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Optimal PlusDR Incentive for Time-of-Use Users Considering the Internal Rate of Return for Energy Storage System Installation

GyuHyeon-Bae and SungSoo-Kim and AhYun-Yoon
Department of Energy & Electrical Engineering
Tech University of Korea

Ichiro SUZUKI
ICEE Conferences Secretariat
Kokurakita-ku, Kitakyushu, Fukuoka 123-4567, Japan

Abstract

Renewable energy generation has the advantage of being environmentally friendly and not requiring fuel costs, but it also has the disadvantage of high variability and uncertainty in its output, which leads to curtailment of renewable energy. To solve this issue, energy storage systems (ESS) and a PlusDR scheme aimed at increasing demand were introduced.

This study presents the optimal incentives to enhance the feasibility of ESS investment for consumers who pay their electricity bills using a time-of-use (TOU) pricing scheme and consider participating in the PlusDR market by installing ESS and optimizing costs through scheduling against TOU rates. These optimal incentives are based on the internal rate of return resulting from the ESS installation, evaluating electric bill savings through ESS scheduling and the initial installation costs.

Keywords: Curtailment, Demand Response, Energy Storage System, Renewable Energy, Time-of-Use

1. INTRODUCTION

Jeju Island in South Korea is a proclaimed Carbon Free Island 2030 (CFI2030) for carbon neutrality and energy independence [1]. Consequently, the share of renewable energy sources has surged, accounting for 19.2% of Jeju's power generation in 2022 [2].

However, environmentally friendly sources such as solar and wind power face challenges due to their intermittent and highly variable output. This variability has led to frequent curtailments, with wind power alone failing to generate 26.2 GWh in 2023 due to output control [3].

To mitigate such curtailments of renewable energy sources (RES), Jeju has been operating a Plus Demand Response (PlusDR) system since March 2021. Unlike traditional demand reduction DR, PlusDR incentivizes consumers to voluntarily increase their power usage during curtailment periods, rewarding them for the increased consumption [4]. However, the increase in curtailment from rising RES outpaces the reduction achieved through PlusDR, highlighting the urgent need for solutions [2].

Energy storage systems (ESS) have emerged as a promising solution to these challenges. By storing and supplying electricity as needed, ESS can reduce electric bills and alleviate output control [5]. However, the high cost of current ESS technologies presents a considerable barrier to adoption. Therefore, attracting investor interest in ESS requires offering appropriate incentives.

There has been considerable research on the changing load patterns of ESS users participating in DR, and the associated incentives and costs [6] by analyzing the appropriate incentives for ESS to provide flexibility to the grid by participating in DR through ESS scheduling and cost-benefits in commercial buildings [7]. We previously evaluated the cost-benefit of ESS savings and participation in DR programs for industrial companies [8].

However, previous studies have primarily focused on demand reduction DR and only considered fixed incentives and cost changes, often neglecting the investment cost of ESS installation. Therefore, there is a need for research analyzing the optimal incentives for PlusDR participation and the Return on Investment from ESS installation.

This study aimed to derive the optimal PlusDR incentives for private customers investing in ESS through an economic evaluation. The optimal incentives are determined by considering the installation costs, investment returns, and electricity bills, clarifying the economic benefits for private customers and potentially increasing the adoption rate of ESS. This paper is structured as follows: Section 2 proposes an optimization model for ESS charging and discharging that accounts for the PlusDR system and pricing characteristics in Korea. Section 3 presents the optimization results based on simulation conditions. The final section summarizes the findings and concludes the paper.

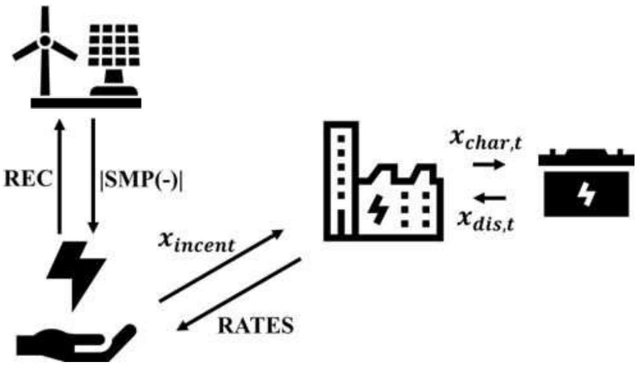

Figure 1. PlusDR Configuration Diagrams

2. Modeling

2.1 Plus DR Policy Analysis

The current PlusDR targets customers who are on a time-of-use (TOU) pricing scheme (Figure 1). The TOU pricing scheme differentiates charges based on high and low electricity usage periods; in Korea, this is divided into off-, mid-, and on-peak periods based on the electricity volume charges.

When users receive a PlusDR signal, they increase their electricity consumption during the specified period. The settlement for this increased usage is based on each customer baseline (CBL), with the Korea Electric Power Corporation settling the increased consumption at the mid-peak rate of spring and fall. The CBL is a predicted standard electricity usage based on the customer's consumption patterns. For PlusDR, the Mid (4/6) CBL is used, which calculates the average electricity consumption from four out of the recent six days, excluding the maximum and minimum consumption days, considering separate calculations for weekdays and weekends.

Table 1 represents part of the 'General Use' table for Jeju Island. For example, a customer under category A-1 receives a compensation of 115.3 KRW if they use an additional 1 kWh of electricity based on the CBL.

Table 1. TOU Pricing Tables [9]

Class		Demand Charge (KRW/kW)	Energy Charge (KRW/kWh)			
			Time period	6–8	3–5 9–10	11–2
A	1	7,220	Off-peak	92.8	92.8	99.8
			Mid-peak	145.7	115.3	145.9
			Peak-load	227.8	146.0	203.4
	2	8,320	Off-peak	87.3	87.3	94.3
			Mid-peak	140.2	109.8	140.4
			Peak-load	222.3	140.5	197.9
	3	9,810	Off-peak	86.4	86.4	93.7
			Mid-peak	139.6	108.5	139.8
			Peak-load	209.9	132.2	186.7

2.2 Symbol and Abbreviation Definitions

Variables

x_{incent}	
$x_{char,t}$	PlusDR incentives
$x_{dis,t}$	ESS charge by time
$u_{char,t}$	ESS discharge by time
$u_{dias,t}$	ESS state of charge by time – binary
$x_{soc,t}$	ESS state of discharge by time – binary
$x_{b,t}$	Battery capacity of the ESS by time
$x_{b,max}$	Power usage by time

Set

$t \in T$	Time set
$k \in K$	Month set

Parameter

C_t	Time-of-use pricing
C_{base}	Contracted capacity – base price
L_t	Customer load by time
CBL_t	Customer CBL by time
SOC_{max}	Battery Max Capacity
SOC_{min}	Battery Minimum Capacity
SOC_{ini}	Initial battery capacity
PCS	Charge & discharge capacity
η	Efficiency
DR_t	DR occurrence by time
M	Constant M for Big-M Method
$COST_{ESS}$	ESS investment costs
E_{RATE}	1 year of Rates before ESS installation
N	Revenue periods / ESS lifetime
IRR	Annualized discount rate

2.3 Objective Function

2.3.1 Definition of Model I

This study conducted two optimizations. The optimization for minimizing TOU electricity charges through the charging and discharging of an ESS is defined as Model I. Model I considers the volume charges and peak loads to minimize the TOU charges.

The objective function for Model I aimed at reducing the volume charges and peak loads is expressed in equation (1).

$$min\left\{\sum_{t=1}^{T}(x_{b,t} * C_t) + \sum_{k=1}^{K}(x_{b,max} * C_{base})\right\} \quad (1)$$

2.3.2 Definition of Model II

For Model II, the objective function incorporates the participation in PlusDR on top of the considerations in Model I. Therefore, the content of the PlusDR settlement is added to the objective function.

Consequently, the objective function for Model II is expressed in equation (2).

$$min\left\{\sum_{t=1}^{T}(x_{b,t} * C_t) + \sum_{k=1}^{K}(x_{b,max} * C_{base}) - i_{Pdr}\right\} \quad (2)$$

$$i_{Pdr} = \sum_{t=1}^{T}\left(L_t - CBL_t + x_{char,t}\right) * x_{incent} \quad (3)$$

Equation (3) is the total of the PlusDR incentive for the year. In this formula, the customer will not receive any incentive if the load and ESS charge in each time period is lower than the CBL.

Model II becomes Non-linear Programming as the product of $x_{char,t}$ and x_{incent}.

2.4 Constraints

2.4.1 Definition of Model I

Model I seeks to minimize the TOU electricity bill through the ESS. Therefore, the constraint formulation uses the ESS optimization formulation. Equation (4) is the constraint on the battery operating range of the ESS.

$$SOC_{min} \leq x_{soc,t} \leq SOC_{max} \quad (4)$$

Equations (5) and (6) are constraints on the operating range of the PCS. Binary decision variables $u_{char,t}$ and $u_{dis,t}$ are set to represent the state of charging and discharging.

In equation (7) We added a constraint to prevent both states from occurring simultaneously through the constraint expression.

$$0 \leq x_{char,t} \leq PCS * u_{char,t} \quad (5)$$

$$0 \leq x_{dis,t} \leq PCS * u_{dis,t} \quad (6)$$

$$u_{char,t} + u_{dis,t} \leq 1 \quad (7)$$

Equation (8) is a constraint on the variation of the ESS battery level given the charge and discharge efficiency. η is the efficiency of charging and discharging. Equation (9) is a constraint that keeps the initial and end values of the ESS balance the same daily.

$$x_{soc,t} = x_{soc,t-1} + \eta * x_{char,t} - \frac{x_{dis,t}}{\eta} \quad (8)$$

$$x_{soc,1} = x_{soc,24} = SOC_{ini} \quad (9)$$

Equation (10) is a constraint on the TOU user's hourly load L_t and the amount of ESS charging and discharging. $x_{b,t}$ is the amount of electricity the customer purchases from the grid.

$$x_{b,t} = L_t + x_{char,t} - x_{dis,t} \quad (10)$$

Equation (11) is the constraint expression to find the maximum peak point of $x_{b,t}$ for calculating the base rate of TOU users in Model I.

$$x_{b,max} \geq x_{b,t} \quad (11)$$

2.4.2 Definition of Model II

Model II will participate in PlusDR while minimizing the TOU electricity bill; therefore, the constraints stated in (4–10) can be set.

Equations (12) and (13) are the constraints to find the peak load at the PlusDR time. In the original equation (11), the user's changing load peak determines $x_{b,max}$. However, because the load increase over CBL is not considered as a peak during the PlusDR time, distinguishing between PlusDR and non-PlusDR times is necessary. DR_t is a binary set of size T, that is, 1 for PlusDR hours and 0 for nonplus DR hours. The Big-M technique is used to linearize the model, to ensure that the constraint in (12) is triggered when DR_t is 1 and the constraint in (13) is triggered when it is 0. Equation (14) is a constraint to prevent the ESS from discharging at PlusDR time.

$$x_{b,max} \geq CBL_t - M * (1 - DR_t) \quad (12)$$

$$x_{b,max} \geq x_{b,t} - M * DR_t \quad (13)$$

$$u_{dis,t} \leq 1 - DR_t \quad (14)$$

To derive the PlusDR payoff in Model II, we introduce the concept of internal rate of return (IRR), which is a discount rate at which the net present value of an investment equals zero and is a metric to evaluate the profitability of a project. However, the calculation of IRR is highly nonlinear. In this study, we used the boundary condition optimization technique to adjust the upper bound of x_{incent} to meet the target IRR by calculating the cash flows from the optimization solution given by the objective function and constraints up to (14). The reason for adjusting the upper bound of x_{incent} is that the objective function is a minimizing function, and the variable is negative. The upper bound is adjusted in 0.01 increments.

Equation (15) is the cash flow for the first year. To calculate the IRR, we assume that the ESS investment is paid in full in the first year.

$$CF_1 = i_{Pdr} + E_{RATE} - elec_c - COST_{ESS} \quad (15)$$

where i_{Pdr} is the result of equation (3) resulting from the optimization. E_{RATE} corresponds to the electricity rate paid before the existing ESS installation. $COST_{ESS}$ is the cost of installing the ESS, and $elec_c$ is the electricity bill resulting from the optimization.

Equation (16) is the cash flow for all years excluding the first year, which is assumed to be a constant cash flow.

$$CF_n = i_{pdr} + E_{RATE} - elec_c \quad 2,3 \ldots \mathrm{N}-1 \in \mathrm{n} \quad (16)$$

Equation (17) is the formula to find the IRR. In this study, we set an IRR target value and adjusted CF_n to meet the target IRR.

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n} = 0 \quad (17)$$

3. Simulation

3.1 Simulation Conditions

Using the model presented in Section 2, we conducted simulations to determine the optimal plus DR and minimize TOU electricity costs. This study optimized the load patterns of TOU customers based on the 2024 TOU rate schedule. Figure 2 shows a graph of load patterns and TOU rates. (b) in Fig. 2 is a weekday graph from Table 1 A-3. The peak load hours on Saturdays shifted to medium-load hours and the peak load hours on Sundays and holidays are shifted to light-load hours [9].

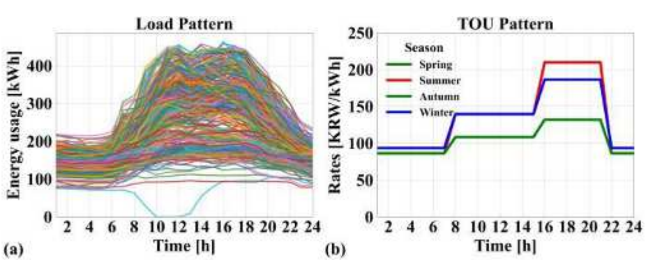

Figure 2. (a) Load pattern. (b) Weekday Graph from Table 1 A-3 TOU Rates.

In this paper, Model I optimized the ESS to reduce the electricity bill of TOU customers without considering the ESS cost. The specifications of the ESS are shown in Table 2.

Table 2. Model I & II ESS Specification (Spec) Sheets

Parameter	Symbol	Value
SOC_{max}	Battery Spec	200 kWh
SOC_{min}, SOC_{max}	Operating Zones	10 – 90 %
SOC_{ini}	Initial Capacity	10 %
PCS	PCS Spec	50 kW
η	Efficiency	90 %

Model II optimizes the TOU rate minimization and PlusDR participation incentives by considering the IRR. The participation periods of PlusDR are March to May and September to October in spring and fall. We also assume that the time of the PlusDR dispatch is fixed between 12 and 15 o'clock in each time zone. The amount of output control is increasing with each passing year [2], and the number of PlusDR participation and performance is increasing accordingly [10]. Therefore, we assume that PlusDR will occur every day in spring and fall in the future.

The installation cost of the ESS was assumed to be fully invested in the first year and the return on the existing electricity bill is considered in subsequent years. The battery and PCS costs of the ESS are based on median prices according to The National Renewable Energy Laboratory (NREL) [11]. The lifetime and cash flow period of the ESS is 15 years.

In general, we used 10% IRR as a benchmark for a stable asset. Energy storage systems are a necessity owing to the growing number of renewable energy sources. Therefore, we assume that the ESS is a stable asset and set a target IRR of 10%.

Table 3. Energy Storage System Cost & Operation Parameters

Parameter	Symbol	Value
N	Revenue Periods	15 years
$C_{battery}$	Cost per kWh	0.46 M KRW
C_{PCS}	Cost per kW	0.47 M KRW
$COST_{ESS}$	Total Cost	117 M KRW
E_{RATE}	Origin Rates	300 M KRW
IRR	Discount Rate	10 %
M	Big-M Constant	1000
DR_t	Time for PlusDR	12 – 15 H

3.2 Analyzing Simulation Results

3.2.1 Result I – Based on Table 2 & 3

In this section, we analyzed simulation results using the model introduced in Section 2 and substituted the data presented in Section 3.1. Table 4 shows the peak load, electricity prices, and optimal incentives for each year under simulated conditions. The cases of Existing and Model I are excluded because they do not have optimal incentives.

Table 4. Simulation: Result I

Model	Contract (kW)	Rates (M KRW)	Incentive (KRW/kWh)
Existing	463.9	300	-
I	424.2	293.8	-
II	424.2	294.6	322.9

Model I have a cost saving of 6.2 million won compared to the previous electricity bill of 3 million won. However, it will take about 19 years of maintenance to equalize the result if it is assumed that the ESS installation cost of 117 million won is simply repaid. This is not economically feasible since the payback period is assumed to be 15 years.

The optimal incentive to satisfy the IRR of 10% is 322.9 KRW/kWh in the optimization of Model II. Based on the current system, the customer's PlusDR incentive is 108.5 KRW/kWh, indicating that the current incentive of the PlusDR system is insufficient to induce ESS adoption.

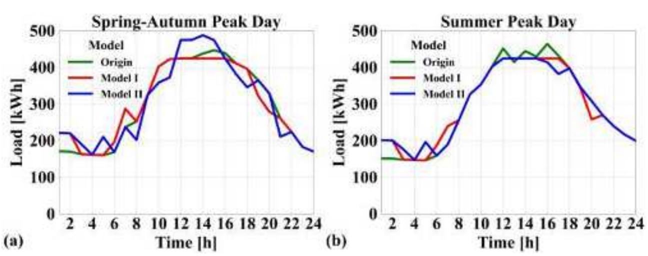

Figure 3. Load Graphs Over Time

Hourly electricity usage comparison of model for peak days during the spring and fall seasons showed that charging was done between 12:00 and 15:00 to qualify for the PlusDR incentive (Figure 3 (a)). The peak load at that time is excluded from the overall peak load consideration. This results in a graph that shows an increase in the customer's electricity usage. In summer, there is no PlusDR, and the TOU rate is minimized (Figure 3 (b)). The TOU rate minimization is not performed in spring and fall, which results in a slight increase in the Model II electricity rate in Table 4.

The results in Table 4 are based on a 15-year investment horizon. Additionally, the TOU rate minimization is performed in summer and winter when PlusDR is not participating. The main reason why it is not economical even in this situation is the high investment cost (the high cost of current ESS). However, the price of lithium-ion batteries is currently on a steady decline. This may be different from the ESS installation cost assumed in the current model.

3.2.3 Result II – Changing ESS Costs

We conducted additional simulations considering the aforementioned decline in ESS installation costs. The capacity of the ESS was kept at 200 kWh/50 kW. The results in Table 5 are the optimal incentives based on the ESS installation costs in Table 3. The price points were selected from the graphs in the NREL report [11].

Table 5. Simulation: Result II – Changing ESS Costs

Pricing by	Incentive (KRW/kWh)	Cost of ESS (M KRW)
Mid – 2024 (origin)	322.9	117.0
Low – 2024	185.6	87.3
Mid – 2025	263.2	103.8
Low – 2025	167.4	82.6
Low – 2030	96.9	67.0

The results in Table 5 show that the optimal PlusDR incentive decreases as the installed cost decreases. The NREL report Low graph shows that the cost of installing an ESS is 96.9 KRW/kWh at 2030 prices, which is less than the current incentive of 108.5 KRW/kWh. Since the cost of ESS installation is currently decreasing, it is possible for the private sector to install ESS for PlusDR participation in the future.

4. Conclusion

In this study, we propose a model to find the optimal incentive for customers under TOU tariffs to install ESS to optimize TOU rates and achieve the target IRR. The simulation results show that a relatively high level of incentive is needed compared to the current policy given the perceived high cost of ESS installation, but the optimal level of incentive could be lowered compared to the current policy given the trend of gradually decreasing ESS installation costs. However, the model assumes that PlusDR occurs every day in spring and fall, which may not be an accurate incentive. Further modeling of PlusDR or output control of renewables is needed for a more accurate assessment.

In the future, Jeju Island is expected to introduce more renewable energy for its CFI 2030 policy. Therefore, the installation of ESS is inevitable. However, the current cost of ESS is not low enough; therefore, additional incentives are needed to encourage their installation. This will allow more renewable energy sources to enter the grid, further contributing to carbon neutrality.

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Contact E-mail Address

GyuHyeon-Bae: bkh8207@tukorea.ac.kr
SungSoo-Kim: sskim@tukorea.ac.kr
Ahyun-Yoon: ay.yoon@tukorea.ac.kr