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Decision making of electricity retailer with multiple channels of purchase based on fractile criterion with rational responses of consumers

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ABSTRACT

This paper presents a novel decision making framework of time-of-use (TOU) price settings and procurement strategies in medium-term planning for an electricity retailer taking into account the rational responses of consumers to the TOU prices. Key ideas of this paper are (1) to introduce the time-series responses of the consumers to the time-varying TOU prices in the medium-term planning; and (2) to find a preferred solution reflecting the preference of the retailer to uncertainty caused by volatile electricity market prices and demand in the non-convex decision making problem. The details of the proposed method to realize the aforementioned key ideas are summarized as follows: (i) assuming the rational responses of the consumers to the time-varying TOU prices offered by the retailers including a decision maker and rival retailers, the decision making problem of the retailer to optimize both the TOU price settings and the purchase allocation in the multiple channels of purchase, i.e., mid-term forward contracts and a short-term day-ahead market, is modeled as the Stackelberg game; (ii) on the non-convex decision making problem formulated as the bi-level programming problem, the preference of the retailer to the uncertainty is reflected by employing the fractile criterion using the stochastic aspiration level specified by the retailer; and (iii) the bi-level programming problem is converted to the mixed integer linear programming problem (MILP), which can be solved by the commercial solver efficiently, by Karush-Kuhn-Tucker optimality conditions and the strong duality theorem. Through the computational experiments, we demonstrate validity of the proposed decision making framework and some findings revealed by introducing the rational response of the consumer.

1. Introduction

Nowadays, deregulation in electricity markets including retail markets is being developed over the world to improve efficiency of electricity generation and retail services. Since the profit of the players in the retail market has volatility due to uncertainty of the day-ahead market prices and demand, risk hedge utilizing multiple channels including forward contracts is significant. Related previous works often employ the stochastic decision making approach for retail market players [1–13]. In several works, decision making models for retailers to determine an optimal portfolio allocation among multiple procurement sources are focused on [5–7,9,10,13,14]. Needless to say, selling price determination is also important for retailers as well as the procurement problem. In case of the selling price determination, the competitive environment due to existence of rival retailers should be taken into account for an appropriate decision making modeling. Several pioneering approaches to integrate the behavior of retailers and consumers in the competitive environment to the optimal selling price and procurement problem are found [5,6,9,10,13]. An approach to motivate consumers towards shifting the demand during the peak periods to off-peak periods is called demand response [8,15,16]. By employing the demand response program, each consumer can benefit by reducing its total cost [15] and the peak-to-average ratio in the aggregate load demand can be also reduced [16]. In particular, the time-of-use (TOU) price would reduce the costs and risks for retailers by giving incentives to customers to realize peak-shaving and/or load-shift [7,8]. Since the demand response is expected to bring benefits to the retailer, we also suppose that the consumers respond rationally to the time-varying TOU prices offered by a retailer who is the decision maker in our model and the other rival retailers to minimize the cost. Note that we call the flexible time-varying price “TOU price” like [8] to distinguish it from the real time pricing depending on the market prices. Unlike the real time pricing, in this paper, the retailer supplies the consumer with the electricity at the agreed TOU selling price once they make the contract.

However, a decision making model for retailers in medium-term

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Nomenclature

A. Sets

Ω	set of scenarios: $\Omega = \Omega_P \times \Omega_D$
Ω_P	set of scenarios for uncertain day-ahead market prices
Ω_D	set of scenarios for uncertain demands of consumers
$\mathcal{T}$	set of periods in a day
$\mathcal{T}^{\mathcal{FP}}$	set of periods in peak hours: $\mathcal{T}^{\mathcal{FP}} \subset \mathcal{T}$
$\mathcal{N}^{\mathcal{FB}}$	set of contracts for base forward contracts
$\mathcal{B}_n$	set of blocks in base forward contract n
$\mathcal{M}^{\mathcal{FP}}$	set of contracts for peak forward contracts
$\mathcal{B}_m$	set of blocks in peak forward contract m
$\mathcal{R}$	set of rival retailers

B. Indices

ω	index of scenarios ($\in \Omega$)
ω_p	index of day-ahead market price scenarios ($\in \Omega_P$)
ω_d	index of demand scenarios ($\in \Omega_D$)
t	index of periods ($t \in \mathcal{T}$)
n	index of base forward contracts ($\in \mathcal{N}^{\mathcal{FB}}$)
b_n	index of blocks of base forward contract n ($\in \mathcal{B}_n$)
m	index of peak forward contracts ($\in \mathcal{M}^{\mathcal{FP}}$)
b_m	index of blocks of peak forward contract m ($\in \mathcal{B}_m$)
r	index of rival retailers ($\in \mathcal{R}$)

C. Decision variables

f	target variable used in the fractile model
λ_t^{sell}	selling price offered at period t [JPY/kWh]
P_{n,b_n}^{FB}	purchasing power in block b_n of base forward contract n at each period [kWh]
P_{m,b_m}^{FP}	purchasing power in block b_m of peak forward contract m at each period [kWh]
P_t^{D+}	increment from base demand in scenario ω at period t for the decision maker [kWh]
P_t^{D-}	decrement from base demand in scenario ω at period t for the decision maker [kWh]
y_ω	binary variable for scenario ω used in the mixed-integer expression of the fractile model
P_t^{r+}	increment from base demand in scenario ω at period t for rival retailer r [kWh]
P_t^{r-}	decrement from base demand in scenario ω at period t for rival retailer r [kWh]

D. Parameters

π_ω	probability of occurrence of scenario ω
λ_{n,b_n}^{FB}	price of block b_n of base forward contract n [JPY/kWh]
λ_{m,b_m}^{FP}	price of block b_m of peak forward contract m [JPY/kWh]
$\overline{P_{n,b_n}^{FB}}$	the maximum value of P_{n,b_n}^{FB} [kWh]
$\overline{P_{m,b_m}^{FP}}$	the maximum value of P_{m,b_m}^{FP} [kWh]
θ	probabilistic assured level of the decision maker about a financial risk, $\theta = (0.0, 1.0]$
$\lambda_{\omega,t}^{DA}$	day-ahead market price in scenario ω at period t [JPY/kWh]
$\lambda_{r,t}^{sell}$	the selling price offered by the rival retailer r to consumers at period t [JPY/kWh]
$P_{\omega,t}^{Base}$	base demand in scenario ω at period t [kWh]
$\lambda_{max,t}^{sell}$	upper bounds of λ_t^{sell} [JPY/kWh]
$\lambda_{min,t}^{sell}$	lower bounds of λ_t^{sell} [JPY/kWh]
P^{cap}	capacity of demand at each period [kWh]
K_t^{D+}	coefficient of increment demand at period t, $K_t^{D+} = [0.0, 1.0]$
K_t^{D-}	coefficient of decrement demand at period t, $K_t^{D-} = [0.0, 1.0]$
ρ_t^{dis}	disutility coefficient by suppressing demand at period t [JPY/kWh]
M^{up}	sufficiently large constants used to linearize the fractile model
M^{low}	sufficiently large constants used to linearize the lower problem

E. Variables

$P_{\omega,t}^{DA}$	electricity power traded in a day-ahead market in scenario ω at period t [kWh]
$R(\omega)$	profit of the retailer at scenario ω [JPY]
δ_t^{FP}	binary variable for describing periods for peak contracts

planning using multiple channels of purchase integrated with (i) time-varying TOU prices (not the real time pricing), (ii) time-series rational responses of consumers to TOU prices, and (iii) the competitive environment cannot be found in related works. The authors have proposed a decision making model for a retailer utilizing day-ahead market integrated with (i) the TOU prices and (ii) time-series response of consumers to the TOU prices [17]. However, the forward contracts have not been considered and the competitive environment also has not been explicitly modeled in our previous research. From this perspective, we incorporate the two types of trades and the rival retailers into the decision making model of the retailer simultaneously. There are multiple channels for the purchase of the electric power, i.e., the day-ahead market, the peak type forward contracts, and the base type forward contracts. Carríon et al. [6] also addresses a similar problem by employing a bi-level stochastic programming approach for future market trading. Unlike the literature [6], however, we focus on a decision making of the retailer considering the time-series rational responses of consumers to the TOU prices in a day divided into 48 periods.

The retailer makes a decision taking into account the demand of consumers in response to the time-varying TOU prices and the competitive selling prices of rival retailers. In perfectly competitive electricity retail market, the consumers are expected to select a retailer who offers the most competitive selling price. In light of recent penetration of demand side controllable loads, it would be natural to expect that the consumers control their demand flexibly in response to the TOU prices. For these reasons, the rational behavior of the consumer is explicitly modeled in this paper instead of using a model with demand elasticity [2–4,7]. In such a situation, the economic relation between the retailer and consumers can be modeled as a Stackelberg game [6,8,12,18,19]. We formulate the game model as a bi-level programming problem to explicitly take into account the rational response of the consumer to the selling prices and competition among rival retailers.

In the above mentioned assumed problem, the decision making of the retailer can be formulated as an optimization problem with multiple criteria, e.g., the expected profit and the financial risk arising from uncertainty of both electricity market prices and demand. For the decision making under uncertainty, it is quite significant to find a preferred solution that satisfies an aspiration level of the retailer with respect to the uncertainty. In the relevant literature, two objective functions of the expected profit and the conditional value at risk (CVaR) are often employed, and they are converted into a single-objective