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# Optimal stochastic energy management of retailer based on selling price determination under smart grid environment in the presence of demand response program

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## HIGHLIGHTS

- Stochastic energy management of retailer under smart grid environment is proposed.
- Optimal selling price is determined in the smart grid environment.
- Fixed, time-of-use and real-time pricing are determined for selling to customers.
- Charge/discharge of ESS is determined to increase the expected profit of retailer.
- Demand response program is proposed to increase the expected profit of retailer.

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ABSTRACT

In this paper, bilateral contracting and selling price determination problems for an electricity retailer in the smart grid environment under uncertainties have been considered. Multiple energy procurement sources containing pool market (PM), bilateral contracts (BCs), distributed generation (DG) units, renewable energy sources (photovoltaic (PV) system and wind turbine (WT)) and energy storage system (ESS) as well as demand response program (DRP) as virtual generation unit are considered. The scenario-based stochastic framework is used for uncertainty modeling of pool market prices, client group demand and variable climate condition containing temperature, irradiation and wind speed. In the proposed model, the selling price is determined and compared by the retailer in the smart grid in three cases containing fixed pricing, time-of-use (TOU) pricing and real-time pricing (RTP). It is shown that the selling price determination based on RTP by the retailer leads to higher expected profit. Furthermore, demand response program (DRP) has been implemented to flatten the load profile to minimize the cost for end-user customers as well as increasing the retailer profit. To validate the proposed model, three case studies are used and the results are compared.



## 1. Introduction

In the smart grid environment, determination of selling price to end-user customers by the electricity retailer is necessary [1]. In this issue, the electricity retailer should procure demand of customers from power market [2], distribution generation units [3], bilateral contracts [4], wind turbine [5], photovoltaic system [6], energy storage systems [7,8], and demand response program [9,10] under uncertainties modeling [11]. Therefore, it is essential that the retailer manage the purchased power from alternative energy resources to maximize his own expected profit. High selling price makes the customers not purchase from this retailer and leads to reduction of retailer profit. Also, low selling price decreases the expected profit of retailer. Therefore, the retailer should determine the optimal selling price with the aim of maximizing the expected profit. Furthermore, the retailer can determine the selling price based on fixed price, time-of-use price or real-time price. Finally, the retailer should manage the uncertainty of pool market price, demand of end-user, wind speed, irradiation and temperature. Finally, demand response program can be used by the retailer as an option enabled via smart grid technology to increase the expected profit.

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**Nomenclature**

*Index*
- $b$ bilateral contract index
- $h$ the generation block index of DG units
- $i$ the minimum OFF-time and ON-time limits modeling index
- $j$ DG unit index
- $s$ scenario index
- $t$ time period index
- $z$ segment index in the price-quota curve

*Sets*
- $B$ number of bilateral contracts
- $H$ number of production blocks of the DG units
- $I$ the maximum amount of minimum OFF-time and ON-time value of DG units running from 1 to max {$MUT_j$, $MDT_j$}
- $J$ number of DG units
- $S$ number of scenarios
- $T$ number of time periods
- $Z$ number of segments in the price-quota curve

*Parameters*
- $Dn_{j,i}$ auxiliary variable for modeling of the MDT constraint
- $D^{offer}(l,z,t,s)$ offered energy of client group in the price-quota curve (kW)
- $DRP^{\max}$ maximum percentage of demand that can be participated in DRP (%)
- $G^{a}_{t,s}$ irradiation of sun in each time and scenario (W/m$^2$)
- $G_{a_0}$ irradiation of sun at the standard condition (W/m$^2$)
- $NOCT$ normal operating cell temperature of PV system (°C)
- $\rho_s$ the probability of scenario
- $P_b^{\max}$ maximum limit of bilateral contracts (kW)
- $P_b^{\min}$ minimum limit of bilateral contracts (kW)
- $P_{j,h}^{MAX}$ rated block power of DG units in a piecewise linear cost modeling (kW)
- $P_{t,s}^{PV}$ available power of PV system (kW)
- $P_{Max,0}^{M}$ maximum power of PV panel at the standard condition (kW)
- $P_{t,s}^{wind}$ available power of wind-turbine (kW)
- $p_r$ nominal power of wind-turbine (kW)
- $P_{charge}^{\max}$ maximum power limit in charging mode (kW)
- $P_{disc}^{\max}$ maximum power limit in discharging mode (kW)
- $R_j^{up}$ ramp up rate limit of DG units (kW/h)
- $R_j^{down}$ ramp down rate limit of DG units (kW/h)
- $Sdg_{j,h}$ rated block cost of DG units in a piecewise linear cost modeling ($/kWh)
- $SP^{offer}(l,z,t)$ offered price of client group in the price-quota curve ($/kWh)
- $T_{t,s}^{a}$ temperature at each time and scenario (°C)
- $T_{M,0}$ module temperature at the standard condition (°C)
- $Up_{j,i}$ auxiliary variable for modeling of the MUT constraint
- $V_{t,s}^{w}$ wind speed (m/s)
- $V_r, V_{ci}, V_{c0}$ rated, cut-in and cut-out wind speed (m/s)
- $X_b^{\max}$ maximum limit of stored energy in the energy storage system (kW)
- $X_b^{\min}$ minimum limit of stored energy in the energy storage system (kW)
- $\chi$ charging efficiency of energy storage system (%)
- $\eta$ discharging efficiency of energy storage system (%)
- $\lambda_{b,t}$ energy price of bilateral contracts ($/kWh)
- $\lambda_{t,s}$ the price for pool market ($/kWh)

*Variables*
- $A(l,z,t)$ binary variable for selecting the selling price offered by the retailer to the client group from the price-quota curve [0,1]
- $C_B$ energy procurement cost from the bilateral contracts ($)
- $C_P$ energy procurement cost from the pool market ($)
- $C_{DG}$ energy procurement cost from the DG units ($)
- $D(l,t,s)$ supplied demand to the client group by the retailer (kW)
- $DRP(l,t,s)$ free variable for possibility of DRP implementation (positive for demand increase and negative for demand decrease) (kW)
- $D^{DRP}(l,t,s)$ supplied new demand considering demand response program to the client group by the retailer (kW)
- $P_{b,t}$ energy procurement from the bilateral contracts (kW)
- $P_t^{BC}$ total energy procurement from the bilateral contracts (kW)
- $P_{t,s}^{charge}$ charged power of energy storage system (kW)
- $P_{t,s}^{disc}$ discharged power of energy storage system (kW)
- $P_{t,s}^{P}$ energy procurement from the pool market (kW)
- $P_{j,h,t,s}^{DG}$ purchased power from the DG units (kW)
- $R_R(l,t)$ the revenue obtained from the client group ($)
- $s_b$ binary variable for selecting the bilateral contracts [0,1]
- $SP(l,z,t)$ price of the interval of the price-quota curve for the client group ($/kWh)
- $SP^{RTP}(l,t)$ real-time selling price by the retailer for the client group ($/kWh)
- $SP^{Fixed}(l)$ fixed selling price by the retailer for the client group ($/kWh)
- $SP_L^{TOU}(l)$ time-of-use selling price in low load level by the retailer for the client group ($/kWh)
- $SP_M^{TOU}(l)$ time-of-use selling price in medium load level by the retailer for the client group ($/kWh)
- $SP_P^{TOU}(l)$ time-of-use selling price in peak load level by the retailer for the client group ($/kWh)
- $U_{t,s}^{charge}$ binary variable for charging mode of energy storage system [0,1]
- $U_{t,s}^{disc}$ binary variable for discharging mode of energy storage system [0,1]
- $U_{j,t}^{DG}$ binary variable for on or off statues of DG units [0,1]
- $X_{t,s}^{b}$ stored energy in the energy storage system (kWh)

*Abbreviations*
- BCs bilateral contracts
- DG distributed generation
- DRP demand response program
- ESS energy storage system
- FP fixed pricing
- GAMS general algebraic modeling system
- MINLP mixed-integer non-linear programming
- PM pool market
- PV photovoltaic
- RTP real-time pricing
- RESs renewable energy sources
- TOU time-of-use pricing
- WT wind turbine