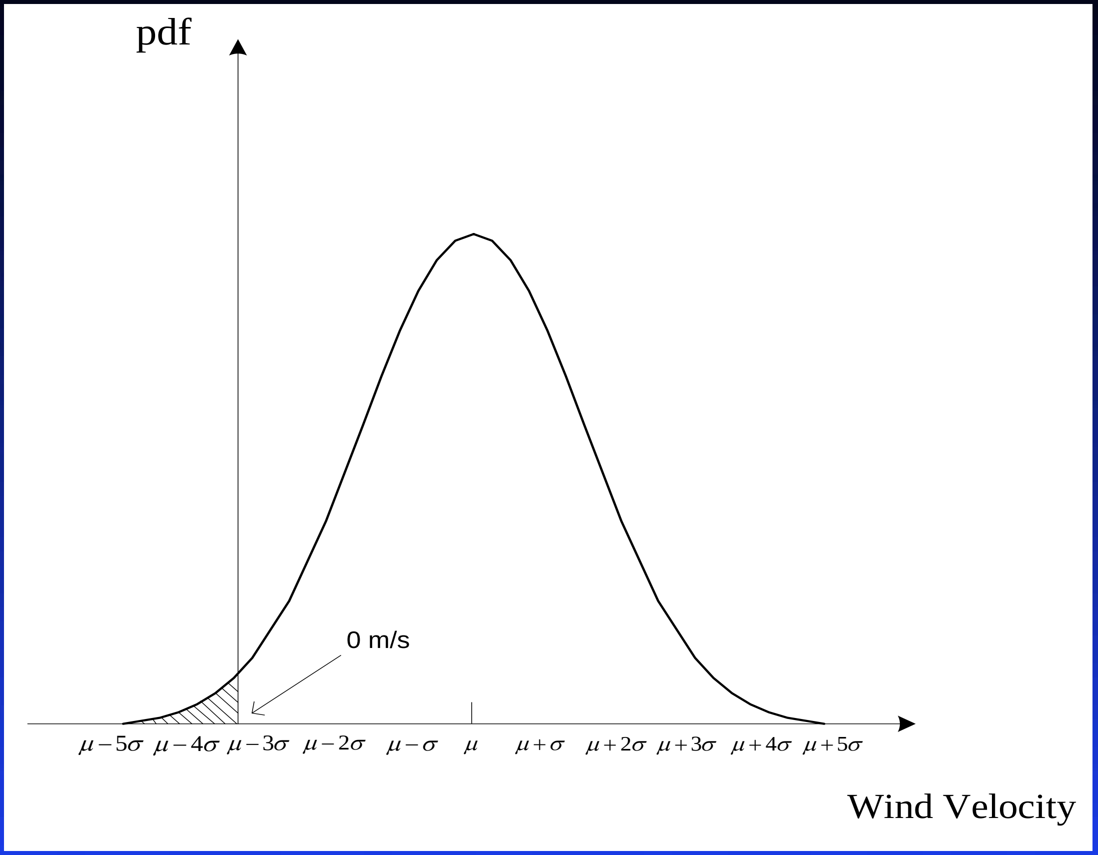
A, B, and C in this equation are formulated in the next page.

$$A = \frac{1}{\left(V_{ci} - V_R\right)^2}\left[V_{ci}\left(V_{ci} + V_R\right) - 4\left(V_{ci} V_R\right)\left(\frac{V_{ci} + V_R}{2V_R}\right)^3\right]$$

$$B = \frac{1}{\left(V_{ci} - V_R\right)^2}\left[4\left(V_{ci} + V_R\right)\left(\frac{V_{ci} + V_R}{2V_R}\right)^3 - \left(3 V_{ci} + V_R\right)\right]$$

$$C = \frac{1}{\left(V_{ci} - V_R\right)^2}\left[2 - 4\left(\frac{V_{ci} + V_R}{2V_R}\right)^3\right]$$

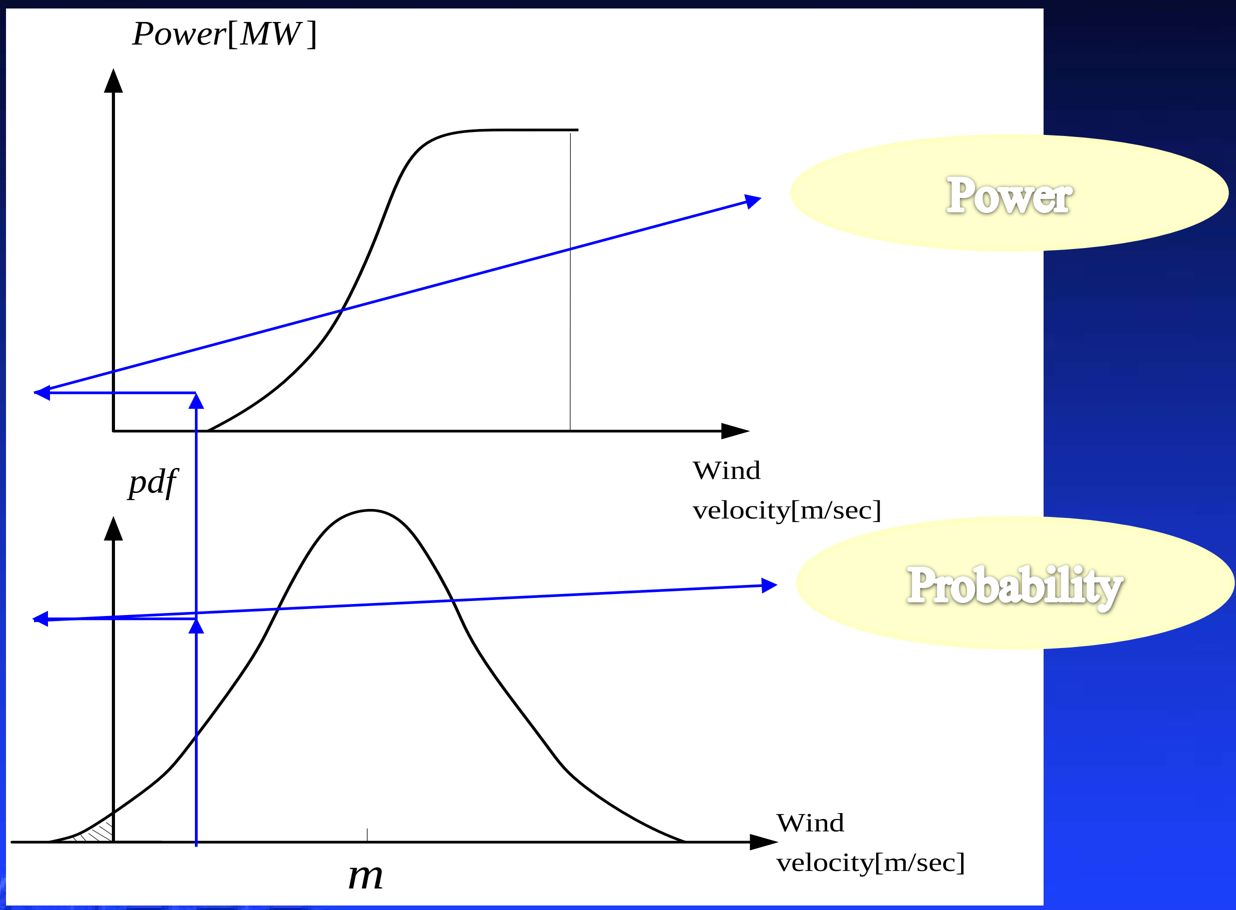
3. Wind Speed Model



❖Wind speed model

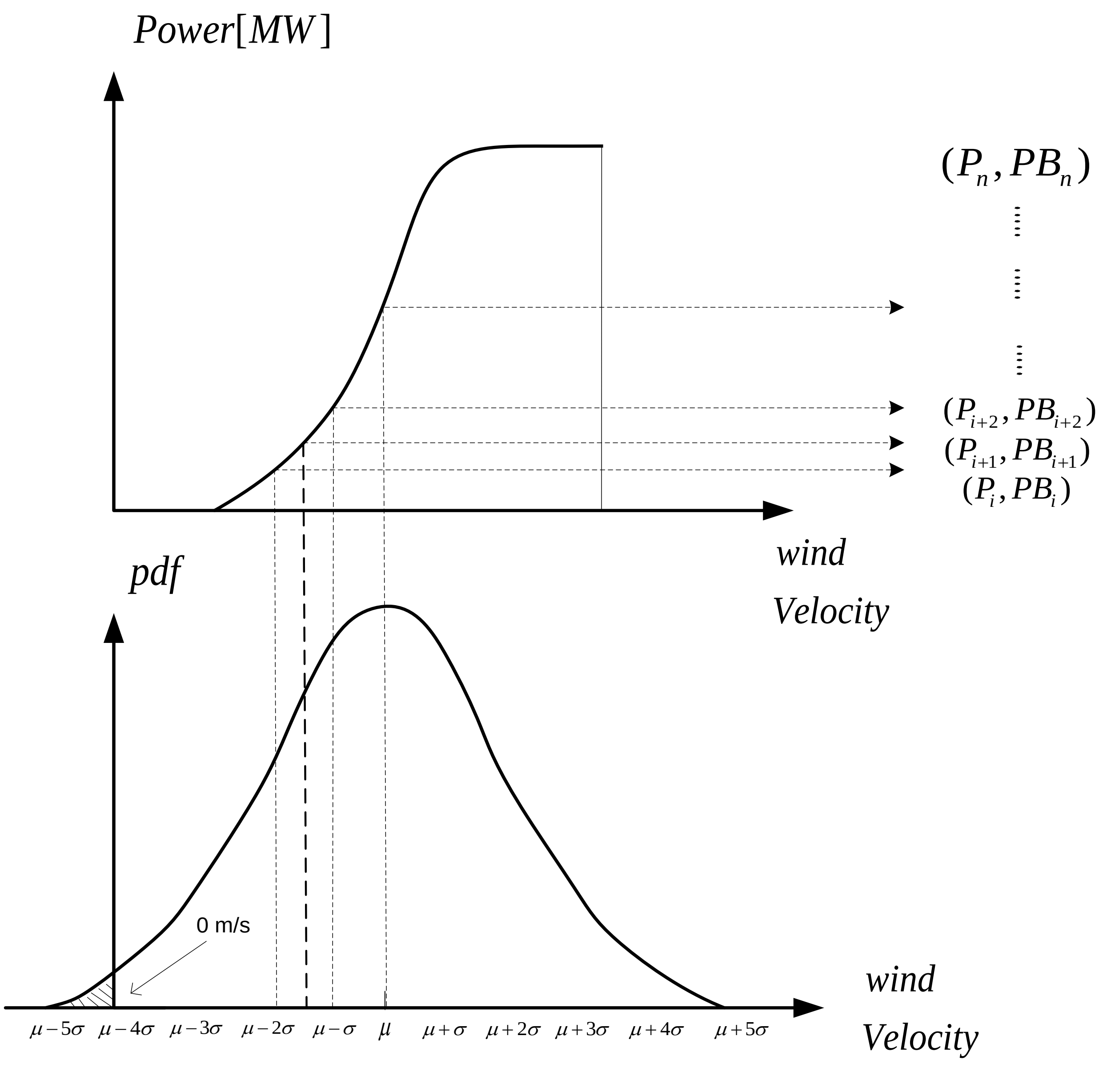
4. WTG Power Multi-state Model

4.1 Wind Power Probability Table



PDF table of
WTG multi-state model

Power	Probability
P_1	PB_1
P_2	PB_2
.	.
.	.
.	.
P_n	PB_n



Power[MW]
(P_n, PB_n)
(P_{i+2}, PB_{i+2})
(P_{i+1}, PB_{i+1})
(P_i, PB_i)
wind Velocity
pdf
0 m/s
$\mu-5\sigma$ $\mu-4\sigma$ $\mu-3\sigma$ $\mu-2\sigma$ $\mu-\sigma$ μ $\mu+\sigma$ $\mu+2\sigma$ $\mu+3\sigma$ $\mu+4\sigma$ $\mu+5\sigma$
wind Velocity

5. Reliability Evaluation of WTG with Multi-state Model

$$\Phi_i = \Phi_{i-1} \otimes f_{oi}$$
$$= (1 - \sum_{j=1}^{NS} q_{ij})\Phi_{i-1}(x) + \sum_{j=1}^{NS} q_{ij}\Phi_{i-1}(x - C_{ij})$$

$\otimes$: The convolution integral operator

Φ_0: Original inverted load duration curve (ILDC)

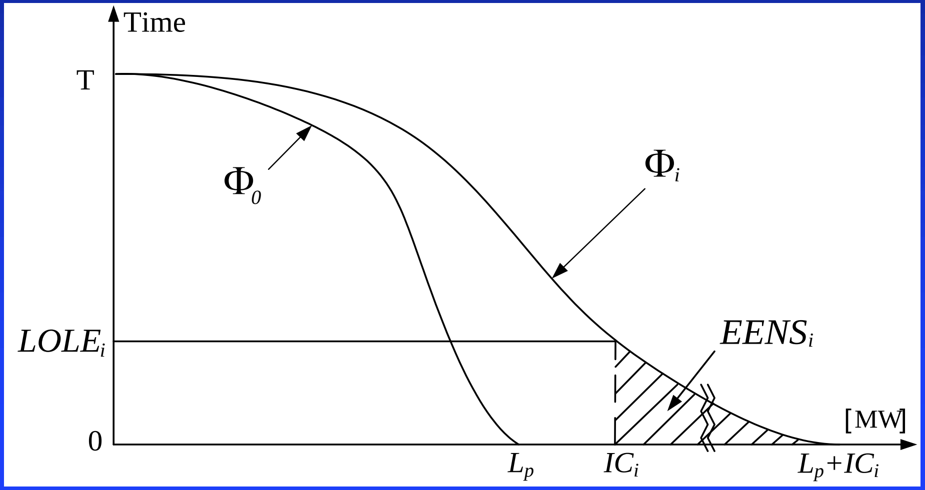
x: Random variable of Φ

NS: The total number of states

f_{oi}: The outage capacity *pdf* of generator *i*

q_{ij}: Forced outage rate (FOR) of generator *i* at state *j*

C_{ij}: Outage capacity of generator *i* at state *j*



$$LOLE = \Phi_{NG}(x)\Big|_{x=IC}$$ [hours/year]

$$EENS = \int_{IC}^{IC+L_P} \Phi_{NG}(x)dx$$ [MWh/year]

$$\Delta \mathrm{E}_i = \mathrm{EENS}_{i\text{-}1} - \mathrm{EENS}_i$$ [MWh]

$$\Delta \mathrm{PC}_i = F_i(\Delta \mathrm{E}_i,\ \mathrm{LOLE}_{i-1})$$ [Won]

$$CF_i = (\Delta E_i / CAP_i / T) \times 100$$ [%]