Optimal Sizing of the ESS for Economic Advantage of PV-ESS Generation

Kyeong Hee Cho, Seul Ki Kim, Eung Sang Kim
Smart distribution research center
Korea Electro-technology Research Institute
Changwon-si, Republic of Korea
E-mail: kx1004xh@keri.re.kr

June Ho Park
Electronic engineering
Busan National University
Busan, Republic of Korea
E-mail: parkjh@pusan.ac.kr

***Abstract*—Renewable energy Portfolio Standard (RPS) was implemented by the government of Republic of Korea. Public institutions have to install the renewable generator according to contract capacity. By mandatory systems like these, renewable energy market is consistently increasing. Photovoltaic power generation (PV) is affected by solar radiation and generate only during the day. If Energy Storage System (ESS) is connected to PV, surplus energy of PV is charged to ESS and ESS discharged to load in peak time period. In this paper, method of optimal sizing ESS for economic advantage for PV-ESS generation is suggested.**

Keywords- ESS sizing; PV-ESS; ESS Design; Economic analysis; Power pattern analysis.

I. INTRODUCTION

Renewable energy Portfolio Standard (RPS) was implemented by the government of Republic of Korea. The RPS system defines that power generation companies that have a 500MW or more of power generation facilities have to generate by renewable energy at a certain percentage of the total. Recently, if customer is public institution, this customer has to install the renewable generator more than 5 percentage of contracted capacity. By mandatory systems like these, market related to renewable energy is consistently increasing. In addition, on September 19, 2016, the Ministry of Trade, Industry and Energy (MOTIE) in Republic of Korea announced a policy to significantly expand the installation of Energy Storage System (ESS) in solar power plants. The purpose of the policy is that power of PV is affected by solar radiation and generated only during the day, so the ESS is connected to PV, surplus energy of PV is charged to ESS in the day and ESS can discharge to grid in peak time period.

The price of the ESS is about 622 [USD] per 1kW, which is very expensive compared to the electricity price. Economic damage may occur due to high investment costs of ESS when operator does not consider economic analysis for PV-ESS generation. Therefore, design is required before installing ESS and the market for ESS design to link PV is expected to expand significantly in Korea.

In this paper, we proposed a method of optimal sizing ESS for economic advantage of PV-ESS generation based on the experience of operating the ESS. Using the proposed method, operators who want to install ESS can reduce the economic risk of high investment cost of ESS and gain a maximum profit from linking PV and ESS.

In Section II, power pattern of PV is forecasted using local weather information. In Section III, the optimal scheduling algorithm of charging and discharging of ESS is explained. In Section IV, method of optimal sizing ESS for economic advantage for PV-ESS generation is proposed. In Section V, general economic analysis method is explained. In the case study from Section VI, ESS is designed for optimal ESS size selection using real solar radiation data. The paper is concluded with Section VII.

II. POWER PATTERN ANALYSIS OF PV

The method for pattern analysis of PV is shown in Figure 1.

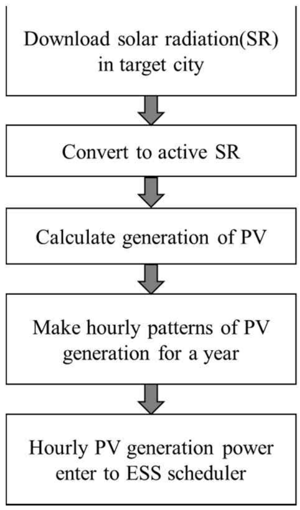

Figure 1. PV forecasting process

First of all, the data tables of Vertical Solar Radiation (VSR) in target city are downloaded. Then, VSR is converted to Active Solar Radiation (ASR) on the inclined surface of PV panel.

If (90- δ) is bigger than θ , then ASR is calculated following equation.

$$ASR = VSR / \cos\theta \tag{1}$$

Else if (90-δ) is smaller than θ, then ASR is calculated following equation.

$$ASR = VSR \times (\cos\theta + \sin\theta / \tan\delta) \quad (2)$$

Where, VSR : Vertical Solar Radiation [kW]
ASR : Active Solar Radiation [kW]
θ: Angle of declination of PV panel
δ : Meridian altitude

Using hourly ASR data, PV generation is calculated using (3) [1].

$$P_{pv} = ASR \times C_{PV} \times \eta_{PCS} \quad (3)$$

Where, P_{pv} : Power of PV system [kW]
C_{PV} : Capacity of PV [kW]
η_{PCS} : Efficiency of PCS [%]

The hourly PV generation pattern is made and entered into ESS scheduler.

III. OPTIMAL SCHEDULING OF ESS

When ESS is connected to PV, the process for optimizing the daily charging and discharging schedule of the ESS is explained in this section. In PV forecasted generation data, maximum hourly peak power value becomes rated output power of PCS.

A. Input data

Input information is a daily PV generation pattern for a year. Unit rate of electricity sales price and characteristics of ESS were entered as a unit price of System Marginal Price (SMP) and Renewable Energy Certificate (REC), available State of Charge (SOC), PCS efficiency and cycle efficiency.

B. Scheduling-charging

There are two constraints. First, the SOC of the battery is limited. The available capacity of battery is estimated by the following equation.

$$C_{BAT\_A} = C_{BAT} \times (SOC_{max} - SOC_{min}) \quad (4)$$

Where, C_{BAT_A} : Available capacity of battery [kWh]
C_{BAT} : Capacity of battery [kWh]
SOC_{max} : Maximum of SOC [%]
SOC_{min} : Minimum of SOC [%]

Second, charging capacity of ESS at target hour i is calculated using the C_{BAT_A} and $P_{pv,t}$.

If $\sum_{t=1}^{i-1} P_{pv,t}$ is bigger than C_{BAT_A}, $P_{cha,i}$ is zero.

Else if $\sum_{t=1}^{i} P_{pv,t}$ is bigger than C_{BAT_A}, then $P_{cha,i}$ calculated following equation.

$$P_{cha,i} = C_{BAT\_A} - \sum_{t=1}^{i-1} P_{pv,t} \quad (5)$$

Else, $P_{cha,i}$ calculated following equation.

$$P_{cha,i} = P_{pv,i} \quad (6)$$

Where, $P_{pv,t}$: Power of PV according to hour t [kW]
$P_{cha,i}$: Charging power at target hour i [kW]
$P_{pv,i}$: Power of PV at target hour i [kW]
t : Time from 1 to 24 [hour]
i : Target hour [hour]

C. Scheduling-discharging

When PV generates electricity power from 6:00AM to 7:00PM, discharge of ESS is zero. The available capacity of battery (C_{BAT_A}) is equally divided in 10 hours from 8:00PM to 5:00AM. Then that amount is discharged. The reason for sharing discharging of ESS is that if the discharge duration is long, the efficiency is high. Table I is the efficiency table of lithium ion battery per discharging current.

TABLE I. LITHIUM ION BATTERY EFFICIENCY PER DISCHARGING CURRENT

Discharge Duration [hour]	Discharge Current [C]	Efficiency [%]
5	0.2	100
1	1	99
0.2	5.2	98
0	10	95

IV. ECONOMIC ANALYSIS

Profit by generation is estimated using a unit price of SMP and REC.

SMP is calculated by adding SMP_{PV} and SMP_{ESS}. Daily SMP profit equations is following.

$$SMP_{PV,d} = \sum_{t=1}^{24}\left(P_{pv,t} \times R_{SMP,unit,t}\right) \quad (7)$$
$$SMP_{ESS,d} = \sum_{t=1}^{24}\left[(P_{dis,t} - P_{cha,t}) \times R_{SMP,unit,t}\right] \quad (8)$$
$$SMP_{total\_month} = \sum_{d=1}^{30} SMP_{PV,d} + \sum_{d=1}^{30} SMP_{ESS,d} \quad (9)$$
$$SMP_{total\_year} = \sum_{m=1}^{12} SMP_{total,m} \quad (10)$$

Where, $SMP_{PV,d}$: SMP profit of PV at d day [USD]
$SMP_{ESS,d}$: SMP profit of ESS at d day[USD]
SMP_{total_month} : Total SMP profit of ESS and PV during a target month [USD/month]
SMP_{total_year} : Total SMP profit of ESS and PV during a target year [USD/year]
m : Target month
$R_{SMP,unit,t}$: SMP unit rate at hour t [USD]

REC is calculated by adding REC_{PV} and REC_{ESS}. Weight of PV is 1.5. When ESS discharged using SOC charged from PV generation, weight of ESS is 5.

$$REC_{PV,m} = \sum_{d=1}^{30}\left[\sum_{t=1}^{24}(P_{pv,t,d} - P_{cha,t,d})\right] \times R_{REC,unit,m} \times W_{PV} \quad (11)$$
$$REC_{ESS,m} = \sum_{d=1}^{30}\left(\sum_{t=1}^{24} P_{dis,t,d}\right) \times R_{REC,unit,m} \times W_{ESS} \quad (12)$$
$$REC_{total\_year} = \sum_{m=1}^{12}(REC_{PV,m} + REC_{ESS,m}) \quad (13)$$

Where, $REC_{PV,m}$: REC profit of PV at m month [USD]

$P_{pv,t,d}$: Power of PV at hour(t) in a day(d) [kW]
$P_{cha,t,d}$: Charging power at hour(t) in a day(d) [kW]
$R_{REC,unit,m}$:REC unit rate at month m [USD]
W_{PV} : Weight of PV [REC]
$REC_{ESS,m}$: REC profit of ESS at m month [USD]
$P_{dis,t,d}$: Discharging power at hour(t) in a day(d) [kW]
W_{ESS} : Weight of ESS link to PV [REC]
REC_{total_year} : Total REC profit of ESS and PV during a target year [USD/year]

$$\text{Total profits} = SMP_{total\_year} + REC_{total\_year} \tag{14}$$

Where, Total profits : Summation profits of SMP and REC for ESS and PV for a year [USD/year]

Profit is estimated and saved according to the capacity of ESS for 20 years. The profit is transposed to Net Present Value (NPV).

$$P_{NPV,after} = P_{NPV,before} \times (1-j)^n \tag{15}$$

Here, n : Period operating ESS [year]
$P_{NPV,after}$: Profit after NPV [USD]
$P_{NPV,before}$: Profit before NPV [USD]
j : Interest rate [%]

The unit price of PCS and battery is entered. Parameter is entered like as increasing rate of SMP, REC and money.

Using economic information, Internal Rate of Return (IRR) is estimated according to candidates of ESS.

$$0 = \sum_{t=0}^{19} \frac{CF_t}{(1+IRR)^t} \tag{16}$$

Here, CF_t : cash flow for each period t
t : xth year from target year

V. Optimal Sizing of ESS

Figure 2 presents the overall flow chart on economic analysis method for finding optimal ESS.

First, information on PV, ESS and price is entered. Using weather information in the target city, PV generation is forecasted. Initial and maximum capacity of ESS is selected and entered by the operator. ESS is scheduled for two cases (C_a, C_b) that are initial and maximum capacity. SMP and REC profit are estimated. Then economic analysis is calculated using PV and ESS cost.

If capacities of two cases are different ($|C_a - C_b| > 0$), another candidate (C_c) is selected as the center value between two cases. Then candidate (C_a) revised a capacity of better economic profit among the candidate capacities. And candidate (C_b) becomes candidate (C_c).

Two candidates are scheduled and calculated again. Iteration is performed until that difference of the two cases ($|C_a - C_b|$) is very small. This difference is set by the operator.

Optimal size ESS is selected among all candidates. We assume generally that the higher the IRR, the more economical it is.

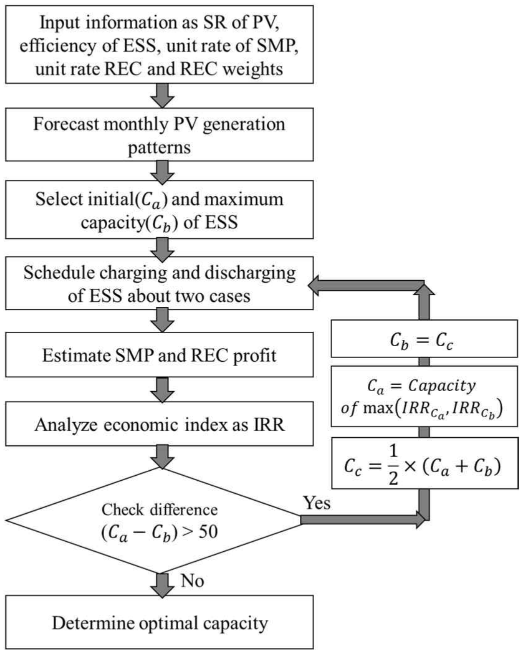

Figure 2. Flow chart of optimal ESS capacity estimation

VI. Case Studies

In the case study, real SR data of Pusan city is downloaded from site of Korea meteorological administration [2]. Using Section II equation, PV power generation power is calculated monthly shown in Figure 3. PV capacity is 450 [kW] and fixed.

The angle of declination of PV panel is 50 [degree]. Meridian altitude is downloaded daily and inserted from the site of astronomy and space science information [3].

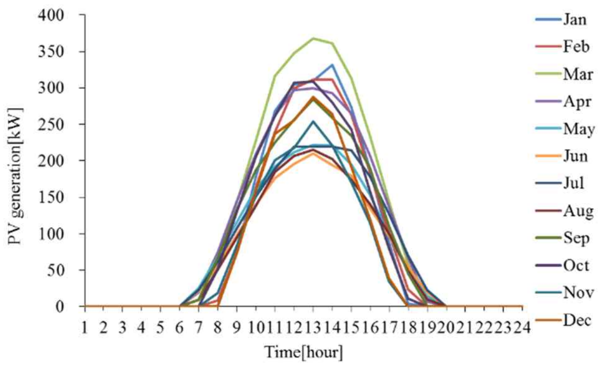

Figure 3. Monthly average pattern of PV forecast results

We assumed the boundary of battery capacity with the initial capacity is 100 [kWh] and maximum capacity is 800 [kWh]. The increasing unit capacity is 100 [kWh].

Rated output of PCS is selected to the maximum value of PV forecasted daily patterns for a year. But if this maximum value is higher than battery capacity, rated output of PCS is battery capacity.

Determination of PCS rated output for each battery capacity is shown in Table II. As it can be seen, in Table II, PCS rated output does not increase linearly according to battery capacity. This means that the maximum value of PV forecasted daily patterns for a year is lower than the battery capacity starting from 700 [kWh]. Therefore maximum power of PCS is limited by 518 [kW].

TABLE II. DETERMINATION OF PCS RATED OUTPUT FOR EACH BATTERY CAPACITY

Cases	Capacity		
	PV[kW]	Battery[kWh]	PCS rated output[kW]
1	450	100	80
2	450	200	136
3	450	300	212
4	450	400	292
5	450	500	372
6	450	600	452
7	450	700	518
8	450	800	518

In the case study, the average of SMP unit rate is about 0.12 [USD/kW] and the average of REC unit rate is about 70.13 [USD/MW].

The profits of SMP and REC for cases of Table II were calculated using equations (7)-(14). SMP profit of ESS and PV during a target month and year were calculated using equation (10) (see Table III). The total REC profit of ESS and PV during a target year were calculated using equation (13) (see Table III). The summation profits of SMP and REC for ESS and PV for a year were calculated using equation (14) as can be seen in Table III. The results of Table III show the accumulated profits for 20 years.

TABLE III. PROFITS ESTIMATION RESULTS FOR EACH CASE

Cases	PV profit [USD]		ESS profit [USD]		Total Profit [USD]
	SMP_{PV}	REC_{PV}	SMP_{ESS}	REC_{ESS}	
1	58,966	52,294	2,801	13,145	127,206
2	55,768	49,402	5,574	26,159	136,903
3	52,590	46,536	8,320	39,056	146,502
4	49,477	43,732	11,006	51,672	155,888
5	46,442	41,002	13,627	63,956	165,027
6	43,490	38,359	16,175	75,854	173,877
7	40,602	35,784	18,665	87,437	182,488
8	37,770	33,264	21,106	98,781	190,920

Using equations (15) and (16), economic analysis results of these cases are shown in Table IV. The NPV of profit has been calculated using equation (15) (see Table IV). The IRR has been calculated using equation (16) as can be seen in Table IV. The accumulated profits during 20 years are presented in Table IV.

The cost of PV and ESS per unit like Table V was inserted to simulation.

TABLE IV. ECONOMIC ANALYSIS RESULTS FOR EACH CASE

Cases	Cost of PV and ESS [USD]	IRR [%]	(Profit-Cost) [USD]	Payback [year]
1	902,972	8.23	713,638	8.79
2	965,599	8.34	774,577	8.72
3	1,038,151	8.26	823,782	8.77
4	1,110,704	8.17	870,195	8.83
5	1,183,256	8.07	913,383	8.90
6	1,241,941	8.13	967,385	8.85
7	1,285,647	8.36	1,034,039	8.71
8	1,329,354	8.55	1,098,357	8.58

TABLE V. UNIT COST OF EACH PV, BATTERY AND PCS

Equipment	Unit	Cost[USD]
PV system	1kW	1,594
Battery of Lithium ion	1kWh	354
PCS	1kW	221
Construction cost	1kW	89

Graph of IRR, PV profit and ESS profit for each case in Table IV are shown in Figure 4. As shown in Figure 4, the IRR was lowest when ESS and PV profits were equal.

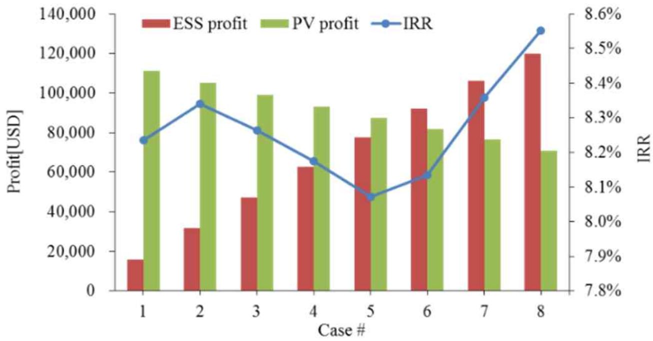

Figure 4. The IRR graph according to battery capacity candidates

In order to apply the algorithm presented in Figure 2, information is entered and PV generation is forecasted. The initial capacity was set at 200 [kWh] and the maximum capacity was set at 3,000 [kWh]. The ESS of two cases was scheduled respectively and their profits were calculated. Also, economy analysis is calculated. Capacity difference of two cases is checked. If this difference is smaller than 50 [kWh], simulation is terminated. If not, simulation is repeated. One capacity among next two cases is center capacity of previous candidates. Another capacity is the capacity of previous candidates with the largest IRR. For example, in the second simulation, previous candidate (C_a) is 200 [kWh], previous candidate (C_b) is 3,000 [kWh]. Therefore candidate (C_c) is 1,600 [kWh], next candidate (C_a) is 200 [kWh] and next candidate (C_b) is 1,600 [kWh].

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TABLE VI. DETERMINATION OF BATTERY CAPACITY BY FIGURE 2 AND IRR RESULTS

Cases	Battery capacity[kWh]	IRR[%]
1	200	8.34
2	3,000	7.17
3	1,600	9.33
4	900	8.71
5	1,250	9.14
6	1,425	9.26
7	1,512.5	9.30
8	1,556.3	9.32

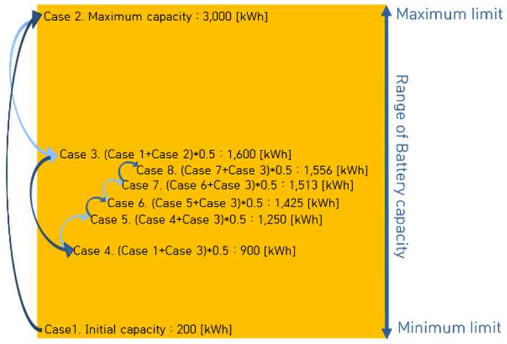

Figure 5. Selection of battery capacity for increasing IRR by Figure 2

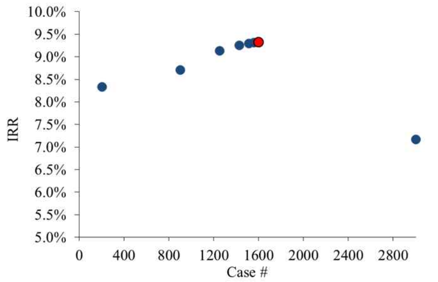

Figure 6. IRR curve according to each case

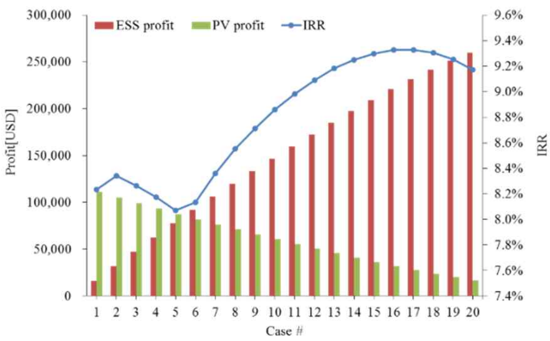

Figure 7. IRR curve while increasing battery capacity by 100

As it can be seen in Figure 5, optimal size, which is 1,600 [kWh], was found by running simulation 8 times. This case depends on the assumed conditions.

In this case study, full combination means all cases of battery capacity increasing by same term from minimum to maximum. Full combination had simulated capacity cases to increase by 100 [kWh] up to 2,000 [kWh]. We depicted the curve of Profits and IRR in Figure 6.

When the battery capacity increasing by 100 [kWh] is simulated, the IRR curve changes as parabolic curve. This method requires 20 iteration and shows that optimal battery size is 1,600 [kWh].

VII. CONCLUSION

In this paper, the method of optimal sizing of the ESS for the economic advantage of PV-ESS generation was proposed. The economic advantage included generation profits of SMP and REC considering REC weight of discharging power of ESS charged from PV.

In the case study, in order to apply the algorithm presented in Figure 2, ESS capacities were selected and scheduled. The generation profits and IRR of each case were calculated for optimal ESS size selection. The simulation repeated until that the difference of capacities was smaller than 50 [kWh]. In the results, the optimal size, which was 1,600 [kWh], was found by running simulation 8 times. For comparison, full combination had simulated all capacity cases to increase by 100 [kWh] up to 2,000 [kWh]. This method requires 20 iteration. Optimal battery size of full combination was 1,600 [kWh]. Since the results were the same, showing that the method applied was accurate and faster.

Using the proposed method, operators who want to install ESS can select the optimal capacity that maximize the profit by linking PV and ESS for generation business. Future work will be focused on comparisons of optimal sizing method of the ESS according to two different goals of demand management and generation business.

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