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A machine learning based stochastic optimization framework for a wind and storage power plant participating in energy pool market

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HIGHLIGHTS

- Wind and storage power plant participating in the pool market is considered.
- The decision-making problem is formulated as a two-stage convex stochastic model.
- Machine learning techniques are leveraged to define scenarios.
- A hybrid clustering technique is used to extract influential scenarios.
- The quality of the proposed techniques is evaluated with a real-world case study.

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ABSTRACT

Renewable energy plants can participate in the energy pool market including day-ahead, intraday and balancing markets. The aim of this work is to develop a decision-making framework for a Wind and Storage Power Plant participating in the pool market to handle the uncertainty associated with the parameters of energy price and available wind energy, which are not known when decisions are to be made. Thus, the problem of maximizing the net income of such a plant participating in the pool market is formulated as a two-stage convex stochastic program. A novel hybrid approach using multivariate clustering technique and recurrent neural network is used to derive scenarios to handle the uncertainty associated with the energy price. Lastly, simulation experiments are carried out to show the effectiveness of the proposed methods using a real-world case study. Operators of variable renewable resource generators could use the proposed framework to make robust decisions and better manage their operations to gain competitive advantage.

1. Introduction

Generation from variable renewable energy resources has increased their involvement in the power market worldwide. Wind farms and solar photovoltaic plants have reached the status of a mature technology, but still face serious challenges when participating in the electricity markets. One of the problems faced by these generators when participating in pool markets (PM) is the time gap between the time when the commitments of selling/buying energy in the markets are made and the actual realization of those commitments. This is not a problem for conventional generators, however, it is a real challenge for *variable renewable resources generators* (VRRG), such as solar plants and wind farms. The operator of a VRRG has limited knowledge concerning the actual availability of the renewable resource in the future, at the time when it must decide its participation in the PM. The PM is made of three different markets, whose definitions give a VRRG operator the possibility of sequentially updating its commitments. These three markets are the following: *day-ahead market* (DAM), *intraday market* (IDM), and *balancing market* (BM) [1]. The first two markets run sequentially. The IDM is run after the DAM and is meant to give the VRRG the possibility of updating generator commitments when more accurate information about uncertain parameters is available. The last one, the BM, gives the possibility of buying/selling energy to compensate the deviations in real time.

In this paper, a wind farm is considered as a VRGG. Moreover, the addition of storage capabilities is studied to take advantage of arbitrage

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Nomenclature

Sets and subindex

S	set of Scenarios
T	set of time slots
s	subindex for scenarios, s = 1,.., Ns
t	subindex for time slot, t = 1,….., T

Parameters

T	number of periods under consideration
$\bar{P}^{wind}$	rated power of the wind farm (MW)
E_0^{ess}	initial energy stored in the ESS (MWh)
η_{in}	charging efficiency of the ESS
η_{out}	discharging efficiency of the ESS
$\bar{E}^{ess}$	maximum energy stored in the ESS (MWh)
$\bar{P}^{ess}$	maximum power to/from ESS (MW)
$SOC_t^{\min}$	minimum state of charge of ESS
κ^{bm}	correction factor of deviation prices in BM.
ρ_s	probability of scenario s
Ns	number of scenarios

Random variables

β_t^{dam}, $\beta_{s,t}^{dam}$	energy price in the DAM (€/MWh)
β_t^{idm}, $\beta_{s,t}^{idm}$	energy price in the IDM (€/MWh)
$\hat{\lambda}_t^{bm,up}$, $\hat{\lambda}_{s,t}^{bm,up}$	energy price of deviation up (€/MWh)
$\hat{\lambda}_t^{bm,dw}$, $\hat{\lambda}_{s,t}^{bm,dw}$	energy price of deviation down (€/MWh)
$\lambda_t^{bm,up}$, $\lambda_{s,t}^{bm,up}$	corrected price of deviation up (€/MWh)
$\lambda_t^{bm,dw}$, $\lambda_{s,t}^{bm,dw}$	corrected price of deviation down (€/MWh)
φ_t, $\varphi_{s,t}$, γ_t, $\gamma_{s,t}$	auxiliary parameters for convex model
$\hat{P}_t^{wind}$, $\hat{P}_{s,t}^{wind}$	wind power available (MW)

Decision variables

$P_{s,t}^{wind}$	wind power actually used (MW)
E_t^{ess}	energy stored in the ESS (MWh)
$P_t^{ess,in}$	power entering the ESS (MW)
$P_t^{ess,out}$	power delivered by the ESS (MW)
SOC_t	state of charge of ESS in time t
$P_{s,t}$	power to/from W&SPP in time t (MW)
$\hat{P}_t^{dam}$	power commited in the DAM (MW)
$\hat{P}_t^{idm}$	power committed in the IDM (MW)
$\hat{P}_t^{pm}$	power commited in the PM (MW)
$P_{s,t}^{pm}$	power actually delivered/taken in the EM (MW)
$\Delta_{s,t}^{pm}$	unbalance in EM (MW)

strategies when participating in several markets. The resulting system is referred to as a Wind and Storage Power Plant (W&SPP) and it can participate in the pool market. The decision-making problem of participation of a W&SPP in the pool market is highly affected by the uncertainty, i.e., several parameters of the problem are not known when the decisions are to be made, i.e., the W&SPP must deal with the lack of information concerning available wind energy and energy prices in each of the considered markets are not known either. The motivation of this paper is to develop a decision-making framework under uncertainty to help VRGG operators make robust decisions concerning their participation strategy in the pool market.

With this aim, the decision-making problem is formulated as an optimization problem under uncertainty. Several approaches to handle uncertainty in an optimization problem already exist. Among them, the stochastic programming approach has been widely used to handle a decision-making problem under uncertainty. When dealing with uncertainty using a stochastic approach, a set of scenarios need to be defined to model the uncertain parameters. Each of these scenarios should correspond to a feasible realization of the uncertain parameters and an associated probability of occurrence. In particular, the stochastic approach has been applied to optimize the participation of power generators, both the traditional and renewable resource-based, in the energy pool markets. Several papers are available in the literature considering the participation of power producers in the day-ahead market (DAM) and real-time or balancing market (BM) under uncertainty. For example, a pumped-hydro system is proposed as a storage system to cope with the variability of the generation of a wind farm in [2], where a two-stage stochastic approach is presented to optimize the expected profit of the system participation in the day-ahead and real-time markets. Scenarios for available wind energy are considered as input data and scenarios for day-ahead prices are generated through input/output hidden Markov model and prices in real-time market are considered as known. On the other hand, a Virtual Power Plant with a Wind farm is considered in [3]. In this case, a two-stage stochastic mixed integer linear program is proposed to maximize its expected profit when participating in the day-ahead and balancing markets. Available wind energy and market prices are considered uncertain and modeled by scenarios. Twenty-five days of data, both for available wind energy and market price, are chosen to generate equiprobable scenarios. A two-stage stochastic mixed integer linear program is also used to optimize the participation of a hybrid wind-solar plant in DAM under uncertainty in market price, available wind and solar energy [4], where scenarios are defined by selecting a number of daily actual data. To optimize the participation of an *Independent Power Producer* (IPP) in day-ahead and real-time markets, a two-stage stochastic approach is proposed in [5], where it groups a wind farm and traditional generation as thermal and hydro plants. Their objective was to maximize the profit of the IPP while ensuring a participation of the wind farm as high as possible. Uncertainty in wind generation and power prices were modeled by scenarios.

However, a comprehensive participation in the pool market including the IDM has received limited attention in the literature. A model to evaluate the participation of a hydro power plant in DAM, IDM, and BM is presented in [6] addressing German market, whereas a rolling horizon optimization framework is proposed in [7] to optimize the participation of a wind farm in DAM and IDM. Only available wind energy is considered uncertain and modeled by scenarios, while electricity prices are considered as known. A strategy to participate in Elbas intraday market is presented in [8] where the DAM prices are certainly known and just balancing prices are forecast by using a statistical regression-type model. A two-stage stochastic approach is proposed in [9], where uncertainty concerning market prices and energy production is considered to study the market integration of an ocean wave power plant. A comprehensive participation of a wind farm with storage in both pool and reserve markets is analyzed in [10], where a multistage stochastic approach is proposed and a forward tree construction algorithm is applied to build the scenario tree modeling uncertainty in market prices and available wind energy.

As already stated, a stochastic approach needs a set of scenarios to be defined to model the uncertainty affecting some of the parameters of the model. There are several approaches available in the literature to generate scenarios. One approach is to consider a deterministic forecast, also called point forecast, of the uncertain parameter as a single scenario. In particular, several techniques were employed to perform a