Energy Proceedings
Vol 51, 2025
ISSN 2004-2965

Optimal Electricity Procurement Plan for Charging Service Providers#

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ABSTRACT

This paper investigates the electricity procurement plan problem for charging service providers. The problem presents two challenges from both the demand and supply sides. On the demand side, the historical charging demand data is unavailable during the planning stage. On the supply side, multiple procurement options, including the spot market, financial power purchase agreements, self-invested power generation and energy storage are available on the market, with different costs, validity duration, and available capacities. To address these challenges, we propose a charging demand model to estimate demand at charging stations and develop cost models for various electricity procurement options. An optimization-based method to manage the electricity procurement portfolio is proposed. This method aims to minimize the total procurement costs while ensuring a reliable supply to meet the forecasted demand. The proposed approach is intended to guide charging service providers' participation in the electricity market.

Keywords: Electric vehicle, charging station, electricity procurement

NONMENCLATURE

Abbreviations	
EV	Electric vehicle
BESS	Battery energy storage system
FC	Forward contract
CO	Call option

1. INTRODUCTION

As the number of electric vehicles (EVs) on the road increases, the requirement for efficient and reliable EV charging services becomes critical. In this context, numerous charging service providers are expected to emerge in the market to operate charging stations by generating, purchasing, storing, and selling electricity to EV drivers. As large energy consumption consumers in the future, one of the central challenges for EV charging service providers is electricity procurement to ensure a reliable and efficient charging power supply [1].

Electricity procurement involves the strategic acquisition of electricity from various electricity providers or self-invested generation units and battery energy storage systems (BESSs). The spot market, including the day-ahead market and real-time market, is the primary source for charging service providers to purchase electricity. Refs. [2, 3] provide energy management solutions for charging stations to optimize electricity purchases from both the day-ahead and real-time markets. The spot market can be highly volatile, with prices fluctuating rapidly due to changes in supply, demand, economic data, and other market dynamics. Various financial power purchase agreements are developed directly between electricity sellers and buyers to hedge against electricity price volatility, which are typically used for medium- and long-term planning. Common agreements include forward contracts, call options, and contracts for differences. In [4], a decision-making framework is proposed for PV-BESSs charging stations to optimize energy procurement and dispatch, where bilateral contracts and real-time pool purchases are considered for power purchase. It effectively characterizes risks through conditional value at risk (CVaR) and demonstrates the trade-offs between expected profit and risk management. Another strategy for electricity procurement is the installation of self-generation units and BESSs, which are attractive options for charging service providers in locations with adequate renewable resources [5].

The electricity procurement problem addressed in this paper faces challenges from both the demand and supply sides. On the demand side, the historical charging demand data is unavailable during the planning stage, necessitating the development of methods to estimate future charging demand in charging stations operated by charging service providers. On the supply side, as large

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

electricity consumers, charging service providers possess considerable bargaining power and multiple options for purchasing electricity from the market, including the spot market, self-generation, BESSs, and financial power purchase agreements. Given the different costs, validity duration, and available capacities associated with these electricity procurement options, charging service providers are interested in how to determine the procurement portfolio to minimize total costs while ensuring a reliable supply to meet forecasted demand. To address this problem, we propose an optimization-based method, incorporating a range of candidate options and real-world constraints, to optimize the electricity procurement portfolio. Our method seeks to offer practical insights for charging service providers to reduce electricity purchase costs. The rest of this paper is organized as follows. In Section 2, we model the charging demand of parking lot charging stations. In Section 3, the optimization problem is formulated. In Section 4, a case study is provided to illustrate the proposed method. Section 5 concludes this paper.

2. CHAEGING DEMAND MODELLING

This section models the charging demand which should be satisfied by the charging service providers. Suppose the charging service providers manage M parking lots. Since there is no available historical charging demand data, the charging demand of each parking lot is estimated based on the historical parking data, which can be obtained from the parking ticket database of each parking lot. Denote the daily number of vehicles parking at the parking lot as G_m. Considering that the historical parking records might lack specific features on vehicle type (EV or internal combustion engine vehicles), the daily number of EVs parking at the charging station is estimated based on the EV penetration rate r_m of the area where the parking lot is located. Then, the daily number of EV parkings at the parking lot m is estimated as $J_m = r_m G_m$. Since vehicle flows on different days show differentiated features in terms of arrival time and parking time, the charging demand is modeled on a daily basis. We divide one day into k time slots and assume the energy and charging states of each EV remain unchanged during each time slot Δt. The available park-starting and park-ending time slots of EV j at parking lot m are given by

$$t_{m,j}^{a} = \text{ceiling}\left(\frac{t_{m,j}^{arr}}{\Delta t}\right),$$

$$t_{m,j}^{d} = \text{floor}\left(\frac{t_{m,j}^{dep}}{\Delta t}\right),$$

where $t_{m,j}^{arr}$ and $t_{m,j}^{dep}$ are the arrival time and departure time of EV j. ceiling() and floor() are roundup function and round down function, respectively. Then the charging demand of EV j is calculated by

$$P_{m,j}^{E} = max\{(t_{m,j}^{d} - t_{m,j}^{a} + 1)\Delta t, (1 - SOC_{m,j})C^{e}\},$$

The arrival SOC of EV is an unknown parameter. The arrival SOC using the Weibull distribution with scale parameter $\lambda = 0.8$ and shape parameter $c = 10$, based on the work in [6]. C^{e} is the average capacity of EV batteries.

By aggregating all charging demand of EVs, the total charging demand that should be satisfied by the charging service providers is given by

$$P^{E} = \sum_{m=1}^{M} \sum_{j=1}^{J_m} P_{m,j}^{e}.$$

3. OPTIMIZATION FORMULATION

A forward contract (FC) is a contractual obligation between charging service providers and power plants to buy (sell) a fixed amount of electricity at a pre-specified price, at a specific future date. The cost of purchasing electricity using forward contracts,

$$C^{FC} = \sum_{k=1}^{K} \sum_{n=1}^{N^{FC}} c_{n}^{FC} P_{k,n}^{FC},$$

where N^{FC} is the number of available FCs on the market. c_{n}^{FC} represents the price of forward contract n. $P_{k,n}^{FC}$ is the power purchased from nth FC.

A call option (CO) is a contract that gives the charging service providers the right, but not the obligation, to buy a fixed amount of electricity by a specific date at a predetermined price (strike price) from the contracted power plant [7]. To obtain this right, the charging servicer pays a fee known as a premium. The cost of purchasing electricity using call option is calculated as

$$C^{CO} = \sum_{d=1}^{D} \sum_{k=1}^{K} \sum_{n=1}^{N^{CO}} (c_{n}^{Pre} + c_{n}^{CO}) P_{n,d,k}^{CO},$$

where N^{CO} is the number of available *COs.* c_{n}^{Pre} and c_{n}^{CO} are the premium price and strike price of nth call option, respectively. $P_{n,d,k}^{CO}$ is the power purchased from the nth CO at time interval k on day d.

The charging service can purchase a small portion of electricity from pool. Hence, the cost of purchasing from the pool is calculated by:

$$C^P = \sum_{d=1}^{D}\sum_{k=1}^{K} c_{d,k}^P P_{d,k}^P,$$

where $c_{d,k}^P$ is the pool price at time interval k on day d, $P_{d,k}^P$ is the quantity of electricity purchased from the pool at time interval k on day d.

The charging service provider can invest in self-power generation units and BESSs. A trade-off between the costs of building and operating self-power generation units and self-energy storage systems and other procurement options is required. In this study, we consider PV based self-power generation. The cost of building and operating PV power generation systems is calculated as

$$C^{PV} = \frac{D}{365}(\alpha^{PV} c^{PV} + o^{PV})x^{PV},$$

where $\alpha^{PV} = \frac{DR(1+DR)^{n^{PV}}}{(1+DR)^{n^{PV}}-1}$ represents the capital recovery factor for PV power generation systems. DR is the discounted factor, n^{PV} represents the lifespan of PV, c^{PV} and o^{PV} are capital and operation costs of PV, respectively. x^{PV} is the planned installation area of PV.

The cost of building and operating self-battery energy storage system is calculated as

$$C^B = \frac{D}{365}(\alpha^B c^B + o^B)x^B,$$

where $\alpha^B = \frac{DR(1+DR)^{n^B}}{(1+DR)^{n^B}-1}$ represents the capital recovery factor for BESSs. n^B represents the lifespan of BESSs, c^B and o^B are capital and operation costs BESSs, respectively. x^B is the planned installation capacity of BESSs.

We assume the charging service provider is risk-neutral, then the charging service provider is interested in minimizing the total electricity procurement cost by optimizing the electricity purchase from the electricity market. The problem is formulated into the

$$\min Q = C^{FC} + C^{CO} + C^P + C^{PV} + C^B,$$

The following constraint ensures that the energy produced from different options is equal to the EV charging demand.

$$\sum_{n=1}^{N_F} P_{n,d,k}^{FC} + \sum_{n=1}^{N_C} P_{n,d,k}^{CO} + P_{d,k}^P + P_{d,k}^{PV} + P_{d,k}^{DIS} = P_{d,k}^E + P_{d,k}^{CH},$$

where $P_{d,k}^{DIS}$ and $P_{d,k}^{CH}$ are discharging and charging power of battery energy storage system at time interval k on day d, respectively. $P_{d,k}^{PV}$ is the power provided by PV power generation at time interval k on day d.

The following inequalities are provided to ensure the forward contract and call option obey the respective capacity and ramp up/down constraints:

$$s_n P_{n,min}^{FC} \le P_{nk}^{FC} \le s_n P_{n,max}^{FC},$$

$$P_{n,k}^{CO} \le s_n P_{n,max}^{CO},$$

$$R_{d,n}^{FC} \le P_{n,k+1}^{FC} - P_{n,k}^{FC} \le R_{u,n}^{FC},$$

$$R_{d,n}^{CO} \le P_{n,k+1}^{CO} - P_{n,k}^{FC} \le R_{u,n}^{CO},$$

where $P_{n,min}^{FC}$ and $P_{n,max}^{FC}$ are the minimum and maximum capacity contracted by FC n, respectively. $R_{d,n}^{FC}$ and $R_{u,n}^{FC}$ are ramp up and down limits of FC n, respectively. $P_{n,max}^{CO}$ is the maximum capacity contracted by CO n. s_n is binary decision variable. s_n represents that the FC/CO n is selected. $R_{d,n}^{CO}$ and $R_{u,n}^{CO}$ are ramp up and down limits of CO n, respectively.

The PV power generation system satisfies

$$0 \le P_{d,k}^{PV} \le \eta x^{PV} I_{d,k}^{PV},$$

where η represents the energy conversion efficiency of PV and $I_{d,k}^{PV}$ is the solar irradiance of the area at time interval k on day d.

The BESS is modelled by

$$E_{d,k+1}^B = E_{d,k}^B + P_{d,k}^{CH} - P_{d,k}^{DIS},$$

where $E_{d,k}^B$ represents the total amount of energy stored in the BESSs. The charging power, discharging power, and energy storage are constrained by

$$0 \le P_{d,k}^{CH} \le P_{max}^{CH} U_{d,k}^{CH},$$

$$0 \le P_{d,k}^{DIS} \le P_{max}^{DIS} U_{d,k}^{DIS},$$

$$E_{d,k}^B \le x^B,$$

$$E_{d,0}^B = E_{d,K}^B,$$

$$U_{d,k}^{CH} + U_{d,k}^{DIS} \le 1,$$

where P_{max}^{CH} and P_{max}^{DIS} are maximum charging and discharging power of BESSs, respectively. $U_{d,k}^{CH}$ and $U_{d,k}^{DIS}$ are binary decision variables to control the charging/discharging process of BESSs, which cannot be charged and discharged at the same time.

4. CASE STUDY

Consider a charging service provider who plans to manage three parking lot charging stations, the charging demand is estimated according to the method given in Section 2 based on the parking recordings of each parking lots. The parking recordings are obtained from [8]. The specifications of forward contracts and call options are given in Table 1 and Table 2 respectively, adapted from [9]. The capital costs for PV and BESSs are 200 $\$/\mathrm{m}^2$ and 150 $\$/\mathrm{kWh}$, respectively. The operational costs for PV and BESSs are 5% of their capital costs. The maximum charging power and discharging power of BESSs are 0.2 MWh and 0.3 MWh, respectively. The energy conversion efficiency of PV is 23%. We consider one day. The pool price is given in Figure 1. The solar irradiance of the area is shown in Figure 2. The numerical simulation is performed by Gurobi solver, on an Intel Core i9-12900 CPU @3.20 GHz, 32 GB RAM.

Table 1. Specifications of forward contracts for one day.

Contract number	Validity duration	Min (MW)	Max (MW)	Price (\$/MWh)
1	[8:00,20:00)	0.5	2	75.84
2	[8:00,20:00)	0.4	2.5	110.64
3	[8:00,20:00)	0.8	2	109.24
4	[14:00,20:00)	0.8	1	109.16
5	[14:00,20:00)	0.6	1.5	113.60
6	[14:00,20:00)	0.8	2.5	111.84

Table 2. Specifications of call options for one day.

Contract number	Validity duration	Max (MW)	Price (\$/MWh)
1	[9:00,22:00)	1	93.81
2	[9:00,22:00)	0.5	91.02
3	[9:00,22:00)	0.8	104.75

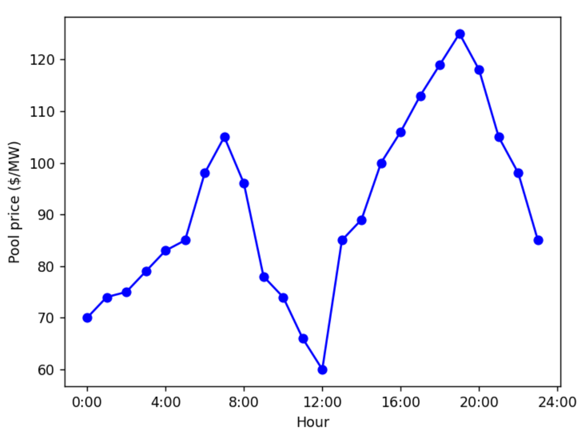

Figure 1. Pool price.

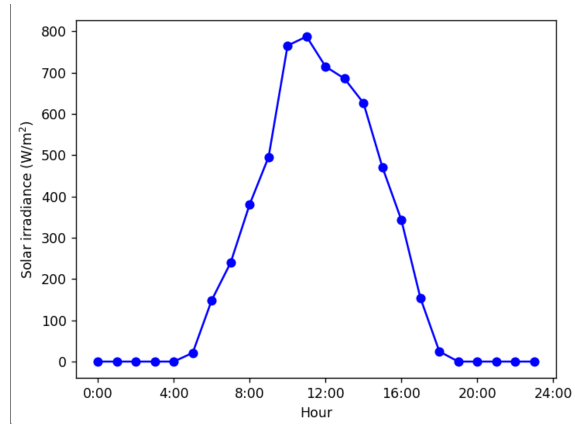

Figure 2. Solar irradiance.

The optimal electricity purchased/generated plan is show in Figure 3. The energy stored in the battery is shown in *Figure 4*. The forward contract 1 and call options 1 and 2 are selected. The minimum total procurement cost is \$ 2,631, where the cost of purchasing/generating from forward contract, call option, pool market, self power generations, and BESSs are \$ 1,267, \$ 497, \$ 421, \$ 407, and \$ 39, respectively.

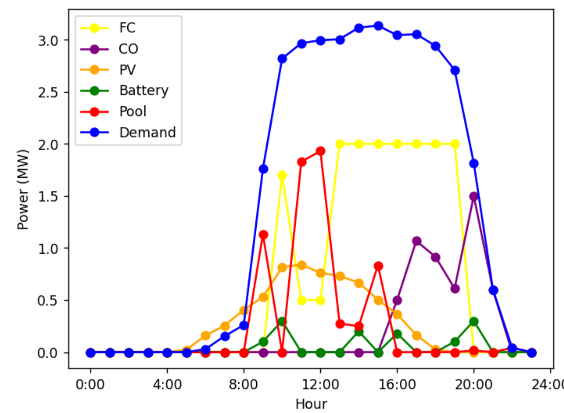

Figure 3. Power purchased/generated from different electricity procurement options for one day.

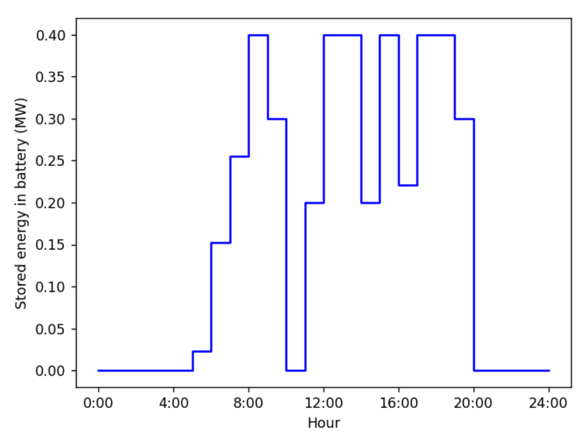

Figure 4. Energy stored in the battery for one day.

5. CONCLUSIONS

This study explores optimal electricity procurement strategies for parking lot charging service providers, aiming to optimize their electricity procurement portfolios. Due to the unavailability of historical charging demand data during the planning stage, a charging demand estimation model is proposed based on parking records. We consider multiple electricity procurement options and formulate an optimization-based framework to minimize the total electricity procurement cost while satisfying the estimated charging demand.

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