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A bi-level risk-constrained offering strategy of a wind power producer considering demand side resources

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ABSTRACT

This paper proposes a stochastic decision making problem for a wind power producer (WPP) in the day-ahead (DA) and balancing markets. In this problem, bidding strategy of the WPP in a competitive electricity market and also its participation to supply demand response (DR) and electric vehicle (EV) aggregators is determined to achieve the maximum profit. In this model, DR and EV aggregators are able to choose the most competitive WPP in such a way that their energy payments be minimized in the scheduling horizon. Therefore, the problem is formulated as a stochastic bi-level programming model with conflict objectives of the WPP and the aggregators. Moreover, owing to the uncertainties associated with market prices, offered prices by rival WPPs, demand of DR and EV aggregators, conditional value at risk (CVaR) is applied to the proposed model. The attained stochastic bi-level problem is transformed to a linear stochastic single level problem with equilibrium constraints using Karush–Kuhn–Tucker (KKT) optimality conditions. The proposed model is evaluated on a realistic case study and the impacts of risk-averse behavior and demand response participants on the decision making problem of the WPP are investigated. Numerical results indicate that with increasing DR participants of 0%, 60% and 100%, CVaR of WPP increases 33.81%, 40.79% and 46.99%, respectively. This means that if the loads are more responsive, the WPP tries to control the profit variability due to the uncertainties of loads.

1. Introduction

The wind-power capacity installed throughout the world has increased drastically in the last years [1]. This development is facilitated via various subsidies and supportive policies that allowed wind power producers (WPPs) to recover their investment costs in advantageous conditions if compared with conventional producers [2]. However, by increasing wind energy, WPPs encounter with a significant challenge to participate in electricity markets due to the power production uncertainty. To cope with this issue, WPPs provide three main practical solutions including optimal wind trading strategies in short-term markets, a joint operation of WPPs and easily controllable resources and increasing the wind power forecasting accuracy. This study focuses on the first two solutions.

WPPs need to develop optimal trading strategies for their participation in the short-term markets to increase expected profits and to make their investments profitable. This issue is addressed in a large number of references in the technical literature. In [2], an offering optimization model for aggregated WPP and flexible loads in DA electricity markets is proposed in which flexible load is considered as a storage unit that can either cover the imbalances of WPP or recover itself according to electricity price and load curve during various hours. In [4], the offering strategy of wind power is evaluated by price-maker WPPs, but in [5] a strategic bidding model for several price-taker plug-in electric vehicle aggregators that participate in both day-ahead energy and ancillary services markets is assessed without focusing on WPP.

Demand response (DR) as a responsive and cost-effective option can be used to facilitate the integration of wind [6], and makes good opportunity in a joint operation with WPPs. The effect of DR programs on the bidding strategies of WPPs has been investigated from different points of view in several works [3,6–12]. For example, in [6], it is expressed that the WPP is obligated to offer its generation to the DA

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Nomenclature

Sets and indices

$(\cdot)_{t,s}$	At time t and scenario s
$(\cdot)_{t,\psi}$	At time t and scenario ψ
Ch	Charge process
D	Index of demand
$w, w'(N_w)$	Indices (set) of WPPs
ℓ	Index that represents responsive loads and charge of EVs
ψ (Ψ)	Scenario index (set) of rivals' offered prices
t (T)	Index (set) of time periods
$s(N_S)$	Scenario index (set) of market prices, demand loads and charge of EVs

Parameters

$Elas_{t,t}(Elas_{t,h})$	Self-elasticity (cross-elasticity) of demand of responsive customers
$E_{t,s}^{T_\ell}$	Total demand of customers (MWh)
$\hat{E}_t$	Total expected demand of customers (MWh)
X_w^{init}	Initial percentage of responsive loads and EVs supplied by each WPP
π_s	Probability of scenario s
$\Pr^{B^+}(\Pr^{B^-})$	Prices of positive (negative) balancing markets (€/MWh)
$\Pr^{DA}$	Price of day-ahead market (€/MWh)
$\Pr_w$	Price signals offered by rival (under study) WPP (€/MWh)
R	The cost modeling the unwillingness of customers and EV owners to go from WPP w to WPP w' (€)
ρ_ψ	Probability of scenario ψ
η^{Ch}	Coefficient of charge efficiency
$\underline{SoC}$ $(\overline{SoC})$	Minimum (maximum) of SoC
E_{batt}^{Cap}	Energy capacity of EV battery (MWh)
$\overline{E}$	Limitation of maximum energy traded with the network (MWh)

Variables

E	The amount of energy supplied by the under-study WPP (MWh)
$E^{B+}(E^{B-})$	The amount of energy traded between the WPP and positive (negative) balancing markets (MWh)
E^{DA}	Energy traded between the WPP and day-ahead market (MWh)
$\Pr_{w0}$	Price signals offered by the WPP (€/MWh)
$\varepsilon_{w,\psi}/\varphi_\psi$	Multipliers associated with obtaining KKT conditions
X_{w_0}	Percentage of customers supplied by the WPP
$Y_{w,w'}$	Percentage of customers transferred among the WPPs
X_w	Percentage of customers supplied by rival WPP w
SOC	State of charge of EV

market. Therefore, its DA forecast errors are compensated using DR. A stochastic multi-layer agent-based model is proposed in [7] in which the wholesale market players including renewable power producers are modeled such that to optimize bidding/offering in the electricity markets without using any risk aversion factor in the model. In [8], a two-stage offering plan is presented in which a WPP participates in the DA market while employing DR to smooth its power variations. Although, in the presented approach the energy trading of WPP is determined for each period, the DR and EV aggregator reaction to choose their energy provider in a competitive market is not addressed. In [10], the positive benefits of DR on the short-term trading of WPPs are investigated from the WPPs' viewpoint. Also, an offering strategy for a price maker WPP participating in both DA and balancing markets is proposed in [11] in which the penetration of DR resources into smart grids is modeled. A bi-level equilibrium model to study market equilibrium interactions between energy storage and wind and conventional generators is assessed in [12] but the effect of DR is not investigated.

In [3], a framework for trading DR resources has been proposed in a separate intraday market in order to improve the WPPs' profit. Then the problem has been solved from the WPPs' viewpoint. Moreover, in [13], a combined scheduling and bidding strategy has been presented for constructing the DA bidding curve of an electric utility including DR option. In the proposed strategy of this reference, units are dispatched by optimizing the retailer's DR programs. An offering optimization model for aggregated wind power and flexible loads in only DA electricity market is proposed in [3]. A stochastic programming approach for the development of offering strategies for a WPP with considering the uncertainties of electricity market prices is investigated in [14] without using any tool to decrease the unfavorable effect of uncertainties.

In the reviewed literature, although the effect of DR actions is discussed on offering strategy of the WPP, the profit of demand side is not considered. Nevertheless, a few research works have studied offering strategy of WPP from the viewpoint of both WPPs and demand side. Moreover, in the reviewed literature, risk management in WPP offering decision strategies is not considered. However, there are some research works, in which different risk management tools such as conditional-value-at-risk (CVaR) are used to model the profit risk associated with the WPPs offering decisions. For example, authors in [2] propose a multi-stage risk-constrained stochastic model to derive the optimal offering strategy for the participation of WPP in both DA and the balancing markets. A risk-based two-stage stochastic optimization problem for the operation of a microgrid is studied in [15] where the uncertainties of renewable energy resources are modeled using a two-stage stochastic programming while the uncertainties of EVs are not assessed. In addition, CVaR index is used to manage the risk level of the microgrid operator decisions. In [16], a platform is proposed to obtain the best offering strategy for a hybrid power plant consisting of a WPP and DR provider in the power market. In this work DR is used to cover uncertainty of wind power and mitigate the imbalance cost. Also, CVaR is used in this research to limit the risk of profit variability while the goal of lower level of the problem is not paid attention. In [17] a comprehensive stochastic decision making model is proposed for the coordinated operation of WPP and DR aggregators participating in the DA market. In this work, CVaR term has been included in the model to account uncertainty around the true outcomes of DA prices and wind power generation, however, the preferences of DR aggregators to minimize their payments is not addressed. A bi-level problem including a single leader and two followers is formulated in [18] in which the WPP aims to maximize its profit through offering into DA market and clearing the deviation in the balancing trading floor. Also, the DR aggregator is able to sell its DR product to the WPP, other competitors and the DA market. A scheme for joining WPPs with non-wind firms by considering both positive and negative balancing costs is studied in [19] without considering any risk measurement tool. In the reviewed works, although, bidding strategy of the WPP in an uncertain environment is studied, the decision making problem of the WPP with considering the preferences of both DR and EV aggregators in a competitive market is not addressed. Market clearing in the presence of uncertain responsive loads based on information gap decision theory concept is performed in [20] where responsive loads are considered as reserve providers to participate in the market by offering their price-quantity capacity bids to the reserve market. Also, risk aversion strategies are used to measure related risk/immunity cost. Table 1 addresses a systematically comparison between the contributions of this paper and some of the recent works in the same subject area.