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Robust Optimization Approach for Generation Scheduling of a Hybrid Thermal-Energy Storage System

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***Abstract*—In this paper, a new framework for optimal generation scheduling of a hybrid thermal-energy storage (HTES) system is proposed. The proposed generation scheduling is formulated based on the profit maximization of the HTES system, concentrating on taking part in the energy market. The proposed hybrid structure integrates energy storage system (ESS) and thermal units in the form of a hybrid system in a way that a physical connection between these two resources is installed. This physical connection lets the HTES operator charge the ESS through thermal units while it is economical. In order to efficiently address the generation scheduling problem in the presence of market uncertainty, a robust optimization architecture is suggested. The proposed robust model is capable of deriving conservative strategies that are robust against the energy market uncertainty. The formulation of the considered robust problem is carried out based on mixed-integer programming (MIP) and is solved via general algebraic modeling system (GAMS) software.**

***Index Terms*—Energy storage system (ESS), generation scheduling, hybrid energy system, robust optimization, thermal units.**

I. INTRODUCTION

Hybrid energy systems, in all power system sectors, bring economical and reliable superiorities [1]. The flexibility of energy storage systems (ESSs) is known as one of the most significant indicators of increasing power system reliability [2]. ESSs hold a wide range of technologies wherein the application of any of those technologies should be evaluated based on so many agents such as economic, public acceptance, and eco-friendly [2]. The integrated configuration of ESSs with conventional generation units and renewable energy sources has been extensively analyzed in the form of hybrid energy systems [3] and [4].

On account of the broad range of published papers in the domain of generation scheduling of hybrid energy systems, here, the authors try to review some works to cover various perspectives in terms of different combinations of energy sources. An economic-environmental generation scheduling model for thermal units coupled with ESS and wind units has proposed in [5], while a multi-stage stochastic approach has suggested for uncertainty modeling. Authors in [6] have presented a novel paradigm for scheduling of a residential hybrid energy system, focusing on stochastic programming. In [7], the authors have concentrated on designing a proper scheduling mechanism for a hybrid energy system consisting of wind, photovoltaic, thermal units as well as the ESS, while a probabilistic technique,i.e., point estimate method, has employed for tackling uncertainties. A risk-involved generation scheduling in the DA energy market for a hybrid energy system comprising thermal, ESS, and photovoltaic units has introduced in [8], taking into account the conditional value-at-risk as the risk evaluation index. In [9], authors have proposed a game-based offering architecture for wind units' participation in the electricity markets coupled with thermal units.

A two-stage cost-emission management method for a typical microgrid owning electric vehicles and demand-side resources has been presented in [10]. Authors in [11] have used stochastic programming to deal with the bidding of a virtual power plant in the day-ahead and intraday markets. In [12], a profit-emission generation scheduling methodology for a wind-photovoltaic-thermal system by taking advantage of the emission trading framework in the form of a scenario-based problem has been suggested. Another economic-environmental scheduling approach for a wind-solar-thermal system, focusing on the possibilistic modeling of uncertainties, has been proposed in [13]. In [14], the authors have developed a scheduling strategy for a cryogenic energy storage system paired with wind farms and responsive loads. The bidding strategy of a virtual power plant with ESSs and a novel demand response model has been proposed in [15]. Focusing on the ESSs, an operating strategy model for a price-maker ESS, along with large-scale green energy resources based on the Nash-Cournot equilibrium framework, has been presented in [16]. In [17], the offering strategy of a wind-ESS system in the day-ahead energy and balancing markets has been assessed, while it treats as a price-maker producer in the day-ahead market. Finally, by adopting robust optimization, the optimal operation scheduling of a price-taker/ price-maker ESS in energy, ancillary services, and regulation markets is analyzed in [18].

In this paper, in opposition to the reviewed papers [5]- [14], a robust optimization approach for optimal generation scheduling of a hybrid thermal-energy storage (HTES) system is established. The HTES system is structured based on the physical coupling between ESS and thermal units. In order to control the risk of uncertain energy market prices, the robust optimization approach is implemented, while this approach is fully capable of deriving risk-mitigating strategies.

II. Deterministic Generation Scheduling Model

The schematic of the proposed HTES system is plotted in Fig. 1. According to this figure, thermal units can either sell the generated energy in the market or transfer it as the charging power to the ESS using the embedded physical coupling between these two resources. Moreover, the ESS is able to either sell/purchase energy in/from the energy market. The purpose of the HTES is to get the most profit, which can be formulated as follows:

$$\text{Max Profit}^{\text{HTES}} = \sum_{t=1}^{N_T} \Bigg[\upsilon_t^T \xi_t + \upsilon_t^{ES,dis} \xi_t - \upsilon_t^{ES,ch} \xi_t - \left(\sum_{g=1}^{N_G} CF_{g,t} \left(\chi_{g,t}^T + \chi_{g,t}^{T,ch} \right) \right) - \left(\sum_{g=1}^{N_G} SUC_{g,t} + SDC_{g,t} \right) \Bigg] \quad (1)$$

where, ξ_t is the market price, υ_t^T, $\upsilon_t^{ES,dis}$ are the sold energy of thermal units and the ESS in the energy market, and $\upsilon_t^{ES,ch}$ is the purchased energy of the ESS from the energy market. $CF_{g,t}$ stands for the operational costs of thermal units, which incurred from generating energy of each thermal unit for selling in the energy market $\chi_{g,t}^T$ and charging the ESS $\chi_{g,t}^{T,ch}$. $SUC_{g,t}$ and $SDC_{g,t}$ refer to start-up and shut-down costs of thermal units. Objective function (1) with the aim of profit maximization is subjected to the following restrictions.

A. Operational constraints of the ESS

Constraints (2)-(7) should be met to model the operation of the ESS effectively.

$$l_t^{dis} + l_t^{ch} \leq 1 \quad \forall t \quad (2)$$

$$\sum_{g=1}^{N_G} \chi_{g,t}^{T,ch} = \upsilon_t^{T,ch} \quad \forall t \quad (3)$$

$$0 \leq \upsilon_t^{ES,dis} \leq \varrho^{dis,Max}.l_t^{dis} \quad \forall t \quad (4)$$

$$0 \leq \upsilon_t^{ES,ch} + \upsilon_t^{T,ch} \leq \varrho^{ch,Max}.l_t^{ch} \quad \forall t \quad (5)$$

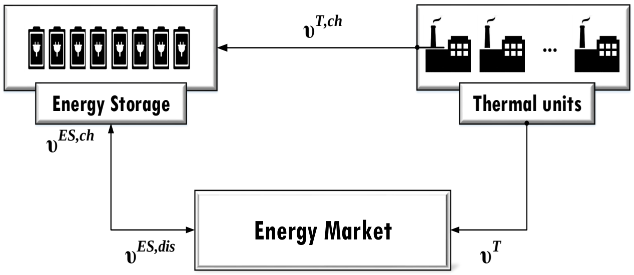

Fig. 1. Schematic of the considered HTES system.

$$\digamma_t^{ES} = \digamma_{t-1}^{ES} + \eta^{ES,ch} \left(\upsilon_t^{ES,ch} + \upsilon_t^{T,ch} \right) - \left(\frac{1}{\eta^{ES,dis}} \right) \left(\upsilon_t^{ES,dis} \right) \quad \forall t \quad (6)$$

$$0 \leq \digamma_t^{ES} \leq \digamma^{ES,Max} \quad \forall t \quad (7)$$

In constraint (2), the ESS is limited to operating in one mode of running, namely, charging or discharging, where l_t^{dis} and l_t^{ch} are binary variables related to discharging or charging state of the ESS. $\upsilon_t^{T,ch}$ refer to the total transferred energy from thermal units to the ESS, while equation (2) calculates this value. Restrictions (4) and (5) are related to bound discharging and charging power of the ESS, respectively, where $\varrho^{dis,Max}$ and $\varrho^{ch,Max}$ represent the maximum permissible discharging and charging power of the ESS, respectively. $\digamma_t^{ES}$ is the energy level of the ESS in each period, and $\digamma^{ES,Max}$ stands for the maximum permissible value of this variable.

B. Operational constraints of the thermal units

Thermal units' operation is subjected to some critical operational constraints, as expressed in (8)-(18).

$$\sum_{g=1}^{N_G} \chi_{g,t}^T = \upsilon_t^T \quad \forall t \quad (8)$$

$$\chi_{g,t}^T + \chi_{g,t}^{T,ch} = \chi_{g,t}^{T,total} \quad \forall t \quad (9)$$

$$\varrho_g^{T,Min} k_{g,t} \leq \chi_{g,t}^{T,total} \leq \varrho_g^{T,Max} k_{g,t} \quad \forall t \quad (10)$$

$$0 \leq \chi_{g,t}^{T,ch} \leq \varrho^{ch,Max} k_{g,t} \quad \forall t \quad (11)$$

$$0 \leq SDC_{g,t} \geq STDC_g j_{g,t} \quad \forall t \quad (12)$$

$$0 \leq SUC_{g,t} \geq STUC_g h_{g,t} \quad \forall t \quad (13)$$

$$\left(\sum_{n=t-MD_g+1}^{t} j_{g,t} \right) + u_{g,t} \leq 1 \quad \forall t \quad (14)$$

$$\sum_{n=t-MU_g+1}^{t} h_{g,t} \leq u_{g,t} \quad \forall t \tag{15}$$

$$j_{g,t-1} - k_{g,t} + h_{g,t} - j_{g,t} = 0 \quad \forall t \tag{16}$$

$$\chi_{g,t-1}^{T,total} \leq \chi_{g,t}^{T,total} + RD_g k_{g,t} + STDL_g j_{g,t} \quad \forall t \tag{17}$$

$$\chi_{g,t}^{T,total} \leq \chi_{g,t-1}^{T,total} + RU_g k_{g,t-1} + STUL_g h_{g,t} \quad \forall t \tag{18}$$

where, $\varrho_g^{T,Min}$ and $\varrho_g^{T,Min}$ denote the allowable power generation range of the thermal units; $k_{g,t}$, $j_{g,t}$, and $h_{g,t}$ are binary variables reflecting the online, shut-down, and start-up states of the thermal units; $STDC_g$ and $STUC_g$ are parameters indicating the shut-down and start-up costs of each thermal unit; MU_g and MD_g express the thermal units' minimum off and on times; $\chi_{g,t}^{T,total}$ is the total amount of generated energy by each thermal unit; RD_g and RU_g refer to the thermal units' ramp down and ramp up rates; $STDL_g$ and $STUL_g$ denote the thermal units' shut-down and start-up ramp rates.

Based on the expressed constraints, restrictions (10) and (11) enforce that the total generated power and the sold energy in the energy marker by any thermal unit should be kept in the thermal units' allowable power generation range. Constraints (12) and (13) represent the costs pertaining to the shut-down and start-up of any thermal unit, whereas constraints (14) and (15) model the minimum off and on times of thermal units [19]. Limitation (16) must always be in place to observe the logical relationship between different operating states of the thermal units. Lastly, restrictions (17) and (18) address the ramping limitations of thermal units.

III. Robust Generation Scheduling Model

The developed deterministic model for the generation scheduling of the HTES system (1)-(18) has been formulated as a mixed-integer programming (MIP) problem. In the deterministic structure, no uncertain parameter exists, and accordingly, the decision-maker solves the intended problem by assuming the full consciousness of unknown parameters. However, it is not a secret that market parameters, especially electricity market prices, will remain unknown to decision-makers until being broadcast by the market operator. In order to cope with the uncertainty in the energy market prices, the robust optimization model is put forward in this paper. In contrary to probabilistic uncertainty characterization techniques, robust optimization does not suffer decision-makers to collect a large amount of historical data to extract the probability distributions [20]. The application of the robust optimization technique can be widely found in power optimization problems. For instance, with robust optimization, the scheduling problem of an integrated heat and power microgrid under market uncertainty has been assessed in [21]. In addition, in [22], the same technique has been applied for the generation scheduling of a hydrothermal microgrid.

TABLE I
Information of the considered ESS.

Parameter	**Value**	**unit**
$\varrho^{dis,Max}$	45	MW
$\varrho^{ch,Max}$	45	MW
$\digamma ES, Max$	225	MWh
$\eta^{ES,ch}$	0.8	constant
$\eta^{ES,dis}$	0.95	constant

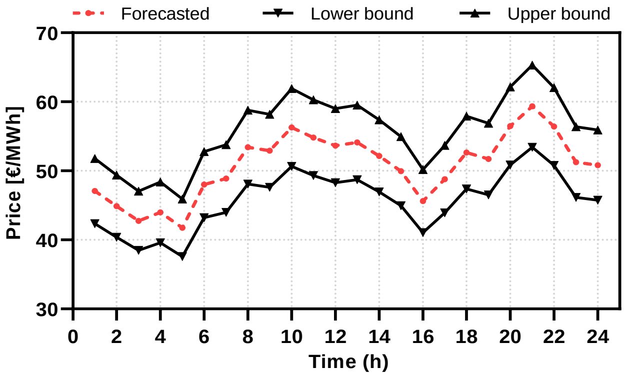

Fig. 2. The forecasted energy market price with its upper and lower bounds at 10% variation.

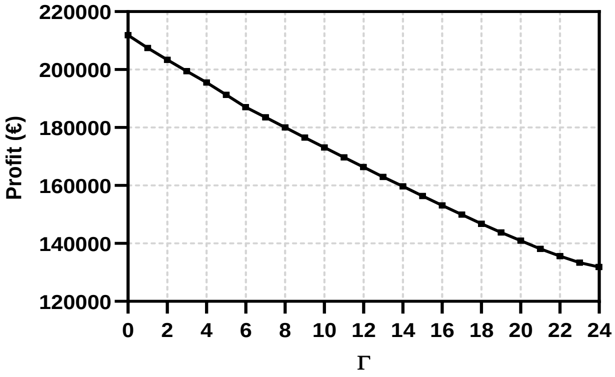

Fig. 3. Profit of the HTES system for various values of Γ.

In the robust framework, the uncertain parameter is modeled via a confidence interval. The general form of transforming a deterministic MIP problem to a robust MIP one has been reported in [20]. Therefore, the robust MIP form of the proposed problem is expressed by equations (19)-(25), while the interested readers on the fundamental concepts of converting a deterministic MIP to a robust MIP problem are encouraged to refer to [20] for more detail.

$$\begin{aligned}\text{Min OF} = &-\left\{ \sum_{t=1}^{N_T} \left[\upsilon_t^T \xi_t + \upsilon_t^{ES,dis}\xi_t - \upsilon_t^{ES,ch}\xi_t \right.\right. \\ &- \left(\sum_{g=1}^{N_G} CF_{g,t}\left(\chi_{g,t}^T + \chi_{g,t}^{T,ch}\right)\right) \\ &\left.\left. - \left(\sum_{g=1}^{N_G} SUC_{g,t} + SDC_{g,t}\right)\right]\right\} \\ &+ \alpha\Gamma + \sum_{t=1}^{N_T} \delta_t \end{aligned} \tag{19}$$

Subject to:

$$\text{Constraints } (2) - (18) \tag{20}$$

$$\alpha + \delta_t \geq \widehat{\xi}_t \mu_t \quad \forall t \tag{21}$$

$$\delta_t \geq 0 \quad \forall t \tag{22}$$

$$\mu_t \geq 0 \quad \forall t \tag{23}$$

$$\alpha \geq 0 \tag{24}$$

$$\left(\upsilon_t^T + \upsilon_t^{ES,dis} - \upsilon_t^{ES,ch}\right) \leq \mu_t \quad \forall t \tag{25}$$

where α and δt denote dual variables of the original robust model [20]; μ_t is an ancillary variable pertaining to the robust framework [20]; $\widehat{\xi}_t$ refers to the symmetric deviation of the energy market price; Γ indicates the conservative level of the decision-maker. Note that $\Gamma = 0$ states the risk-neutral condition, whereas $\Gamma \in [1, 24]$ reflects conservative decision-making states.

IV. Simulation Results

In this paper, the considered HTES system is constituted by an ESS and fourteen thermal units. All required information on thermal units has been adopted from [5]. Table I shows the technical features of the ESS. According to this table, the capacity of the stored energy in the ESS is considered as five hours of its full discharging rate. In this paper, a ten percent symmetric variation in the energy market prices is assumed to obtain the upper and lower bounds of the uncertain energy market, as portrayed in Fig. 2.

The proposed robust MIP generation scheduling model for the HTES system is coded in general algebraic modeling system (GAMS) and is solved via CPLEX solver. Fig. 3 reports the profit of the considered HTES system for various values of Γ in the proposed robust generation scheduling structure. From Fig. 3, it can be observed that larger values of Γ eventuate in lower profit of the HTES system. It is important to remark that the highest profit is obtained for $\Gamma = 0$, representing the risk-neutral scheduling strategy.

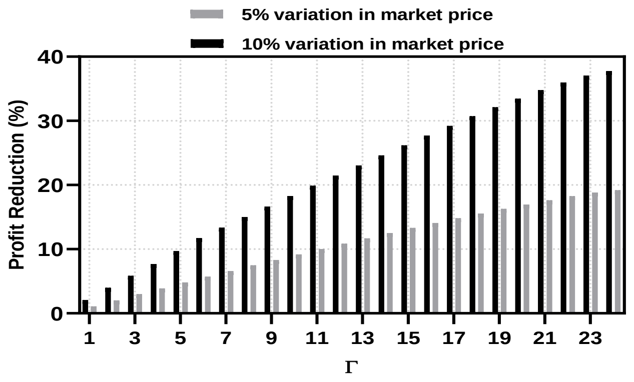

Fig. 4. Profit reduction of the HTES system in conservative scheduling approaches compared to the risk-neutral strategy.

The profit reduction of the HTES system in conservative scheduling strategies ($\Gamma \in [1, 24]$) compared to the risk-neutral approach ($\Gamma = 0$) is depicted in Fig. 4. According to this figure, the lowest profit reduction is obtained at the lowest value of Γ, while the greatest profit reduction experiences in the largest value of Γ. Furthermore, in order to evaluate the impact of a smaller confidence interval of the energy market prices on the profit reduction of the HTES system, another analysis based on the five percent symmetric variation in the uncertain source is carried out, and the results are given in Fig. 4. The obtained results demonstrate that the greater the confidence interval of the interval parameter, the greater the profit reduction is.

Fig. 5 shows the sold energy by thermal units in the risk-neutral and robust strategies. It is worth to mention that, hereinafter, the robust strategy refers to the most conservative scheduling approach, namely, $\Gamma = 24$. A comparison between the sold energy in these two strategies shows that in all time intervals, the risk-neutral scheduling has a greater or equal amount of the traded power than the robust strategy. Furthermore, the highest difference between the amount of sold energy in these two strategies occurs at periods with the lowest and the most significant values of expected energy market prices, namely, hours 3 and 5 and hours 20 to 22, respectively.

The sold energy of the ESS in both risk-neutral and robust attitudes is shown in Fig. 6. According to this figure, the ESS attitude in both strategies in terms of selling power is similar. In both risk-neutral and robust approaches, the ESS only sells energy during hours 20-22 with the highest energy market price, while the amount of the traded energy is equal in both strategies. The charging energy of the ESS from two origins, i.e., energy market and thermal units, in robust and risk-neutral states is depicted in Fig. 7. From Fig. 7, it is revealed that HTES tends to charge the ESS during the lowest price periods, i.e., third and fifth periods. By altering the HTES approach from the risk-neutral to the robust strategy, the system decreases 3 MW of its charging power from the energy market and

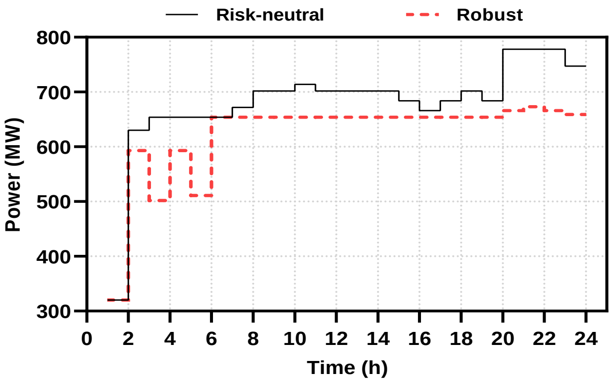

Fig. 5. The sold energy of the thermal units in two different approaches.

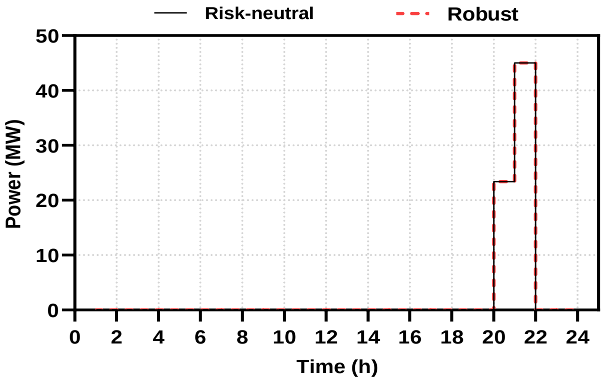

Fig. 6. The sold energy of the ESS in two different approaches.

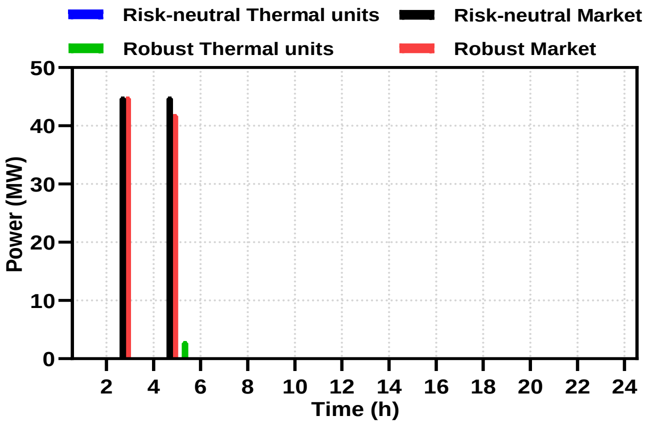

Fig. 7. The charging energy of the ESS in two different approaches.

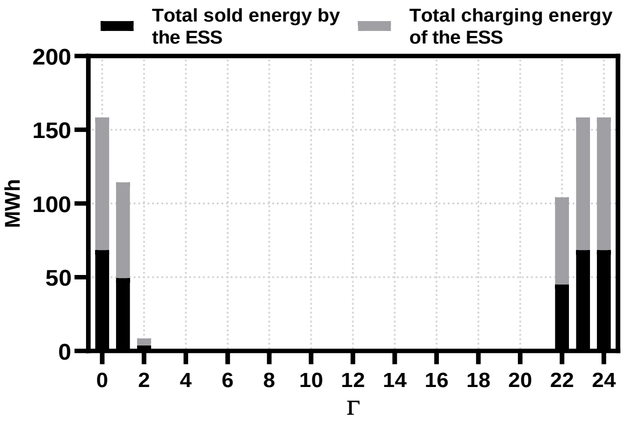

Fig. 8. Total purchased and sold energy by the ESS in the entire scheduling horizon for different values of Γ.

procure this amount of energy from thermal units.

To have a broader view of the charging and discharging strategies of the ESS in the proposed risk-constrained scheduling structure, the total amount of charging and discharging of the ESS in the entire trading horizon, and for all values of Γ have been reported in Fig. 8. As seen in this figure, for Γ=0-2, the ESS decides on participation in the market in the hope of selling energy at higher prices. For Γ=3- 21, the ESS decides on not operating at all, while for Γ=22-24, it resumes its activity in the market in the hope of purchasing electricity at lower prices.

V. CONCLUSION

To address the generation scheduling strategy of an HTES system in the energy market, a robust-based structure was proposed in this paper. The robust optimization was utilized to mitigate the risk of uncertain source, namely, the energy market price. The suggested model was tested on a typical HTES system, and results were obtained. The results demonstrated that as the risk-mitigating attitude of the HTES system increases, the profit is lowered. Further, as the confidence interval of the uncertain source, i.e., the energy market price, is increased, the HTES system is exposed to more significant values of profit reduction. It was also revealed that the amount of sold energy by thermal units are reduced by more focusing on a robust strategy. In contrast, the ESS approach in the market entirely depends on the risk-aversion degree of the HTES system. The ongoing investigation is focused on establishing a comparative generation scheduling framework under various uncertainty handling techniques, such as information gap decision theory, scenario-based approach, and robust optimization structure, whereas the degradation cost of the ESS is addressed adopting the methodology proposed in [23].

REFERENCES

[1] J. Lian, Y. Zhang, C. Ma, Y. Yang, and E. Chaima, “A review on recent sizing methodologies of hybrid renewable energy systems,” *Energy Conversion and Management*. 2019.

[2] JM. Baumann, M. Weil, J. F. Peters, N. Chibeles-Martins, and A. B. Moniz, “A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications,” *Renewable and Sustainable Energy Reviews*. 2019.

[3] S. M. Zahraee, M. K. Assadi, and R. Saidur, “Application of artificial intelligence methods for hybrid energy system optimization,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 617-630, 2016.

[4] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, “Hybrid energy storage system for microgrids applications: A review,” *J. Energy Storage*, vol. 21, pp. 543-570, 2019.

[5] H. Khaloie et al., "Coordinated wind-thermal-energy storage offering strategy in energy and spinning reserve markets using a multi-stage model," *Appl. Energy*, vol. 259, p. 114168, Feb. 2020.

[6] Y. Jiang et al., "Day-ahead stochastic economic dispatch of wind integrated power system considering demand response of residential hybrid energy system," *Appl. Energy*, 2017.

[7] S. S. Reddy, "Optimal scheduling of thermal-wind-solar power system with storage," *Renew. Energy*, vol. 101, pp. 1357-1368, 2017.

[8] H. Khaloie et al., "Offering Strategy of Thermal-Photovoltaic-Storage Based Generation Company in Day-Ahead Market," in *Electricity Markets*, Springer, 2020, pp. 113-133.

[9] M. Banaei, M. Oloomi-Buygi, and S. M. Zabetian-Hosseini, "Strategic gaming of wind power producers joined with thermal units in electricity markets," *Renew. Energy*, vol. 115, pp. 1067-1074, 2018.

[10] A. Rabiee, M. Sadeghi, J. Aghaeic, and A. Heidari, "Optimal operation of microgrids through simultaneous scheduling of electrical vehicles and responsive loads considering wind and PV units uncertainties," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 721-739, 2016.

[11] D. Wozabal and G. Rameseder, "Optimal bidding of a virtual power plant on the Spanish day-ahead and intraday market for electricity," *Eur. J. Oper. Res.*, 2020.

[12] H. Khaloie et al., "Co-optimized bidding strategy of an integrated wind-thermal-photovoltaic system in deregulated electricity market under uncertainties," *J. Clean. Prod.*, vol. 242, p. 118434, 2020.

[13] J. Xu, F. Wang, C. Lv, Q. Huang, and H. Xie, "Economic-environmental equilibrium based optimal scheduling strategy towards wind-solar-thermal power generation system under limited resources," *Appl. Energy*, 2018.

[14] F. Kalavani, B. Mohammadi-Ivatloo, and K. Zare, "Optimal stochastic scheduling of cryogenic energy storage with wind power in the presence of a demand response program," *Renew. Energy*, 2019.

[15] W. Tang and H.-T. Yang, "Optimal operation and bidding strategy of a virtual power plant integrated with energy storage systems and elasticity demand response," *IEEE Access*, vol. 7, pp. 79798-79809, 2019.

[16] P. Zou, Q. Chen, Q. Xia, G. He, and C. Kang, "Evaluating the contribution of energy storages to support large-scale renewable generation in joint energy and ancillary service markets," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 808-818, 2015.

[17] H. Ding, P. Pinson, Z. Hu, J. Wang, and Y. Song, "Optimal offering and operating strategy for a large wind-storage system as a price maker," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4904-4913, 2017.

[18] J. Arteaga and H. Zareipour, "A Price-maker/Price-taker model for the Operation of Battery Storage Systems in Electricity Markets," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6912-6920, 2019.

[19] H. Khaloie, A. Abdollahi, M. Rashidinejad, and P. Siano, "Risk-based probabilistic-possibilistic self-scheduling considering high-impact low-probability events uncertainty," *Int. J. Electr. Power Energy Syst.*, vol. 110, pp. 598-612, Sep. 2019.

[20] J. M. Morales, A. J. Conejo, H. Madsen, P. Pinson, and M. Zugno, *Integrating renewables in electricity markets: operational problems*, vol. 205. Springer Science & Business Media, 2013.

[21] M. Nazari-Heris, B. Mohammadi-Ivatloo, G. B. Gharehpetian, and M. Shahidehpour, "Robust short-term scheduling of integrated heat and power microgrids," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3295-3303, 2018.

[22] M. Nazari-Heris, S. Madadi, and B. Mohammadi-Ivatloo, "Optimal management of hydrothermal-based micro-grids employing robust optimization method," in *Classical and recent aspects of power system optimization*, Elsevier, 2018, pp. 407-420.

[23] S. Esmaeili, A. Anvari-Moghaddam, and S. Jadid, "Optimal operation scheduling of a microgrid incorporating battery swapping stations," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 5063-5072, 2019.