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Evaluating the benefits of coordinated emerging flexible resources in electricity markets

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HIGHLIGHTS

- Variable renewable energy sources create a flexibility gap in power system operation.
- BESs, PEV PLs and DR are modeled as flexible options.
- DR programs have remarkable impacts in terms of cost and emission reduction.
- PEV PL is not a favorable flexible option by its own due to uncertain behavior of PEV owners.
- Coordinated operation of PEV PLs and BESs under TOU program is the most effective generation mixture.

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ABSTRACT

Increasing share of variable renewable energy sources (VRESs) with the aim of tackling climate changes impose several techno-economic challenges to power system operation. VRESs reduce the available flexibility by displacing existing flexible units due to their priority in dispatch and simultaneously enhance the need for additional flexibility due to their uncertain nature. In this light, the system is faced with a flexibility gap. One way to cover the created flexibility gap is the incorporation of emerging flexible resources into power systems operation. On this basis, this paper proposes a comprehensive flexible generation portfolio including bulk energy storages (BESs), plug-in electric vehicle parking lots (PEV PLs), and demand response (DR) programs. A stochastic market-based model is proposed to coordinate the interactions among these flexibility providers considering different sets of uncertainty, such as wind power generation and PEV owner's behavior. Finally, various generation mixtures are prioritized based on the system operator's economic, technical, and environmental desires to provide a guideline to opt the most effective generation mixture in the context of flexibility promotion.

1. Introduction

1.1. Motivation and related works

Wind power provides new challenges at high penetration levels, since its variable nature increases the need for additional operational flexibility. Operational flexibility aims at securely covering the possible variations at least cost by using enough online flexible resources. Typical solutions to achieve this goal can be separated into two main categories. The first one focuses on designing novel market mechanisms to incentivize flexibility provision in system operations [1–3]. The second one deals with the incorporation of flexible alternatives such as Bulk Energy Storages (BESs), Demand Response (DR), and Plug-in Electric Vehicle Parking Lots (PEV PLs) to the generation mixture. It is noteworthy that there is a huge interest for using these emerging technologies around the world in last few years. In the case of BESs, the pump hydro storage technology is the most widely used BES. However, other BES technologies such as compressed air energy storages as well as advanced batteries gain more attention recently due to the fact that they need no specific geographic location and therefore can be installed across the transmission networks without certain

Abbreviations: ARMA, Autoregressive Moving Average; BES, Bulk Energy Storage; DC, Direct Current; DR, Demand Response; EDRP, Emergency Demand Response Program; G2V, Grid-to-Vehicle; PEV PL, Plug-in Electric Vehicle Parking Lot; RTS, Reliability Test System; SCUC, Security-Constrained Unit Commitment; SO, System Operator; SOC, State of Charge; SOE, State of Energy; TOPSIS, Technique for Order Preference by Similarity to Ideal Solution; TOU, Time of Use; V2G, Vehicle-to-Grid.

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Nomenclature

Indices

b, b'	index of system buses $b = 1, \ldots, NB$
es	index of bulk energy storages $es = 1, \ldots, NES$
i	index of conventional units $i = 1, \ldots, NG$
j	index of loads $j = 1, \ldots, NJ$
k	index of segment for linearized incentive payment cost curve $k = 1, \ldots, NK$
l	index of transmission lines $l = 1, \ldots, L$
m	index of segment for linearized fuel cost $m = 1, \ldots, NM$
n	index of PEVs $n = 1, \ldots, N$
NB	number of network buses
NES	number of bulk energy storage units
NG	number of conventional generation units
NJ	number of load points
NK	number of segments for the piecewise linearized incentive payment cost curve
NM	number of segments for the piecewise linearized fuel cost curve of units
NPL	number of PEV parking lots
NT	number of hours under study
NW	number of scenarios
NWF	number of wind farms
pl	index of parking lots $pl = 1, \ldots, NPL$
PTP	index of peak time period hours
t, t'	index of time periods $t = 1, \ldots, NT$
$t_n^{arv/dep}$	index of arrival/departure time of PEV n
w	index of scenarios $w = 1, \ldots, NW$
wf	index of wind farms $wf = 1, \ldots, NWF$

Parameters and variables

$C_{es,t}^{ES\_Eng}$	offered energy cost of BESs in discharging mode (\$/MW h)
$C_{es,t}^{ES\_UC/DC}$	offered cost of up/down capacity reserve of BESs (\$/MW)
$C_{es,t}^{ES\_UE/DE}$	offered cost of up/down deployed reserve of BESs (\$/MW h)
$C_{i,t}^{G\_UC/DC}$	offered cost of up/down capacity reserve of conventional generation units (\$/MW)
$C_{i,t}^{G\_UE/DE}$	offered cost of up/down deployed reserve of conventional generation units (\$/MW h)
$C_{i,t,m}^{G\_Eng}$	offered piecewise energy cost of conventional generation units (\$/MW h)
$C_{pl,t}^{PL\_Eng}$	offered energy cost of PLs in PL to grid mode (\$/MW h)
$C_{pl,t}^{PL\_UC/DC}$	offered cost of up/down capacity reserve of PEV PLs (\$/MW)
$C_{pl,t}^{PL\_UE/DE}$	offered cost of up/down deployed reserve of PEV PLs (\$/MW h)
$C_{wf}^{WP\_spill}$	cost of wind spillage (\$/MW h)
$cap_{n,t_n^{arv},t_n^{dep}}^{PEV}$	battery capacity of EV n (kW h)
$Cap_{pl,t}^{PL,Sc}$	aggregated battery capacity of parking lot (MW h)
$d_{j,t}^0$	initial electricity demand before DR (MW)
$DR^{\max}$	maximum DR participation level
$E_{t,t'}$	price elasticity of demand
$F_{l,t}^0/F_{l,w,t}$	power flow through line l in the base-case and scenarios (MW)
$I_{es,t}^{DeES}/I_{es,t}^{ChES}$	binary indicator of discharge/charge status of BESs
$INC_{j,t,k}$	incentive of segment k in linearized total incentive curve (\$/MW h)
$LRDR_{j,t,k}$	slope of segment k in linearized total incentive curve (MW h)
$LS_{j,w,t}$	load shedding of load j (MW h)
MPC_i	minimum production cost of conventional generation units (\$)
$N^{PL,\max}$	maximum number of car spaces in the parking lot
$N_{pl,t}^{PL,Sc}$	aggregated number of PEVs in the parking lot
$N_{t^{arv},t^{dep}}^{PEV}$	aggregated number of PEVs that arrived to PL at t^{arv} and departed from PL at t^{dep}
$P_{es}^{ChES,\max}$	maximum charging power of BESs (MW)
$P_{es}^{DchES,\max}$	maximum discharging power of BESs (MW)
$P_{es,t}^{ChES}, P_{es,t}^{DchES}$	scheduled charge/discharge power of BESs (MW)
$P_i^{\min}/P_i^{\max}$	minimum/maximum output of units (MW)
$P_{i,t,m}^e$	generation of segment m in linearized fuel cost curve (MW h)
$P_{i,w,t}$	actual power generation of generation units (MW)
$P_{pl,t}^{En,G2PL}$	injected power of grid to PL (MW)
$P_{pl,t}^{En,PL2G}$	injected power of PL back to the grid (MW)
$P_{wf,t}^{WP,\max}$	forecasted wind generation of wind farms (MW h)
$P_{wf,w,t}^{W}$	actual wind generation of wind farms (MW h)
$P_{wf,w,t}^{WP\_spill}$	wind power spillage of wind farms (MW h)
$r_{es,w,t}^{ES\_up/dn}$	deployed up/down spinning reserve of BESs (MW h)
$r_{i,w,t}^{G\_up/dn}$	deployed up/down spinning reserve of conventional generation units (MW h)
$r_{pl,w,t}^{PL\_up/dn}$	deployed up/down spinning reserve of PEV PLs (MW h)
$R_{es,t}^{ES\_UC}, R_{es,t}^{ES\_DC}$	scheduled up/down reserve capacity of BESs (MW)
$R_{i,t}^{G\_UC}, R_{i,t}^{G\_DC}$	scheduled up/down reserve capacity of conventional generation units (MW)
$R_{pl,t}^{PL\_UC}, R_{pl,t}^{PL\_DC}$	scheduled up/down reserve capacity of PEV PLs (MW)
RU_i/RD_i	ramp up/down limits of units (MW/h)
SC_i	start-up offer cost of conventional generation units (\$)
$soc_n^{PEV,\min/\max}$	truncation region for the initial SOC of PEV n
$soc_{n,t_n^{arv},t_n^{dcep}}^{PEV}$	initial SOC of PEV n
$SOC_{pl}^{\min}/SOC_{pl}^{\max}$	min/max SOC level of parking lot
$SOE_{pl,t}^{PL,Sc}$	aggregated state of energy of parking lot as a result of arrival/departure of PEVs (MW h)
$SOE_{pl,w,t}^{PL}$	aggregated state of energy of PL (MW h)
$SOE_{es}^{ES,\min/\max}$	minimum/maximum energy limit of BESs (MW h)
$SOE_{es,w,t}^{ES}$	stored energy level of BESs (MW h)
$SUC_{i,t}$	start-up cost of conventional units (\$)
$U_{i,t}$	binary on/off status indicator of generation units
$U_{pl,t}^{PL2G}/U_{pl,t}^{G2PL}$	binary status indicator of PL2G/G2PL operation mode of PL
$Voll_{j,t}$	value of lost load j (\$/MW h)
X_l	reactance of line l
α_{es}^{ini}	initial percent charging of BES before scheduling (%)
$\Gamma^{charge}, \gamma^{discharge}$	charging/discharging rates of pevs (kw/h)
$\delta_{b,t}^0/\delta_{b,w,t}$	voltage angle of network buses in the base-case and scenarios (rad)
$\eta_{Ch}^{ES}, \eta_{Dch}^{ES}$	charge/discharge efficiency of BESs
$\eta_{Ch}^{PL}, \eta_{Dch}^{PL}$	charge/discharge efficiency of parking lot
$\mu_{soc}, \sigma_{soc}^2$	mean value and variance related to SOC of PEVs
π_w	probability of scenario w
ρ^{ini}	initial electricity price before DR (\$/MW h)
$\rho_j^{LTP/OTP/PTP}$	electricity tariffs of low-load, off-peak and peak time periods in TOU program (\$/MW h)
τ	spinning reserve market lead time (h)
ψ_t^{PL}	net electrical charging percentage due to contract of PEV owners for desired SOC