Hybrid robust-stochastic bidding strategy for integrated power to gas and compressed air energy storage systems coordinated with wind farm

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By increasing the penetration of renewable energy sources with probabilistic nature, the power system is faced with operating and management challenges. Therefore, employing coordinated energy storage systems is a great choice that could better deal with inherent uncertainties. This paper presents an optimal bidding strategy for coordinated energy storage systems consists of compressed air energy storage and power to the gas facility integrated with wind energy to participate in the day-ahead market. In addition, to mitigate wind energy fluctuation by charging and discharging schemes, excess wind energy can be stored and converted to gas based on gas condition prices through the power to the gas facility. The proposed bidding strategy is addressed by a hybrid stochastic-robust optimization approach, which the wind power uncertainty is modeled by scenario-based stochastic method, while day-ahead electricity prices are handled via robust optimization approach, with the purpose of profit maximization. Thereafter, based on the optimal charging and discharging scheme, the hourly bidding and offering curves are generated. Numerical results reveal the effectiveness of the proposed method in the mitigation of wind energy curtailment and profit maximization. © 2021 Journal of Energy Management and Technology

keywords: *Bidding strategy, wind generation, CAES system, P2G facility, hybrid robust/stochastic optimization.*

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NOMENCLATURE

Abbreviations:

P2G	Power to gas
RES	Renewable energy source
ESSs	Energy storage systems
DAM	Day-ahead market
SNG	Synthetic natural gas
ROA	Robust optimization approach
IGDT	Information gap decision theory
RMILP	Robust mixed-integer linear programming

Index:

t	Index of time
s	Index of scenario

Constants:

HR_d	Heat rate of CAES in discharging mode
VOM^{C}	Operation and maintenance costs of CAES in charging mode
$\mathrm{VOM}^{\exp}$	Operation and maintenance costs of CAES in discharging mode
$P_c^{\max}$	Maximum compression CEAS capacity in charging mode
$P_{\exp}^{\max}$	Maximum generation CAES capacity in discharging mode
$\mathrm{E}_{\min}$	The minimum energy level of CAES
$\mathrm{E}_{\max}$	The maximum energy level of CAES
ER	CAES energy ratio
E_{ini}	The initial energy of CAES

$P_{\max}^{P2G}$	The maximum power operation of P2G facility
$G_{\min}$	The minimum level of gas storage tank
$G_{\max}$	The maximum level of gas storage tank
η_{P2G}	The energy conversion efficiency of the P2G facility

Variables

λ_t^e	The forecasted electricity price at time t and scenario s
π_t^{NG}	Gas price at time t
$P_{t,s}^W$	The total produced wind energy at time t and scenario s
π_s	Probability of scenario
$P_{t,s}^{dis}$	The produced power by CAES in discharging mode at time t and scenario s
$P_{t,s}^{ch}$	The consumed power by CAES in charging mode at time t and scenario s
$OC_{t,s}$	The operation cost of CAES at time t and scenario s
$E_{t,s}$	The energy level of CAES at time t and scenario s
$P_{t,s}^{P2G,gas}$	The gas produced by the P2G at time t and scenario s
$P_{t,s}^{P2G,da}$	Charging P2G facility by purchased power from the day-ahead market at time t and scenario s
$P_{t,s}^{w,da}$	The produced wind power for selling to the day-ahead market at time t and scenario s
$P_{t,s}^{w,curt}$	The value of wind power curtailment at time t and scenario s
$u_{t,s}^{ch}/u_{t,s}^{dis}$	The CAES status in charging/ discharging modes at time t and scenario s

1. INTRODUCTION

A. Motivation

Presently, employing renewable energy sources (RES) especially photovoltaic cells and wind power plants in most industrialized countries, has significantly grown to cope with global warming and environmental issues. According to the international energy agency (IEA) reports, the share of wind power productions is forecasted to reach around 11.6% of the total global electricity production in 2030, and their penetration will shoot up to 14.8% by 2050 [1]. Growing the integration of RESs has made great challenges associated with its probabilistic nature. The energy storage systems (ESSs) are known as one of the flexible sources to cope with RES's uncertainties, which can improve the power systems flexibility [2]. Energy storage technologies are designed to balance altering energy demand on a daily basis. Employing an ideal method of integration of storage devices with sources of renewable energy generation not only significantly enhance the overall system efficiency, but also reduce carbon emission during power production [3]. The ESSs are applied in many various kinds, such as battery storage, compressed air energy storage (CAES), power to gas facility (P2G), etc. CAES is one of the high-efficiency large-scale energy storage devices which can improve system reliability, integrate entirely with RESs mainly wind farms, and be operated in the range of a minute to an hour of time. Besides, employing the novel storage technologies such as P2G facility is made meaningful growth of electricity and natural gas systems due to series of global, economic, and environmental advantages [4]. P2G facility converts the surplus power of renewable energy generations to natural gas by chemical processes which can improve the system's flexibility and enhance interdependency between electricity and gas grids. One of the numerous impressive abilities of P2G is to compete in the deregulated market, which has created a competitive environment at every level of negotiating electricity prices. In the competitive power market, participants have an opportunity to trade electricity by submitting their own bids/ offers [5].
The coordinated energy storage devices integrated with wind energy to determine an optimal bidding strategy, needs to be extensively studied from an economic and technical point of view. Bidding strategy problems are highly correlated with maximizing profit, reducing the risks of power benefits in a competitive environment, and finding an optimal bidding strategy, that requires a suitable bidding structure. Since, there are multiple uncertainties associated with their stochastic nature and electricity market variability such as electricity price, it is required to be discussed in succeeding studies.

B. Literature review

Commercialized P2G facilities have considerably gained much attraction in recent years, as large capacity energy storage solutions. From an environmental stand point , P2G technology illustrates most effectiveness in decarbonization of the power industry in the different highlighted projects in [6]. In [7], authors have been presented an overview of the role of P2G technology in different energy system architectures. In [8], a mathematical method for operating of a real option of P2G device in presence of electricity price uncertainty to obtain the capacity of P2G is proposed. In [9], the impact of P2G on the economic operation of power system for a simple case in Denmark is demonstrated and a multi-period scheduling approach for the operation of P2G based on the optimal DC power flow is considered. The results show that coordinated P2G facility can minimize the operating cost of the system by 4% and has decreased wind power curtailment by 2%. An economic and environment-friendly optimization method for a coupling model including P2G technology, wind farms, and carbon capture power plants (CCPP) is presented in [10]. The coupling of CCPP and P2G is considered as a solution to reuse CO2 and decrease the carbon emission, wind power curtailment, and gas dependent degree. In [11], the impact of P2G technology has been studied as an emerging flexible resource to decrease the curtailment of the co-sizing of wind and solar PV capacity with a probabilistic nature. In [12], the technical performance of the P2G conversion facility is treated and its economic performance is evaluated. Also, the conceptual aspects of P2G facility in a more comprehensive analysis framework in multiple sectors, by considering some methods with direct impact on the power system is presented in [13].
The implementation of the coordinated RES-ESSs with interaction between gas and power systems due to series of global, economic, and environmental advantages has grown significantly in recent years [14]. Several comprehensive studies are focused on the scheduling of P2G facility integrated with power and a natural gas system. In [15], an optimal

operation scheme for coordinated P2G facility and gas-fired power plant (P2G-GFPP) in presence of renewable energy for eco-emission aspects is provided. In [16], an optimal operation of the coordinated electrical and natural gas systems with P2G facility in presence of uncertainties of the wind turbine (WT) and photovoltaic (PV), is analyzed. In [17], a stochastic approach is provided to investigate the optimum strategy for the integrated operation of gas-fired units and a P2G facility in the regulation market. In [18], a new method for optimal day-ahead scheduling of a P2G facility and natural gas load administration in the coordinated power and natural gas markets is provided for the cost minimization of gas consumption. In [19], an original methodology to evaluate the economic and operational feasibility of P2G facility and investigating its impact on electricity and gas networks is provided. The surplus electricity is converted to hydrogen and SNG through electrolysis and methanation processes, which can be used in the natural gas network as a means of saving and transporting the generated gas. In [20], a coordinated system including gas-fired units (GFUs), P2G facility, and wind farms considering robust optimization method is analyzed as an optimal integrated gas-power system framework. In [21], an excellent economic dispatch model of integrated electricity and gas systems with the bidirectional power flow is proposed to show the economic impact of P2G by employing the highest wind power production. In [22], a coordinated natural gas, heat, and power dispatch model, including a wind farm and P2G facility, is investigated. An integrated energy system including a six-node natural gas system, six-bus power system, and a district heating system to simulate the proposed model, is considered. The benefits of P2G technology, such as reducing wind power curtailment, operating costs reduction, and pollution emission reduction, are achieved in this paper. A new scheme of a virtual power plant connected with P2G and gas storage tank with a multi-objective scheduling considering uncertainty and demand response is constructed in [4]. The proposed model employs a power-gas-power cycle by scheduling the P2G system, gas storage tank, and conventional gas turbine (CGT). Also, converting CO2 to methane is considered to solve the problems of gas shortage, pollutant emissions, and environmental problems.

A revision of the latest studies on the variety of CAES past and recent technologies for enhancing the fundamental understanding of CAES is provided in [23]. In [24], authors have given a review of CAES conditions, technical advantages, basic principles, CAES notions, and recent progress of CAES in the power industry. In [25], a simplistic CAES trade model is intended to respond when the storage unit is not in the charge-discharge form, it can act as a gas-fired unit. In the proposed coordinated system, the wind power and market electricity prices uncertainties through coordinating the wind power plant with the CAES facility is completely analyzed. Similarly, in [26], the steady-state input/output model of CAES with an adaptable method, which is named small-scale tri-generative CAES facility, has been investigated. An efficient CAES system considering wind turbine (WT), photovoltaic (PV) system, and DR programs is studied in [27] for flatting the load curve and minimizing the operating cost of thermal unit and CAES system regarding the technical and physical constraints. Also, the operation of a common GFPP coordinated with a wind producer and a CAES facility system is studied in [28] to meet demand at minimum operating costs. According to the simulation results, using CAES reduces total operating cost more than % 6.7.

The coordinated storage systems integrated with wind energy can be considered as a feasible solution to cope with wind power variability by determining an optimal bidding strategy. Determining an optimal bidding strategy depends on how much bidders act rationally in the market, as well as how much the programmed computational performance for operation can maximize system's profit. Due to various uncertainties in a bidding strategy problem, such as price and wind generation uncertainties, the use of probabilistic approaches is an essential way. To operate the coordinated storage systems and achieve an optimal bidding strategy for trading electricity, different approaches have been used, including robust optimization approach (ROA), stochastic programming, information gap decision theory (IGDT), etc. In such an area, some studies in previous literature, have determined the optimal bidding strategies for various electricity market participants considering the mentioned methods. In [29],an optimal operation scheduling of distribution network in the presence of electric vehicle parking (EV) as an energy storage device considering robust optimization method with the aim of cost minimization was employed. In [30], a virtual power plant (VPP) including wind turbine, CHP units, and heat storage devices in the presence of battery energy storage was analyzed considering stochastic programming approach to meet the wind power uncertainty. In [31], the authors have formulated an stochastic programming method for a coordinated wind turbine and P2G facility to maximize system's profit and achieve an optimal bidding strategy structure. An stochastic programming scheduling for a microgrid consists of microturbines, wind energy and PV panels in the presence of energy storage devices was presented by [32] to maximize the system's profit. In [33], a co-optimization structure of P2G technology and demand response (DR) programs for integrated gas and power networks to mitigate wind energy fluctuation is developed. The investigated model is a two-stage stochastic framework for a multi-objective problem considering uncertainties associated with wind energy output, electricity demand, and gas load to store the surplus wind energy production as gas in natural gas storage in off-peak times and inject it to the gas-fired units in on-peak periods.

Also, a bi-level optimization problem for scheduling a microgrid considering integrated EVs storage systems was investigated by [34]. The capability of P2G facility among an energy hub system considering DRP using stochastic programming method was analyzed by [35] with the aim of cost minimization. In [36], a self-scheduling problem of the CAES system integrated with solar farm by using an IGDT method is analyzed. This CAES system is operated in the charging, discharging, and simple-cycle mode and can compress the excess thermal energy recovery. The proposed IGDT method handles uncertainties using both opportunity and robust functions. The risk-seeker strategy obtains maximum profit from high solar generating, and the risk-averse strategy confirms minimum profit if the produced electricity by the solar farm is less than the predetermined amount. In [37], an optimal strategy for an integrated wind aggregator- CAES system to participate in day-ahead, intraday, and balancing market is analyzed via a stochastic optimization approach. In [38], a two-stage stochastic programming framework is presented to attend to the operator of a hybrid system, including CAES, wind, and thermal units. The goal of the proposed model is maximizing the profit by participating in energy and spinning reserve markets. Additionally, an adaptive robust self-scheduling scheme for resolving the wind power uncertainty and price forecast errors in a coordinated wind producer-CAES system, is presented in [39]. According to the achieved results, considering systematic-plans for direct sales of wind generation in high-price periods or storing energy using the CAES system in the low-price periods and discharge it at a later time with an increase in optimal profit. In [40], an IGDT-based risk-constrained bidding strategy is proposed for a merchant CAES system considering price uncertainties in the DAM. In [41], a new robust multi-objective power and gas flow (RM-PGF) for a coordinated electricity and natural gas system with gas turbines and P2G facility is proposed to implement an effective way with the aim of improvement the energy efficiency considering an environmentally friendly and reliable energy supply. In [42], a robust optimization method for coordinated electricity and natural gas systems in a DAM for the energy hub is introduced. The proposed energy hub in this study involves the natural gas power plant, the P2G facility, and the natural gas storage. The P2G facility significantly reduces the wind power curtailment by converting surplus power to SNG. In [43], authors have investigated the impact of injecting H2 produced by the P2G facility throughout a ROA on a small integrated electrical and natural gas system. Also, a hybrid robust-stochastic approach for a CAES system to maximize its profit, in presence of the uncertainty correlated to the market price and the maximum capacity of the cavern, is provided in [44].

C. Contribution and Novelty

Reviewed literature has described the importance of the optimal bidding strategy of the coordinated storage system framework that enables the interdependency between multi-energy carriers such as electricity and natural gas systems. In this paper, a coordinated CAES-P2G facility integrated with wind energy is proposed to achieve an optimal bidding strategy for maximizing profit in the energy market while in previous studies the coordination between two storage devices regarding to the interaction of electricity and natural gas systems has rarely been analyzed. Various methods have been advised for obtaining an optimal bidding strategy considering uncertainties. This work focuses on a new non-deterministic self-scheduling model, whereby the problem is formulated according to integration of stochastic programming methodology and the assumptions of ROA to achieve an optimal bidding and offering strategies with the aim of system's profit maximization. The proposed hybrid stochastic-robust method is applied to cope with the wind production uncertainty by using a scenario-based stochastic programming and the electricity price uncertainty by implementing ROA according to the worst-case scenarios. To reveal the main contributions of this work, Table1 compares the novelties with similar works. The major contributions of this study are summarized as follows:

- Proposing the hybrid system including CAES, P2G, and wind farm to facilitate power integration of the renewable energy in the integrated energy markets.
- Proposing the hybrid robust/ stochastic approach to cope with the wind power and day-ahead electricity prices uncertainties to achieve a realistic model.
- Using the excess wind power for storing and converting the P2G facility in order to participate in the gas market based on gas price.
- Optimizing the CAES and P2G charging and discharging schemes for the different levels of the robustness.
- Building the bidding and offering curves for the large-scale hybrid system for the different conservation levels of the system operator.

D. Paper organization

The remainder of this paper is organized as follows: Section 2 provides a brief explanation of the P2G concept. The section 3 is represented the problem description. In section 4, the problem formulation of the introduced model including objective function and related constraints based on stochastic programming method is presented. The proposed hybrid stochastic-robust scheduling of coordinated system is introduced in Section 5. Numerical results are presented and discussed in Section 6. Finally, Section 7 is provided the principal conclusions of this paper.

Table 1. Comparison of this article with similar works

Ref	Coupled system	Bidding strategy	components			Uncertainty modeling	
			CAES	P2G	wind	robust	stochastic
[11]	×	×	×	✓	✓	×	×
[21]	✓	×	×	✓	✓	×	×
[25]	×	✓	✓	×	✓	×	✓
[31]	×	✓	×	✓	✓	×	✓
[36]	×	×	✓	×	×	×	×
[37]	×	✓	✓	×	✓	×	✓
[38]	×	×	✓	×	✓	×	✓
[40]	×	✓	✓	×	×	×	×
[42]	✓	×	×	✓	×	✓	×
[43]	×	×	×	✓	✓	✓	×
[44]	×	✓	✓	×	×	✓	✓
Our work	✓	✓	✓	✓	✓	✓	✓

2. P2G CONCEPT

P2G facility, as an emerging flexible resource, intensifies energy system flexibility, convert surplus power at time of excess supply, and establish bidirectional coupling between power and gas system [42]. It enables the owners to utilize cheap power to achieve higher profits by selling the produced SNG to the gas market. The main process of the P2G facility is based on the electrochemical process which can be summarized into two main process. In the first which called electrolysis, water is decomposed into the oxygen and hydrogen. The second process is named methanation consume CO2 as a row material to produce SNG. Both processes consume electricity power as the input energy [17]. The specific chemical reactions are described by:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

There is a general notation to convert electricity into other energy vector which is determined as power-to-X. Although, hydrogen will be an important economical fuel in the future, nowadays, some challenges such as highly combustible, low energy density, and restriction of hydrogen injection into gas network are caused to power-to-gas has several priorities over the power-to-hydrogen [7]. The schematic diagram of the P2G technology is shown in Figure 1. Electrolysis splits water into oxygen and hydrogen by consuming the surplus electrical energy. The produced hydrogen is directly pumped into storage devices for hydrogen-based industries or is combined with CO2 in the

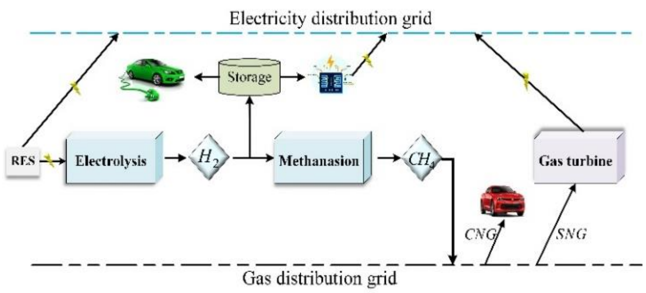

Fig. 1. Overall schematic of the P2G technology.

methane catalytic device during the methanation process, and the CH4 that is final production can be released to the gas market for obtaining economic benefits.

3. PROBLEM DESCRIPTION

The fast-growing penetration of wind power in recent years has been performed an important role in producing clean and sustainable energy. However, due to its uncertain nature, the power system has faced multiple challenges. To cope with the challenges caused by wind energy, utilization of ESSs has been significantly increased in the power system. Due to the wind power uncertainties and also electricity price unpredictability, storage facilities may not be able to effectively participate in the electricity market for trading the electricity in the energy market. Therefore, achieving the optimal bidding/offering strategies is so essential. In a competitive electricity market, each participant presents its bidding/offering for each hour of the day in such a way as to maximize the system's profit. Then, the hourly market clearing prices are calculated by collecting the given bidding and offering curves by the market operator. In this paper, a comprehensive mathematical formulation of a coordinated scheduling of coordinated CAES-P2G facilities integrated with wind energy is addressed. The problem structure is schematically represented in Figure 2. In order to achieve optimal offering and bidding strategies, a hybrid stochastic-robust method is characterized. The uncertainty of wind power is considered in the proposed approach by scenario-based stochastic programming formulation, while the electricity price uncertainty is handled using ROA. It is assumed that all components owned by the same entity. It should be noted that the coordinated CAES-P2G facilities have been employed as promising options to decrease the wind power curtailment. The proposed framework empowers the system's owner to employ cheap electricity energy at low-price periods, save the surplus power for long-term storage and make it beneficial by trading the produced power and SNG in both electricity and natural gas markets.

4. PROBLEM FORMULATION

The proposed framework of this study is providing an optimal bidding/offering strategy to maximize the system's profit considering wind power production and electricity price uncertainties. To this end, the stochastic programming model is initially considered for optimizing the problem with the wind uncertainty, while the hybrid stochastic-robust approach is presented to study the uncertainty of the electricity price. In this section, the objective function based on scenario-based stochastic framework and corresponding constraints are defined.

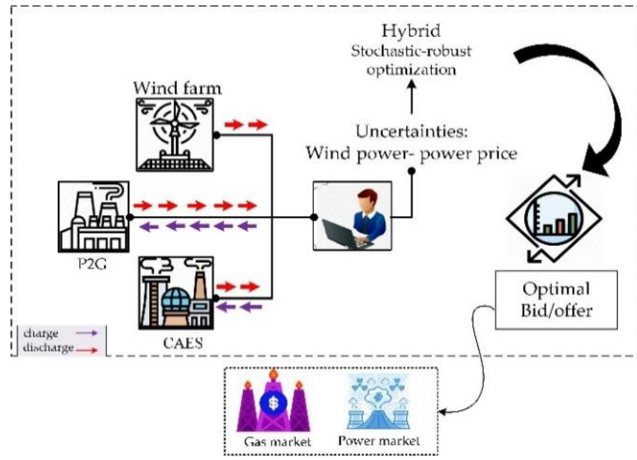

Fig. 2. Overall structure of the proposed model with different components.

A. Stochastic bidding strategy of CAES-P2G and wind farm

This section represents the mixed integer linear programming (MILP) based stochastic optimization problem to obtain the optimal strategy for production and consumption of the assumed storage facilities in the DAM. The main objective of the coordinated system is to achieve optimal scheduling for maximizing the system profit that is determined based on the difference between total revenue and cost. The objective function of the proposed scheduling framework can be mathematically stated as follows:

$$Z = MAX \sum_{s=1}^{N_s} \pi_s \left[\sum_{t=1}^{T} \left[\overbrace{\left(\left(P_{t,s}^{dis} - P_{t,s}^{ch} \right) \times \lambda_t^e - OC_{t,s} \right)}^{(I)} + \overbrace{\left(\pi_t^{NG} \times P_{t,s}^{P2G,gas} - \lambda_t^e \times P_{t,s}^{P2G,da} \right)}^{(II)} + \overbrace{\left(P_{t,s}^{W,da} \times \lambda_t^e \right)}^{(III)} - \overbrace{\left(C_t^{W,curt} \times P_{t,s}^{W,curt} \right)}^{(IV)} \right] \right] \quad (3)$$

The first term in objective function Eq. (3) represents the CAES profit, considering operation cost. Total profit achieved by the P2G facility including revenue from selling natural gas and purchasing electricity from the upstream grid is shown by second term of Eq. (3). Third term of objective function Eq. (3) represents the participation of wind farm in the DAM. Finally, the fourth term expressed the curtailment cost of wind energy.

B. Problem constraints

The objective function is restricted by multiple constraints that are discussed in the following.

- CAES constraints

The constraints associated with the CAES operation are represented by Eq. (4) - Eq. (10). The operation costs in discharging and charging modes is given in Eq. (4). Logical limitation on the CAES operation is represented in Eq. (5) which indicates that CAES can only operate in one mode (charging/ discharging).

The value of charged and discharged power by CAES facility are limited by the maximum values as respectively described by Eq. (6) and Eq. (7). The current energy capacity of CAES facility is represented by Eq. (8). The energy capacity of CAES is bounded by minimum and maximum values as Eq. (9). The equality condition for initial (t=0) and final (t=24) operating states of CAES is represented by Eq. (10).

$$OC_{t,s} = \left[P_{t,s}^{dis}\left(HR_d \times \pi_t^{NG} + VOM^{\exp}\right)\right] + \left[P_{t,s}^{ch} \times VOM^{c}\right] \quad (4)$$

$$u_{t,s}^{ch} + u_{t,s}^{dis} \leq 1 \quad (5)$$

$$0 \leq P_{t,s}^{ch} \leq P_{\max}^{c} \times u_{t,s}^{ch} \quad (6)$$

$$0 \leq P_{t,s}^{dis} \leq P_{\max}^{\exp} \times u_{t,s}^{dis} \quad (7)$$

$$E_{t+1,s} = E_{t,s} + P_{t,s}^{ch} - P_{t,s}^{d} \times ER \quad (8)$$

$$E_{\min} \leq E_{t,s} \leq E_{\max} \quad (9)$$

$$E_{t=0} = E_{t=24,s} \quad (10)$$

- P2G constraints

The P2G constraints are defined by Eq. (11) - Eq. (16). Consumed power by the P2G facility is represented by Eq. (11), which contains charging by the wind farm and the power purchased from the DAM. The amount of consumed power and purchased electricity for charging the P2G are limited by the maximum and minimum values as respectively expressed by Eq. (12) and Eq. (13). The maximum and minimum limitations of amount of natural gas stored in the P2G tanks is shown in Eq. (14). The hourly amount of stored gas in the P2G at any time is presented in Eq. (15). Constraint Eq. (16) expresses the P2G facility efficiency.

$$P_{t,s}^{P2G,cons} = P_{t,s}^{P2G,da} + P_{t,s}^{P2G,W} \quad (11)$$

$$P_{\min}^{P2G} \leq P_{t,s}^{P2G,cons} \leq P_{\max}^{P2G} \quad (12)$$

$$0 \leq P_{t,s}^{P2G,da} \leq P_{\max}^{P2G} \quad (13)$$

$$G_{\min} \leq G_{t,s} \leq G_{\max} \quad (14)$$

$$G_{t,s} = G_{t-1,s} + G_{t,s}^{ch} - G_{t,s}^{dis} \quad (15)$$

$$P_{t,s}^{P2G,gas} = P_{t,s}^{P2G,da} \times \eta_{P2G} \quad (16)$$

- Wind farm constraints

The total wind power depends on the wind speed with probabilistic nature. The relationship between power produced by wind farm and hourly wind speed is formulated by Eq. (17). According to constraint Eq. (18), the wind curtailment amount could not exceed the actual wind power produced [45].

$$P_W(V) = \begin{cases} 0 & V_{t,s}^{ws} < V_{cut-in}, V_{t,s}^{ws} > V_{cut-out} \\ P_{wind_{rated}} \times \left(\frac{V_{t,s}^{ws} - V_{cut-in}}{V_{rated} - V_{cut-in}}\right)^3 & V_{cut-in} \leq V \leq V_{rated} \\ P_{wind_{rated}} & V_{rated} \leq V_{t,s}^{ws} \leq V_{cut-out} \end{cases} \quad (17)$$

$$P_{t,s}^{W,curt} \leq P_{t,s}^{W} \quad (18)$$

5. HYBRID STOCHASTIC-ROBUST OPTIMIZATION

The ROA is a risk-averse method that can address optimization problems in the presence of severe uncertainties as a powerful tool. In a robust optimization technique, it's not necessary to have full information about the distribution function of the uncertain parameter, and the problems are optimized according to the worst-case scenarios in decision-making process. This method has a low computation burden and just some limits of the uncertain parameter, such as its minimum and maximum amounts, are required. The standard MILP formulation of the robust optimization method is determined as follows:

$$\underset{X_j,\forall_j}{\text{Minimize}} \sum_{j=1}^{M} e_j x_j \quad (19)$$

Subject to:

$$\sum_{j=1}^{M} a_{nj} x_j \leq b_n \qquad n = 1, \ldots.N \quad (20)$$

$$x_j \geq 0 \qquad \text{j} = 1,\ldots\text{M} \quad (21)$$

$$x_j \in \{0,1\} \qquad \text{for some j} = 1,\ldots\text{M} \quad (22)$$

In Eq. (19), e_j is set of the coefficients of the objective function that are input parameters with known minimum and maximum amounts, $x_j$is the set of decision variables. If d_j is considered as deviation from the nominal coefficient, so each coefficient e_j is placed in the predefined interval $[e_j, e_j + d_j]$. Additionally, for every robust mixed integer linear problem (RMILP) an integer control parameter Γ_0 (Gama) is needed to employ the RO formulation that has an integer value in interval $[0, |J_0|]$ where $\{j|d_j \geq 0\}$ should be proposed. If $\Gamma_0 = 0$, the price variation is ignored and if $\Gamma_0 = 1$, all price variation in the objective function is designated. Accordingly, the RMILP problem in Eq. (19)-Eq. (22) can be rewritten as follow [44]:

$$\underset{X_j,\forall_j}{\text{Minimize}} \sum_{j=1}^{M} e_j x_j + z_0 q_0 + \sum_{j=1}^{M} q_j \quad (23)$$

Subject to:

$$z_0 + q_{0j} \geq \text{d}_j y_j \quad \text{j} \in \text{J}_0 \quad (24)$$

$$q_{0j} \geq 0, \quad \text{j} = 1,\ldots\text{M} \quad (25)$$

$$y_j \geq 0, \quad \text{j} = 1,\ldots\text{M} \quad (26)$$

$$z_0 \geq 0 \quad (27)$$

$$x_j \leq y_j, \quad \text{j} = 1,\ldots\text{M} \quad (28)$$

Where y_j is an auxiliary variable of the ROA. Also q_{0j} and z_0 are dual variables of the optimization problem that are utilized to count the minimum and maximum limits of coefficients e_j. According to the provided formulation, and by expanding the stochastic programming method in section 4, the proposed hybrid stochastic- robust optimization method can be reformulated as follows:

$$MaxZ = \sum_{s=1}^{N_s} \pi_s \left[\sum_{t=1}^{T} \left[\left(P_{t,s}^{dis} - P_{t,s}^{ch} \right) \times \lambda_t^e - OC_{t,s} + \left(\pi_t^{NG} \times P_{t,s}^{P2G,gas} - \lambda_t^e \times P_{t,s}^{P2G,da} \right) + \left(P_{t,s}^{W,da} \times \lambda_t^e \right) - \left(C_t^{W,curt} \times P_{t,s}^{W,curt} \right) \right] \right] + Z_0\Gamma_0 + \sum_{t=1}^{T} q_{0t} \quad (29)$$

Based on the standard model of a MILP model, equation Eq. (29) can be reformulated as Eq. (30). Accordingly, the ultimate objective function and related constraints are reformulated as follow:

$$MinZ = -\sum_{s=1}^{N_s} \pi_s \left[\sum_{t=1}^{T} \left[\left(P_{t,s}^{dis} - P_{t,s}^{ch} \right) \times \lambda_t^e - OC_{t,s} + \left(\pi_t^{NG} \times P_{t,s}^{P2G,gas} - \lambda_t^e \times P_{t,s}^{P2G,da} \right) + \left(P_{t,s}^{W,da} \times \lambda_t^e \right) - \left(C_t^{W,curt} \times P_{t,s}^{W,curt} \right) \right] \right] + Z_0\Gamma_0 + \sum_{t=1}^{T} q_{0t} \quad (30)$$

Subject to:

$$P_{t,s}^{ch} + P_{t,s}^{P2G,da} - P_{t,s}^{dis} - P_{t,s}^{W,da} \leq y_t \quad (31)$$

$$(4) - (18), \ and \ (24) - (28) \quad (32)$$

The proposed coordinated CAES-P2G with wind farm allows the system's operator to obtain an optimal bidding/offering strategies and schedules operating with the purpose of profit maximization. The schematic of the proposed hybrid robust-stochastic method in the bidding strategy of CAES-P2G and wind farm system is depicted in Figure 3. The main steps of the proposed method are described as follows:

Step1: At first, the initial data including P2G, CAES and wind farm characteristics and etc., are considered as input data.

Step2: By employing the method in Section 4 based on the stochastic model for speed uncertainty, multiple scenarios for wind power production using Weibull distribution are generated.

Step3: The scenario reduction process is considered to reduce the number generated scenarios to desired scenarios.

Step4: The ROA under worst-case scenarios is employed for getting the power price curve and charging/discharging amount of the coordinated system for each hour.

Step5: The price curve obtained by the RO method according steps of Γ is achieved.

Step6: The optimal bidding and offering curves is determined for participating in the DAM.

6. NUMERICAL SIMULATION

A. Case study

The proposed hybrid robust/stochastic approach provided in Sections 4 and 5, is applied on a case study in order to express the applicability of the assumed methodology. The integrated test system contains a P2G facility, a CAES system, and a wind

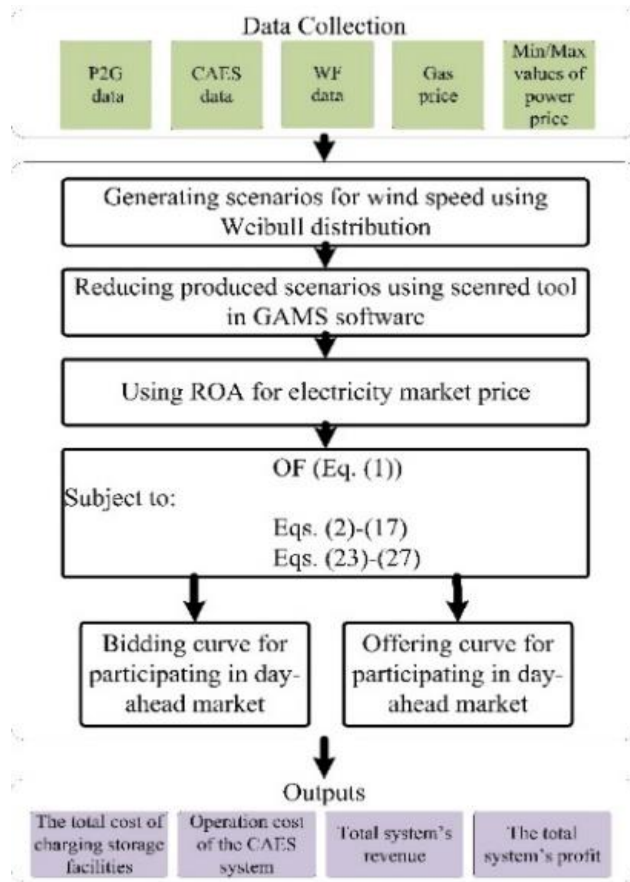

Fig. 3. Schematic of the proposed robust-stochastic approach.

farm. All the characteristics of P2G facility and the CAES system are given in Table 2 and 3, respectively. Based on forecast results, the corresponding day-ahead market price, and the gas price are given in Table 4 [46].

Table 2. Parameters of the P2G facility [17]

$P_{min}^{P2G}/P_{max}^{P2G}$	G_{min}/G_{max}	η_{P2G}	$P_{max}^{P2G,str}$	$P_{max}^{P2G,rel}$
2/20	5/50	50	5	5
(MW)	(MWh)	$(\%)$	(MW)	(MW)

Table 3. Parameters of CAES system [47]

HR_d	VOM^{exp}/VOM^c	$P_{max}{}^c/P_{max}{}^{exp}$	E_{min}/E_{max}	ER
4.185	0.37/0.37	50/50	0/3000	0.75
$(^{Gj}/_{MWh})$	$(^{\$}/_{MWh})$	(MW)	(MWh)	

All the equations are solved as a MILP problem that are accomplished in the GAMS software environment by CPELX solver. The 1000 scenarios based on Monte Carlo simulation have been generated to simulate wind power uncertainty which is subjected to the Weibull distribution function with corresponding characteristics in [48]. To decrease the computational burden of the optimization problem, the number of scenarios is lessened

Table 4. Forecasted amounts of prices and wind generation

Time	Gas price	Power price	Time	Gas price	Power price
1	29/194	22/3	13	40/2	27/1
2	21/72	21/85	14	40/71	28/9
3	21/08	23/4	15	40/5	23/85
4	21/75	23/8	16	41/11	29/4
5	21/3	17/45	17	33/28	16/8
6	21/37	22/5	18	29/9	25
7	40/1	25/3	19	22/95	25
8	39/9	20/9	20	21/55	27/6
9	40/6	18/4	21	22/59	24/5
10	39/9	28/7	22	22/03	27
11	39/03	23/1	23	22/2	25/96
12	29/9	29/6	24	20/25	23

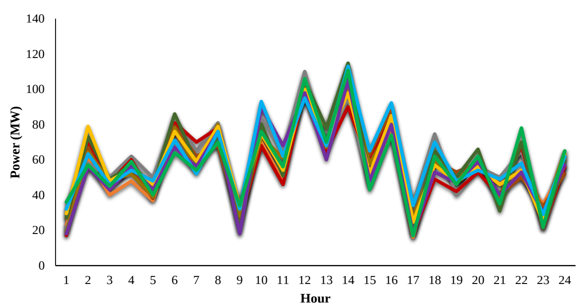

Fig. 4. Wind power scenarios.

to 10 most probable scenarios using SCENRED tool. The wind power generated in 10 reduction scenarios are depicted in Figure 4.

B. Simulation results

The robustness function is employed to cope with the price uncertainty in DAM. The parameter gamma (Γ) is used to control the level of robustness in the objective function as presented in Section 5. For evaluating the power price uncertainty under a conservative approach, Γ has been increased from zero to one with six steps. The guaranteed level of profit versus Γ is depicted in Figure 5. Observe from Figure 5 that the profit decreases for wider value of Γ. A wider range of Γ associated with a more conservative case in which wider value of forecasting error of electricity price is taken into account. According to Figure 5, when Γ is equaled to zero (stochastic optimization framework), the profit equals to $ 46163.841 which means not taking into account the variations of price. When Γ=1, which means the maximum conservative case, the profit equals to $ 42193. Actually, when Γ increases, the power price has been increased during the hours of power purchased to the grid, and has been decreased during the hour of selling electricity. This action results reducing the total profit.

Based on these outcomes, the robust profit of the coordinated system is reduced due to being robust versus uncertain the max potential of the system. Figure 6 also demonstrates corresponding resulting price profiles versus Γ coefficient.

The charging and discharging quantities of CAES facility and

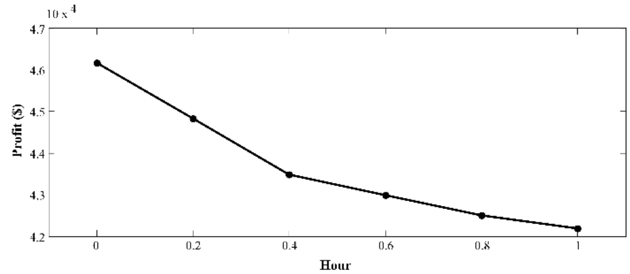

Fig. 5. Profit of DAM considering robust optimization method.

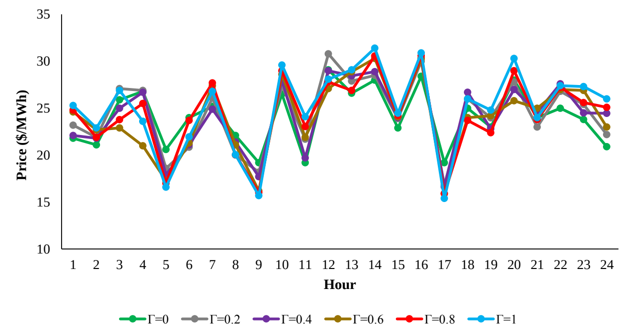

Fig. 6. Obtained price profile for each Γ quantity.

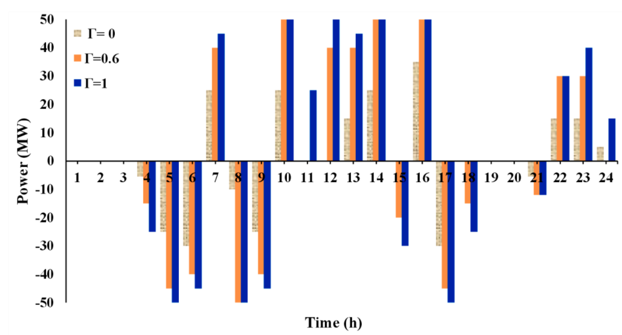

Fig. 7. The hourly CAES charging/discharging scheduling.

P2G are respectively represented in Figure 7 and 8. These figures illustrate the obtained scheduling for the three considered values of parameter Γ which depict various levels of risk and robustness in the solution. The produced power is displayed as a positive number and negative numbers show the power quantities to charge the storage at each hour. The system's operator purchases the power from the upstream grid at the off-peak hours and sells when the electricity price reaches higher value. As we observe, in the first sequence (Γ=0), the charge/discharge quantity have the lowest level compared to the higher robustness levels. For higher values, by selecting a more robust strategy, the power prices during selling hours are higher than other times. The performance of both storage devices is well visible at low-price periods, as well as high price hours.

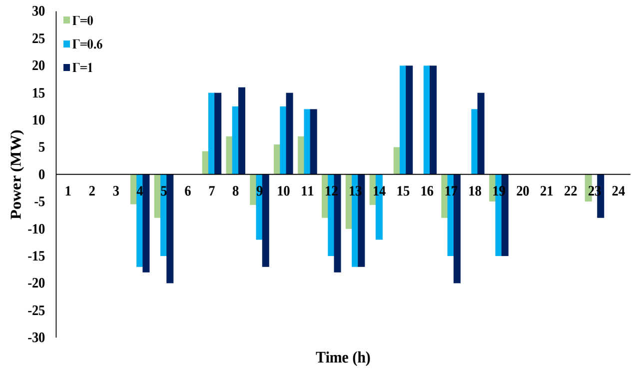

Fig. 8. The hourly P2G charging/discharging scheduling.

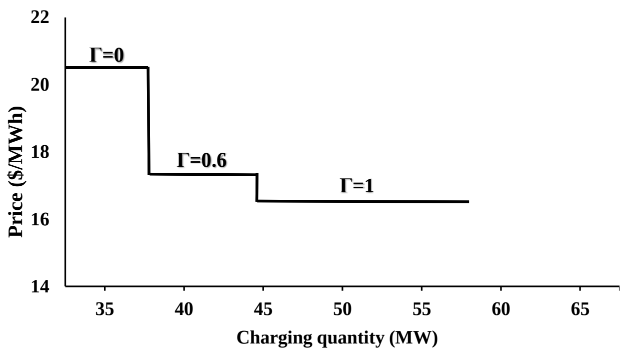

Fig. 9. Optimal bidding curve of the proposed system at time 5.

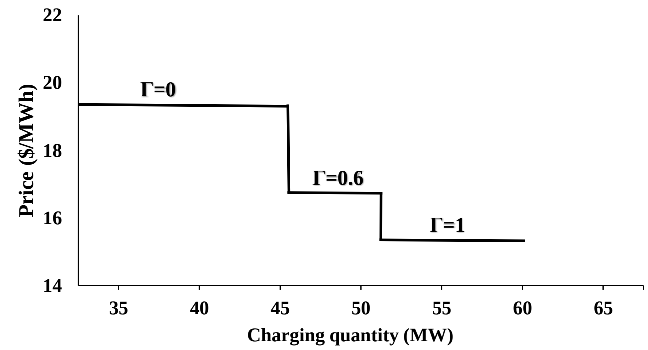

Fig. 10. Optimal bidding curve of the proposed system at time 9.

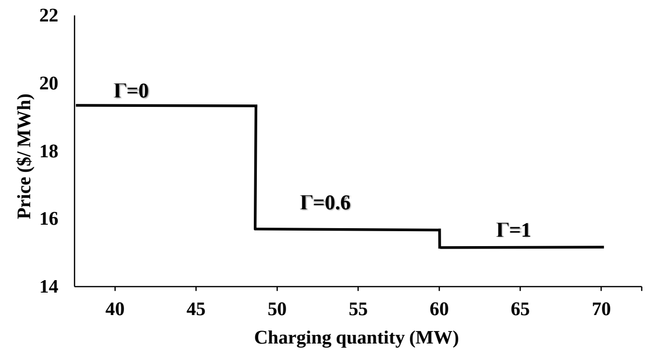

Fig. 11. Optimal bidding curve of the proposed system at time 17.

C. Bidding / offering curves

Basically, in order to construct bidding/ offering curves, some price and quantity power pair based on step-wise bidding/offering curves are assigned.

Obtained optimal bidding curves for times 5, 9, and 17 are illustrated in Figures 9-11, respectively for various gamma values. Respect to these figures, the required information for the test system is obtained to bid quantities for the DAM. Actually, bidding curves illustrate that the increasing of power price will decrease purchasing electricity from the upstream grid. In hour 5, as shown in Figure 9, in the first sequence, when Γ=0, the charging demand and resulted power price for the storage facilities (based on Figure 6) equal to (37 MW, 20.6 $/MWh). Therefore, these values are bided as the first step of the bidding curve. The charging power quantity and electricity price for the second step when Γ = 0.6, equals to (45MW, 17.3$/MWh), and the third step is obtained (58MW, 16.6 $/MWh), for Γ= 1.

Figure 10 indicates the bidding curve for hour 9. Based on this figure, when Γ is considered zero, storage devices are charging with 46MW and the power price is 19.2 $/MWh. The pair of charging power quantity and electricity price for second and third steps is obtained (52MW, 16.2$/MWh) for Γ=0.6, and (60MW, 15.7$/MWh) for Γ= 1.

The bidding curve for hour 17 is depicted in Figure 11. According to this figure, the storage system suggests 48 MW to the DAM for charging, and the corresponding price of the first step is 19.1 $/MWh. The pairs of charge power and electricity price for the second and third steps are (60MW, 15.9$/MWh) and (70MW, 15.4$/MWh) for Γ=0.6 and Γ=1, respectively. It should be noted that, by increasing the control parameter Γ in any step from zero to one, the obtained power to the DAM has been increased.

Figures 12-14 show the gained optimum offering curves for hours 10, 14, and 16 that provide discharging quantity blocks and offering power prices for different gamma values. According to Figure 12, which shows the offering curve for hour 10, the discharging quantity and electricity price of the first sequence considering Γ=0 is (115MW, 26.5$/MWh). The second pair of discharging power/electricity price is (132.5MW, 28.6$/MWh) which these values are obtained based on Γ= 0.6. The third step for hour 10, which Γ is fixing on 1, equals to (140MW, 29.6$/MWh). In fact, the discharged power value in Γ=1 is higher than other cases in order to cope with price uncertainty.

The offering curves and quantity/price blocks for hours 14 and 16 are obtained by the same way. Figure 13 shows offering curve at hour 14 and the determined amounts for the first, second and third sequence are (120MW, 28$/MWh), (150MW, 30.3$/MWh), and (165MW, 31.4$/MWh), respectively. Similarly, the offering curve in Figure 14, is related to hour 16 which its three steps includes (78MW, 28.4$/MWh), (95MW, 30.3$/MWh), and (109MW, 30.9$/MWh), for different gamma values.

As it can be seen, by increasing the uncertain parameter of Γ the bidding power for charging the storage systems is reduced, which means that being robust against the power price uncertainty. In the other word, increasing Γ value will result in more conservancy level. Besides, by increasing the value of Γ, the

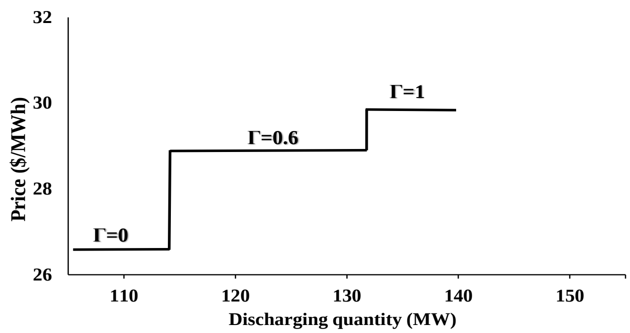

Fig. 12. Optimal offering curve of the proposed system at time 10.

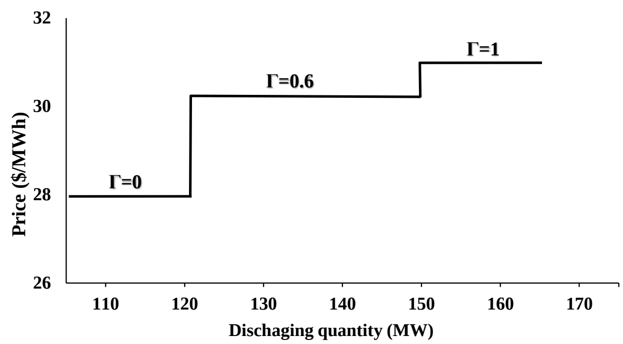

Fig. 13. Optimal offering curve of the proposed system at time 14.

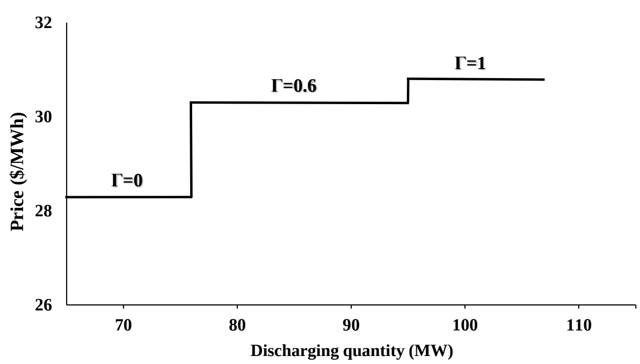

Fig. 14. Optimal offering curve of the proposed system at time 16.

coordinated storage system offer power at higher price to the market. Being charged in lower electricity prices and on the other hand being discharged in on-peak hours, maximum profit of the proposed coordinated system is obtained.

According to above descriptions, in order to verification of the result, the computational time, and daily profit of the proposed method for assumed system are compared with similar works, which is introduced in the Table 5.

By comparing the profit and computational time achieved in these realizations using the assumed hybrid method with similar works, it is deduced that applying the concept of hybrid stochastic-robust approach facilitates solving bidding/offering problem and finding how the coordination of storage devices can decrease the wind power curtailment and improves the owner's profit in presence of price uncertainty.

Table 5. Computational time of proposed paper and similar works

Similar works	[37]	[42]	[44]	Our work
Computational time(sec)	97	53	138	72
Profit ($)	4208	4116	4358	42193

7. CONCLUSION

This work suggests a novel mathematical model of the bidding strategy for a hybrid system including CAES, the P2G facility, and the wind farm based on a hybrid robust/ stochastic approach. The coordination of energy storage facilities with wind energy for participating in the day-ahead energy markets, was suggested as a promising option for developing the wind power uncertainty accommodation and making a substantial profit for the system's owner. The scenario-based stochastic method was used to handle the wind power uncertainty, while the day-ahead power price was captured by the ROA. For being robust against price uncertainty, the control parameter (Γ) takes any value in the interval [0, 1]. The following conclusions can be summarized from the numerical results:

- Integrating the hybrid system including CAES, P2G, and the wind farm improves the interdependency between electrical and gas markets, which helps the system operator's participation in both cases achieve more profits.
- Integrating the wind farm with large-scale bulk energy storage (CAES, P2G) using the hybrid robust/ stochastic approach reduces wind energy curtailment and increases the integration of the wind energy into the electrical system.
- With the increase of robust parameter (Γ) from 0 to 1, the total profit reduces. In other words, the operator chooses the high conservative level which results in profit reduction. Total profit equals to \$ 46163.841 when $(\Gamma = 0)$, while for the maximum conservative case $(\Gamma = 1)$ equals to \$ 42193. This means that being severely robust versus the system's uncertainty decreases by 8.5% of system's profit.
- The optimal bidding/offering curves for charging and discharge schemes of bulk energy storage systems and wind farms were obtained for different values of (Γ). By increasing (Γ), both bulk energy storage systems are charged more for the time period with lower prices and discharged more to participate in both natural gas and day-ahead electrical markets.

In future work, an integrated demand response program with the proposed bidding strategy of the hybrid system, as well as considering a comprehensive model of power and natural gas networks in the presence of the CAES, P2G, and wind energy can be considered.

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