Operation Pattern Analysis of Electric Vehicle Taxis considering Electricity Market Price

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***Abstract*— Demand response plays a vital role in the optimal use of renewable energy resources. This paper aims to identify the most efficient operational patterns for taxi operators transitioning to electric vehicles (EVs). To achieve this, this paper compares the fuel expenses of traditional vehicles against the costs of electricity, optimized for charging opportunities. The result shows that employing night shifts and operating at half capacity are the most effective strategies for minimizing energy costs. Consequently, the adoption of EVs for demand response not only provides financial incentives for transportation operators but also supports demand management and enhances the efficient utilization of renewable energy.**

***Index Terms*—Electric vehicles, Demand Response, Electricity Market, Numerical simulation, Feasibility Study**

I. Introduction

This paper investigates the adoption of electric vehicles (EVs) for demand response to reduce the curtailment of renewable energy production. Renewable energy output fluctuates significantly throughout the day and in response to weather conditions, often leading to excess supply over demand during daylight hours, which necessitates the reduction of output [1]. Utilizing EV battery storage for demand response emerges as a crucial strategy to mitigate such reductions [2] [3]. This research focuses on the application of EVs by transportation operators managing large fleets.

Previous studies have concentrated on specific transportation operators, examining demand response and Vehicle to Grid (V2G) systems. For example, research by Yoneda [4] simulate an EV charging and discharging energy management system within a car-sharing service, forecasting electricity prices based on the Japan Electric Power Exchange (JEPX) and evaluating a preference model for car-sharing. The reasons why this study focused on taxis are: there are many studies on V2G, but few studies that focus on specific transportation providers; the taxi fleet has a high utilization rate of approximately 50%, so there are many waiting vehicles, which is likely to be effective for demand response; and there are few cost comparisons with Liquefied Petroleum Gas (LPG) used for taxis, rather than with electricity or oil costs.

The contribution of this paper is verification of energy costs linked to the use of EVs by taxi operators, considering the unique traits of the taxi industry. Characterized by diverse operational patterns, our verification process considers these variations [5]. Moreover, the study incorporates dynamic pricing analysis, where electricity rates are subject to change based on supply and demand equilibrium [6]. This paper calculates and verifies different energy costs, including LPG fuel prices and electricity rates, following various operational patterns, target periods, and utilization rates.

TABLE I TYPES OF ENERGY COSTS

Types of Energy Costs	Description
LPG	Fuel cost for traditional internal combustion engine vehicles running on LPG
Simple Charging	Charging electricity cost when charging is done after the operation hours
Optimized Charging	Charging electricity cost minimized through optimization

TABLE II COMPARISON CONDITIONS

Comparison Conditions	Description
Vehicle Operational Patterns	Three patterns: day shift, night shift, and alternate day shifts
Optimization Target Period	Three months starting from February, May, and August 2023
Vehicle Utilization Rates Two patterns	100% or 50%

The outline is as follows: In Section II, the problem that is considered in this study is formulated. In Section III, the developed approach for verification is presented. In Section IV, the results of the verification are verified by the numerical simulation. In Section V, conclusions are presented.

II. Problem Formulation

A. *Energy Costs*

The main goal of this paper is to determine the most cost-efficient operational strategies for taxi operators transitioning to EVs, focusing on energy expenses. We formulated an optimization problem designed to reduce the charging electricity costs for a single EV taxi, considering electricity market prices. Through this, we simulate the potential savings in energy costs that can be achieved by optimizing charging

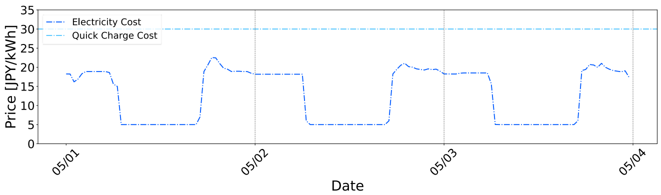

Figure 1 Variable Electricity Retail Rates in May 2023

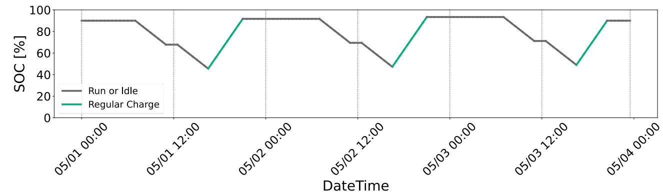

Figure 2 SOC transition during simple recharging in daytime day shift with full utilization rate

TABLE III OPERATIONAL PATTERNS

Operational Patterns	Description
Day Shift	7:00 ~ 16:00 with 1 hour break
Night Shift	18:00 ~ 27:00 with 1 hour break
Alternate Day Shift	8:00 ~ 28:00 with 3 hours break

practices. The energy costs we compared are presented in TABLE I .

Additionally, the scenarios under comparison are outlined in TABLE II, with details on each scenario to be discussed subsequently. We will perform a comparative analysis of energy costs for each scenario.

B. Electricity Market Prices

In this paper, the electricity rates for EV charging are determined by dynamic pricing, which is tied to the market prices at JEPX. Specifically, the electricity rates for EV charging were calculated as the area prices from JEPX plus a transmission charge, assumed to be 5 JPY/kWh per kilowatt-hour (kWh). For rapid charging scenarios, our cost calculations were based on existing service charge models. These models do not rely on electricity market prices but instead use a system that calculates charges based on the duration of use.

The illustration below depicts the trend in electricity rates for February 2023. A horizontal line in Figure 1 indicates the price per kWh for using rapid charging services.

C. Operational Patterns

Typical taxi operators utilize a variety of vehicle operational patterns; therefore, this paper examines different patterns to evaluate how variations in vehicle operation impact the electricity costs associated with EV driving. Taxi operation patterns can generally be divided into three categories: day shift, night shift, and alternate day shifts. In smaller cities and rural areas, day shifts are predominant, whereas in larger cities, where street-hailing is more frequent, alternate day shifts are more common. Although the exact operating and break times might differ across operators, this paper characterizes each operational pattern as TABLE III.:

Figure 2 illustrates the transitions of the State of Charge (SOC) throughout a day shift (full operation) when using simple charging methods. Horizontal segments of the graph signify "idle" periods, downward slopes denote "driving" periods, and upward slopes indicate periods of "regular charging" or "rapid charging."

TABLE IV SYMBOLS IN CHARGE OPTIMIZATION

Name	Description
$slots\_per\_day$	Number of steps per day
$total\_slots$	Total number of steps in the optimization period
$S_{idle}[i]$	Boolean variable for idle state (0 or 1)
$S_{run}[i]$	Boolean variable for driving state (0 or 1)
$S_{regular}[i]$	Boolean variable for normal charging (0 or 1)
$S_{quick}[i]$	Boolean variable for rapid charging (0 or 1)
$SOC\ [i]$	Charging rate at step *i* [%]
SOC_{max}	Upper limit of charging rate [%]
SOC_{min}	Lower limit of charging rate [%]
SOC_{start}	Lower limit of charging rate at the start of operation [%]
T_{start}	Number of steps at the start of the day's operation (0 ~ 48)
T_{end}	Number of steps at the start of the day's operation (0 ~ 48)
T_{break}	Number of break steps per operation
$P\ [i]$	Electricity rate at step *i* [JPY/kWh]
P_{quick}	Rapid charging service charge [JPY/min]
C_{EV}	EV battery capacity [kWh]
$E_{regular}$	Normal charging output [kW]
E_{quick}	Rapid charging output [kW]
E_{run}	Power consumption during driving [kW]
P_{LPG}	LPG fuel economy based on distance [JPY/km]
V	Average speed of taxi [km/h]

TABLE V CONSTANTS IN CHARGE OPTIMIZATION

Description	Value
Average Speed during Taxi Operation	25 [km/h]
EV Taxi Battery Capacity [7]	60 [kWh]
EV Taxi Energy Consumption [7]	0.13 [kWh/km]
Standard Charger Output [8]	6 [kW]
Fast Charger Output [9]	50 [kW]
Fast Charging Usage Fee [9]	25 [JPY/min]
Additional Charges such as Wheeling Charges on JEPX Electricity Price	5 [JPY/kWh]
LPG Mileage [10]	16.8 [km/L]
LPG Price [11]	110 [JPY/L]

Owing to uniform operating and break times, the graph exhibits a consistent pattern. Charging begins right after the operation period concludes with regular charging (depicted in green), and the vehicle stays idle until the commencement of the next operation period.

TABLE VI VEHICLE STATUSES

Status	Description	Possible Time Periods
Idle	The vehicle is idle, with no increase or decrease in SOC	Outside operating hours, During breaks in operating hours
Driving	The vehicle is driving, with a decrease in SOC	During operating hours
Normal Charging	The vehicle is connected to a normal charger, with an increase in SOC	Outside operating hours
Rapid Charging	The vehicle is connected to a rapid charger, with an increase in SOC	During breaks in operating hours

III. CHARGE OPTIMIZATION APPROACH

A. Parameters and Constants

The symbols in this problem are listed in TABLE IV. The constants in this problem are listed in TABLE V.

B. Objective function

The objective function of this paper is to minimize the charging electricity price for EV taxi driving, as shown in Equation (1).

$$\min \sum_{i=0}^{total\_slots} \left(P\,[i] \times E_{regular} \times S_{regular}\,[i] + P_{quick} \times S_{quick}\,[i] \times 30 \right) \quad (1)$$

C. Constraints

This paper presents constraint conditions applicable across all steps as follows. Equation (2) imposes constraints on the State of Charge (SOC) within upper and lower limits.

$$SOC_{min} \le SOC\,[i] \le SOC_{max} \quad (2)$$

Equation (3) ensures that at step i, an EV can only assume one of the following statuses: idle, driving, normal charging, or rapid charging. The specific time periods each status can occur are detailed in TABLE VI.

$$S_{idle}[i] + S_{run}[i] + S_{regular}[i] + S_{quick}[i] = 1 \quad (3)$$

Equation (4) constrains the SOC at step i+1, calculating the next step's SOC using boolean variables $S_{regular}$, S_{quick}, and S_{run}.

$$SOC\,[i+1] = SOC\,[i] + S_{regular}[i] \times \frac{E_{regular}}{C_{EV}} \times \frac{1}{2} + S_{quick}[i] \times \frac{E_{quick}}{C_{EV}} \times \frac{1}{2} - S_{rum}[i] \times \frac{E_{run}}{C_{EV}} \times \frac{1}{2} \quad (4)$$

Normal charging is not performed during operating hours, hence the constraint during these times is as follows:

$$if\ \{\, T_{start} \le i\ (\mathrm{mod}\ slots\_per\_day) \le T_{end} \,\} \quad S_{regular} = 0 \quad (5)$$

Equation (6) imposes a constraint on the minimum SOC at the start of operation, as a certain level of SOC is deemed necessary for normal operations.

$$if\ \{\, T_{start} = i\ (\mathrm{mod}\ slots\_per\_day)\} \quad SOC[i] \ge SOC_{start} \quad (6)$$

Equation (7) relates to constraints during break times. As the status during these times can only be "idle" or "rapid charging," a constraint is set so the number of steps assuming status during the day's operating hours equals T_{break}.

$$\sum_i \left(S_{quick}[i] + S_{idle}[i] \right) = T_{break} \quad (7)$$

Outside operating hours, since the statuses "driving" and "rapid charging" are not taken, the constraints are as follows:

$$if\ not\ \{\, T_{start} \le i\ (\mathrm{mod}\ slots\_per\_day) \le T_{end} \,\} \quad S_{run} = 0 \quad S_{quick} = 0 \quad (8)$$

IV. CASE STUDY

After adjusting the target period and utilization rate, the outcomes of the energy cost calculations for LPG gas, simple charging, and optimized charging are depicted in Figure 3. Independent of the utilization rate and target period, the energy costs associated with employing EVs during night shifts prove to be the lowest. This outcome is attributed to the opportunity to charge the vehicles during the day, when the reduction of energy output is more likely in Figure 4.

Additionally, under many conditions, the energy costs for alternate day shifts emerge as the highest. This is believed to result from the extended operation times characteristic of alternate day shifts, which require the utilization of rapid charging. Rapid charging incurs a higher cost per charge in Figure 5.

Regardless of the utilization rate and the period considered, energy costs are lowest when EVs are used during night shifts (Figure 6 and Figure 7). This is likely because night shifts can charge the vehicles during the daytime, when output curtailment is more likely to occur. Moreover, under most conditions, the energy costs for alternate day shifts are the highest. This is thought to be due to the necessity of using fast charging for alternate day shifts, which has a higher unit charging cost.

The reduction in energy costs achieved by introducing EVs in place of traditional internal combustion engine vehicles fueled by LP gas is believed to result from the differences between the fuel costs of traditional vehicles and the electricity costs of EVs. The rate of energy cost reduction from optimizing charging operations is greater for patterns with a 50% utilization rate. This is thought to be because the longer available time for charging allows for charging during periods when electricity rates are lower.

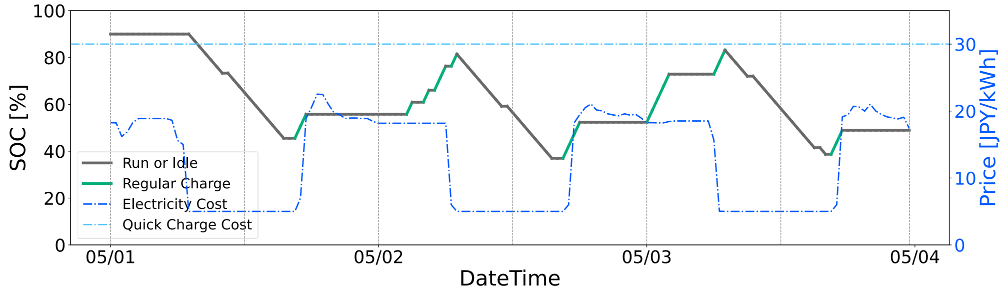

Figure 3 SOC and electricity rates at optimum charging of Day shift with 100% utilization in May 2023

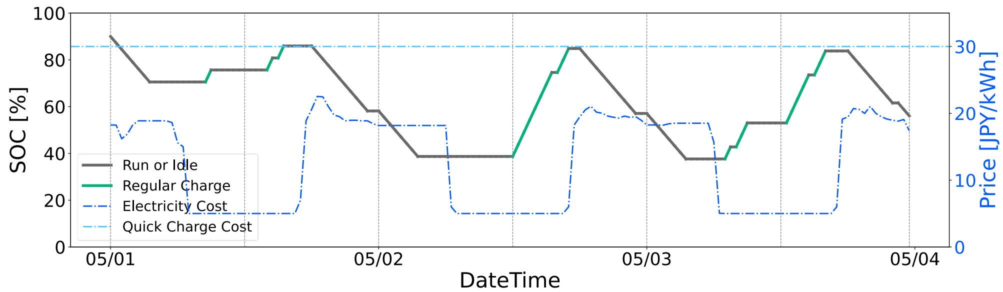

Figure 4 SOC and electricity rates at optimum charge of Night shifts with 100% occupancy in May 2023

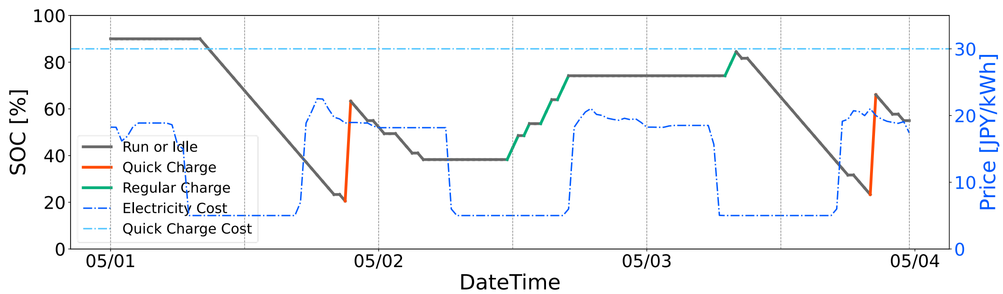

Figure 5 SOC and electricity rates at optimal charging of Alternate Day Shifts with 100% utilization rate in May 2023

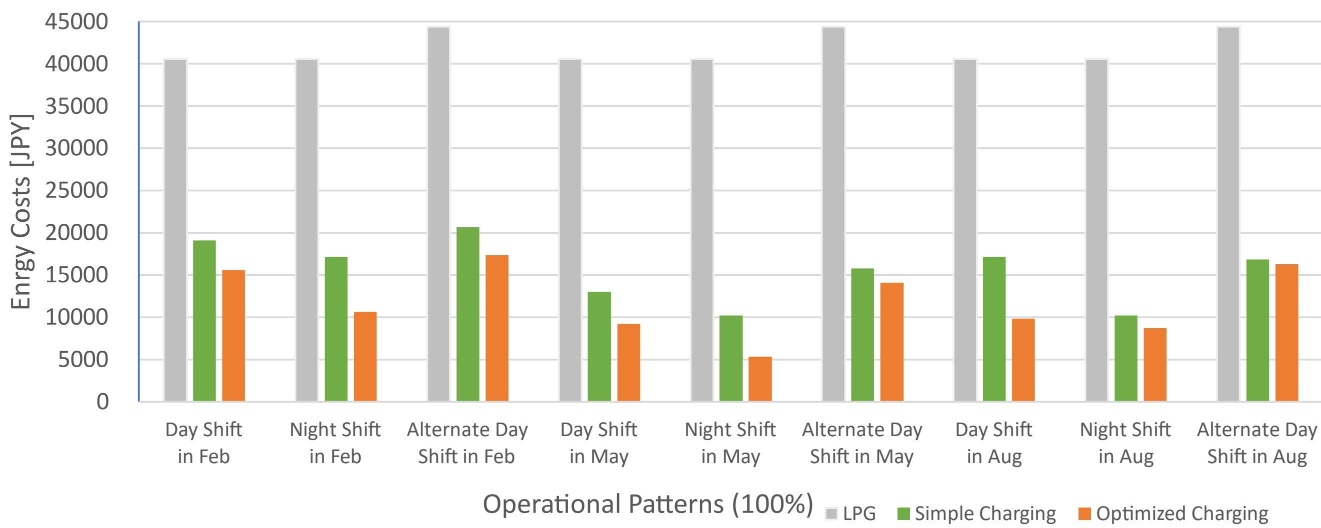

Figure 6 Energy cost calculation results with 100% utilization rate

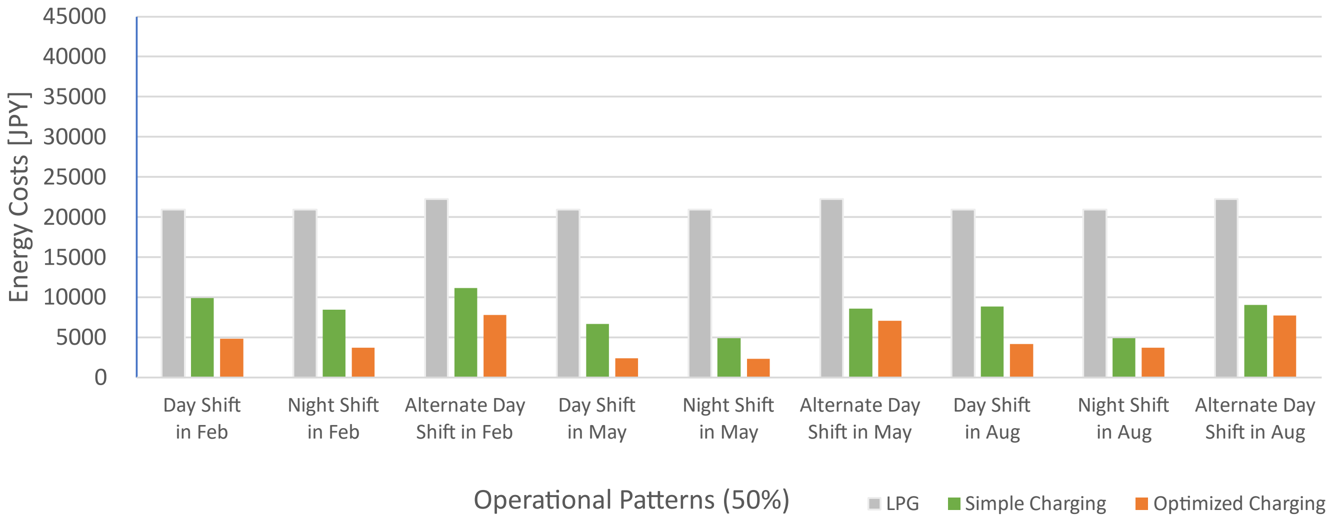

Figure 7 Energy cost calculation results 50% utilization rate

V. CONCLUSION

Switching from LPG gas to simple charging resulted in approximately a 60% reduction in costs, while transitioning from simple charging to optimized charging yielded about a 30% reduction in costs. Therefore, utilizing EVs for demand response can simultaneously secure incentives for transportation operators and promote demand adjustment and the effective use of renewable energy. Moreover, the cost reduction rate of night shifts was superior across almost all operational patterns, and a 50% utilization rate demonstrated greater cost savings due to optimized charging operations.

Future research directions include analysis considering the variation in EV energy consumption across different seasons, analysis accounting for battery degradation due to rapid charging, and comprehensive evaluation analysis that includes initial costs and running costs associated with EV adoption.

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