Application of Small-Scale Compressed Air Energy Storage in the Daily Operation of an Active Distribution System

Mojtaba Jabbari Ghadi[1], Ali Azizivahed[1], Dillip Kumar Mishra[1], Li Li[1], *Jiangfeng* Zhang[1], Miadreza Shafie-khah[2], and João P. S. Catalão[3,*]

[1] *Dept. Electrical and Data Engineering, University of Technology Sydney, Sydney, Australia*
[2] *School of Technology and Innovations, University of Vaasa, Vaasa, Finland*
[3] *Faculty of Engineering of University of Porto and INESC TEC, Porto, Portugal*
* *catalao@fe.up.pt*

Abstract: While compressed air energy storage (CAES) has many applications in the field of generation and transmission power systems based on the state-of-the-art, this paper proposes the application of small-scale CAESs (SCAESs) in form of a storage aggregator in the daily operation of an active distribution system (ADS), joining the distribution system operator (DSO) for the participation in the day-ahead (DA) wholesale market. An innovative two-agent modelling approach is formulated. The first agent is responsible for aggregating SCAES units and the profit maximization of the aggregator is based on the distribution local marginal price. The DSO as the second agent receives the DA scheduling from the independent SCAES aggregator and is thus responsible for the secure operation of the ADS, utilizing solar and dispatchable distributed generation (DG) as well as purchasing power from the wholesale market. Linear programming is used for the formulation and optimization of the SCAES aggregator, while a bi-objective optimization algorithm (with the objectives of minimum operating cost as well as minimum power loss and emissions in different scenarios) is employed for DSO scheduling. The results show that the CAES aggregator can offer a considerable impact for power loss reduction, specifically, when diesel generators are not committed in the system operation (i.e., where emission has very low values between 10000-12000 kg). Additionally, the CAES aggregator could reduce the operation costs of the grid in a wide range of operations, even though for the scenario in which the CAES units are not under the control of the DSO anymore and also are scheduled to maximize their own profit. Moreover, results demonstrated that CAES units can be a significant voltage control device for a distribution grid with different objectives. Finally, some conclusions are duly drawn.

Keywords: Compressed air energy storage, Aggregator, Distribution system operator, Solar generation, Local marginal price.

1. Introduction

1.1 Motivation and Literature Review

Future power systems are anticipated to contain plugin electrical vehicles, wind, solar, and other interconnected micro energy grids [1, 2]. This growing integration of distributed renewable sources has caused considerable uncertainties to distribution networks. The role of energy storage units can mitigate the uncertainties in such situations. Energy storage systems as an essential part of power systems help grid operators to maintain the continuous power supply and improve the system reliability [3].

There exist a variety of energy storage units with different levels of maturity. Presently, the most-used kind of energy storage is pumped-storage hydropower (PSH). PSHs can be constructed cheaper, especially for the storage of very large capacity in comparison to other types of energy storage [4]. However, establishing a PSH storage takes typically 3-5 years which is not acceptable considering the current fast growth of electric power systems. Besides, large-scale battery storage units are another promising technology for the operation of electric power systems [5].

The battery storage units are utilized mainly for ancillary services or to support the large-scale wind and solar integration, by the provision of frequency regulation, grid stabilization as well as solar and wind power smoothing. It is noteworthy that the high investment cost is one of the most highlighted issues related to the employment of battery storage technology. Shorter life cycle compared to other storage technologies is another noticeable deficiency of battery storage.

Over the past decades, a variety of diverse methods to realize compressed air energy storages (CAESs) have been undertaken. CAES units are demonstrated to be a practical solution to store power produced by solar, wind, or other renewable energy units. The ability of storing a huge quantity of energy in the form of compressed air is one of the most beneficial features of these CAESs [6, 7]. Fast response, low maintenance costs, longer life cycle, no need to dispose chemical wastes are among other advantages of CAESs. These factors have attracted significant attention of researchers for the employment of this technology.

CAESs have been utilized for different proposes in power systems. In the case of large-scale CAESs, authors in [8] propose a coordinated bidding strategy for a hybrid power plant (including a commercial CAES and a wind aggregator) to participate in day-ahead, balancing intraday electricity markets. A similar study considering conditional value-at-risk to manage the financial risk in different scenarios of financial risk levels is presented in [9] while a gas turbine in the form of a simple cycle operation mode is added to the CAES.

In [10], operation strategy of a merchant CAES is formulated to reach optimal offering and bidding strategies for selling and purchasing the electricity, so that the risks related to errors of the price forecast can be controlled using information gap theory. Moreover, the proposed methodology is utilized to make separate hourly curves for bidding and offering.

Ref. [11] presents a robust adaptive technique for a wind power producer jointed with a CAES system to optimally schedule the participation of coupled aggregator in the electricity market. The uncertainties associated with wind power and price forecasts are modelled using robust optimization.

Large-scale CAES systems have been also employed in [12], as an energy storage technology for energy hubs [13], transmission capacity/cost issues [14], day-ahead energy markets [15], considering wind power [16], demand response [17], and price arbitrage [18].

Along with the decentralization of electric power systems as well as restructuring energy markets during recent decades, the involvement of small-scale renewable energy sources and storage units has been growing significantly. Therefore, integration of small-scale CAESs (SCAESs) has found considerable attentions for the applications in active distribution systems (ADSs) and microgrids.

However, the utilization of a small-scale CAES imposes a cost (mainly an investment cost) for the grid operator, the costs of re-dispatching, the curtailment costs of renewable energies, as well as the costs to import electricity from upstream grids are reduced. In fact, in addition to potential applications of CAES for distribution grid in the case of future restructured ancillary markets (i.e., primary and secondary frequency and reserve markets), this type of storage system can offer affordable solutions to manage the uncertainty of distribution grids with high penetration of renewable energies. In other words, distribution-size CAESs can provide continuous reactive power support all day long, unlike on-load tap changers or shunt capacitors whose voltage regulation strategy is discrete and suffers from a very low switching frequency [19]. Besides, there are a number of potential applications for the management of micro-grids, specifically when operating in islanding mode.

In this regard, some papers have used CAES to manage the uncertainties of renewable energies. To this end, an energy conversion system including compressed air and wind power is presented in [20] which can provide both distributed storage and energy provision for microgrids. Employing mixed-integer linear programming, the optimal wind power capacity, storage capacity, and transmission line capacity to the microgrid are calculated. In other words, capabilities of CAES are included to configure an expansion planning for a microgrid.

In [21], a novel model of low-emission microgrid is proposed in which CAES units are utilized due to their high overall efficiency and flexibility. A similar study is accomplished in [22] so that the system operator tends to minimize costs of carbon emission and grid operation through utilization of an energy hub model of CAESs integrated with a multi-energy distribution grid. The authors construct a hub of energy which includes a 13-node district heating network and a 13-bus power distribution grid. In fact, low-carbon economic dispatch is modelled to reach some optimal operating points for an energy hub in the distribution level.

Authors in [23] use CAES units to tackle uncertainties of wind power. Besides, the CAES is introduced as an alternative to manage the commitment of expensive diesel generators in the distribution system. A mixed-integer programming model and GAMS software are used to minimize the operation cost and wind curtailment of the grid. Ref. [24] deploys CASE to manage power imbalance of a microgrid including micro-turbines and renewable energy sources. The proposed methodology minimizes the total power loss, voltage deviation, emission, and operation costs during the operating period. Multi-objective grey wolf algorithm is applied for optimization task.

In [25], authors for the first time look at the potential applications of using microgrid-scale CAESs as the back-up devices. As a novel approach, detailed dynamic modelling of CAES is employed for technical analysis of case studies. Then, potential benefits evaluation of the CAES for energy and back-up management is presented.

In [26], electrical-thermal design of the distribution-size CAES coupled with a packed-bed heat exchanger is modelled in the ADS operation, where CAES unit as an efficient energy storage would surpass existing shortages of battery storage systems. The conversion rates (electrical-to-thermal and thermal-to-electrical) have been calculated for the CAES operation accurately. The paper proposed two new conversion rates for distribution grid-size CAESs. Furthermore, an electric vehicle charging station (EVCS) as an alternative energy storage technology is optimally coordinated with the operation strategy of the SCAES in ADSs. To model the behaviours of the EVCS, Gaussian Copula probability distribution function is employed which makes EVCS simulation more realistic.

In a similar work, an optimal operation of the ADS is addressed by [27] in which a private renewable-based microgrid is modelled using a stochastic bi-level programming technique for the joint scheduling energy and reserve power. Additionally, two scenarios of having small-scale CAES and parking lots of electric vehicles are considered in this paper. Although a new outline is presented for the participation of the system's independent players in separate electricity markets, the operation of the grid is under the responsibility of DSO.

In [28], a two-stage optimization planning-scheduling model is proposed for microgrid in which the CAES model is utilized to deal with wind power uncertainties. To this end, preventive maintenance is employed to prevent wind power random failure based on a risk aversion model. A two-objective planning model is developed in the first stage by authors, that including voltage deviation and power loss of the grid which determines the optimal size and location of wind generation units. Then, in the second stage, a stochastic scheduling technique is presented to balance power exchange costs of MG, charging/discharging power of CAES, outputs of DG units.

Another multi-objective optimization approach is adopted in [29] to reach the optimum exergy efficiency and investment cost for a combined system including solar energy, CAES, and a combined cooling, heating and power unit. During the off-peak period, the presented configuration stores the electric power surplus of the gas turbine while it is released during on-peak time. In [30], quick start-up time and high ramp rate abilities of the SCAES are employed. SCAES is used in [31] for frequency control, jointly with wind power in [32].

1.2 Contributions

As it can be inferred from the literature review, CAES storage units in the distribution level are conventionally operated as an asset of the distribution system operator (DSO). However, this consideration is not valid anymore along with restructuring distribution markets in which private sectors tend to invest and operate renewable sources and energy storage units based on financial factors independent of network security. However, the DSO is allowed to constrain generation and storage units to maintain the safe operation of ADSs. This point elaborates the critical issue with a large number of previous studies that evolving structure of energy markets, specifically in distribution and retail levels, are not under monopoly of the DSOs. On the other side, private investors would not intend to participate in the current the markets that their profit will be determined by scheduling provided by DSOs. To solve the mentioned deficiencies, the authors propose presented two-stage scheduling of the ADSs. In this framework, owners of CAES units aim to maximize their profit only subject to the security of the grid operation. To this end, a novel structure of market operation is proposed in this paper in which, an aggregator is developed for privately owned CAES units. Noteworthy that the scheduling of aggregator is not constrained to the financial benefits of grid operator anymore which means, based on the price received from the DSO, the CAES aggregator schedules storage units to reach maximum profit for CAES owners. Then, the DSO as the second agent needs to maintain the security of the grid by coordinating CAES aggregator schedules and the power provision from grid assets (i.e., power generation of renewable sources, diesel units and power needed to be purchased from the day-ahead market).

Therefore, the novel contributions are the following:

- Proposing a two-agent methodology aimed at the operation of distribution systems applicable for restructured distribution power markets which consider private owners of storage units in form of a storage aggregator; This structure has been proposed for the first time in the distribution grid considering a novel restructured distribution market.
- Linearizing the formulated profit maximization problem for the CAES aggregator and solving it using a linear optimization toolbox for the two-stage day-ahead scheduling of distribution-grid assets;

- Optimizing the operation of the grid considering the scheduling of CAES aggregator, aiming at the concurrent minimization of emissions and power losses using multi-objective optimization approaches which is a combination of heuristic methods and linear programming.

The rest of the paper is planned as follows. Section 0 presents the aggregated configuration of the proposed structure. A mathematical formulation of this structure is detailed in Section 0. A solution methodology is described in Section 0. Case study and results are provided in Section 0. Finally, the paper is concluded in Section 0.

2. System Configuration

The aggregated configuration and power/data exchange of the units for the aimed methodology is provided in Fig. 1.

Fig. 1: A structure of the proposed ADS configuration.

As can be seen, SCAES units are not under the operation of the DSO anymore and have been aggregated. The reason behind such an aggregation is that the small-scale distributed generation and energy storage units in most of the countries are not permitted to partake in the electricity market based on regulations and policy of markets [33]. Hence, the aggregation of storage units is an obligatory decision. In such a situation, two different structures can be considered for the participation of CAES aggregator.

First, the aggregator can participate in the day-ahead market individually and separate from DSO to enjoy the profit earned from price arbitrage in the market. However, there always exists some risks for the aggregator due to fluctuations and uncertainties of the energy price. Consequently, CAES owners may take a part of the faced risks. Second, the DSO participates in the market, and certain values of distribution local marginal price (DLMP) for different buses in different hours are sent to the CAES aggregator. This hourly DLMP (i.e., received from DSO) is normally lower than the market price. In the second framework, the benefit of aggregator will be a share of CAES owners' profit (i.e., determined with a bilateral contract with the owner).

This paper follows the second structure in which no risk is considered for aggregator and CAES owners. In both structures, scheduling of CAESs is needed to be sent to the DSO. After receiving the schedule from the aggregator, DSO needs to optimally schedule the power generation of diesel units and power purchase from the day-ahead market to satisfy its own objectives considering the grid load demand and power forecast of solar units. Besides, the secure operation of the distribution system is a non-compromising issue for DSO, which is subject to grid constraints. In this paper, it is assumed that solar units are non-dispatchable. Noteworthy, the distributed model of ADS is used for the power flow simulation.

3. Problem Formulation

In this section, the mathematical formulations for DSO objectives, CAES aggregator modeling, and operational constraints are provided.

3.1 Objective functions

$$Opt\{Objective\} = [\min f_1 \ , \min f_2 \ , \min f_3 \ ] \tag{1}$$

$$f_1 = Em = F^e \sum_{i=1}^{N_{DG}} \sum_{t=1}^{N_T} \left(a_i^{DG} P_{i,No}^{DG} + b_i^{DG} P_{i,t}^{DG}\right) U_{i,t} \tag{2}$$

$$f_2 = P^{Loss} = \sum_{t=1}^{N_T} \sum_{l=1}^{N_{Bus}} \sum_{m>l}^{N_{Bus}} G_{l,m} \begin{bmatrix} V_{l,t}^2 + V_{m,t}^2 - \\ 2V_{l,t} V_{m,t} cos\left(\delta_{l,t} - \delta_{m,t}\right) \end{bmatrix} \tag{3}$$

$$f_3 = OC^G = \sum_{t=1}^{N_T} P_t^{GRI} \, \pi_t^{Mar} + \pi^f \sum_{i=1}^{N_{DG}} \sum_{t=1}^{N_T} \left(a_i^{DG} P_{i,No}^{DG} + b_i^{DG} P_{i,t}^{DG}\right) U_{i,t} \tag{4}$$

In this paper, three objectives are considered for DSO. The first one is to minimize the emissions produced by diesel generators in (2) [34]. a_i^{DG} and b_i^{DG} are the fuel consumption coefficients of diesel unit i, $P_{i,No}^{DG}$ is the nominal capacity of diesel unit i, $P_{i,t}^{DG}$ is power generation of diesel unit i at time t, F^e is the fuel-to-emission conversion rate, and $U_{i,t}$ refers to the ON/OFF status of diesel units. The second objective is to minimize the total active power loss of the distribution network in (3) [35]. $G_{l,m}$ is the branch conductance between l^{th} and m^{th} buses, $V_{l,t}$ and $\delta_{l,t}$ refer to the magnitude and phase angle of the voltage of l^{th} node at time t, respectively. The third objective is to minimize operating cost of the grid OC^G which includes the cost of buying power P_t^{GRI} from the day-ahead energy market and the fuel cost of running diesel units. Parameters π_t^{Mar} and π^f are the energy price in the day-ahead market and the fuel price, respectively. The operating and maintenance cost of diesel units are not considered in this paper.

3.2 CAES aggregator formulation

$$V_{j,t}^{CAE,Inj} = a_j^{Inj} P_{j,t}^{CAE,Inj} \qquad \forall t, \forall j \quad (5)$$

$$V_{j,min}^{CAE,Inj} U_{j,t}^{CAE,Inj} \le V_{j,t}^{CAE,Inj} \le V_{j,max}^{CAE,Inj} U_{j,t}^{CAE,Inj} \qquad \forall t, \forall j \quad (6)$$

$$P_{j,t}^{CAE,Dis} = a_j^{Dis} V_{j,t}^{CAE,Dis} \qquad \forall t, \forall j \quad (7)$$

$$V_{j,min}^{CAE,Dis} U_{j,t}^{CAE,Dis} \le V_{j,t}^{CAE,Dis} \le V_{j.max}^{CAE,Dis} U_{j,t}^{CAE,Dis} \qquad \forall t, \forall j \quad (8)$$

$$U_{j,t}^{CAE,Inj} + U_{j,t}^{CAE,Dis} \le 1 \qquad \forall t, \forall j \quad (9)$$

$$S_{j,0}^{CAE} = S_{j,N_T}^{CAE} = S_{j,ini} \qquad \forall j \quad (10)$$

$$S_{j,min}^{CAE} \le S_{j,t}^{CAE} \le S_{j,max}^{CAE} \qquad \forall t, \forall j \quad (11)$$

$$S_{j,t+1}^{CAE} = S_{j,t}^{CAE} + V_{j,t}^{CAE,Inj} - V_{j,t}^{CAE,Dis} \qquad \forall t, \forall j \quad (12)$$

$$P_t^{ACE} = \sum_{j=1}^{N_{CAE}} P_{j,t}^{CAE,Dis} - P_{j,t}^{CAE,Inj} \qquad \forall t \quad (13)$$

$$OC_t^{CAE} = \sum_{j=1}^{N_{CAE}} P_{j,t}^{CAE,Inj} VOM_{j,t}^{CAE,Inj} + P_{j,t}^{CAE,Dis}\left(HR_j^{CAE,Dis} H_{NG} + VOM_{j,t}^{CAE,Dis}\right) \qquad \forall t, \forall j \quad (14)$$

$$\max Rev^{ACE} = \sum_{t=1}^{N_T} (P_t^{ACE} \pi_t^{DLP} - OC_t^{CAE}) \quad (15)$$

In the case of presented SCAES, two operation phases of air injection Inj and power discharge Dis are considered. To this end, the stored energy $V_{j,t}^{CAE,Inj}$ in the storage tank of CAES j at time t is formulated by (5); where a_j^{Inj} is the charging energy conversion rate and $P_{j,t}^{CAE,Inj}$ is the active power consumed to charge CAES. The amount of hourly energy storage as defined in (6) is limited to the minimum $V_{j,min}^{CAE,Inj}$ and maximum $V_{j,max}^{CAE,Inj}$ hourly storage capacities; where $U_{j,t}^{CAE,Inj}$ is a binary indicator of injection operation mode. The power produced during the discharging mode of the CAES $P_{j,t}^{CAE,Dis}$ as a function of discharging energy conversion rate a_j^{Dis} and required stored energy $V_{j,t}^{CAE,Dis}$ is calculated in (7).

As indicated in (8), this required energy during discharge mode is limited to the minimum value $V_{j,min}^{CAE,Dis}$ and maximum value $V_{j.max}^{CAE,Dis}$ due to physical limitations of conversion systems; where $U_{j,t}^{CAE,Dis}$ is the binary indicator of discharging mode of the CAES. Obviously, a CAES unit can be operated in only one of the states of idle, charging, or discharging mode during each time step in (9). Besides, the energy stored in the storage tank of CAES at the first hour of scheduling $S_{j,ini}$ and at the last hour S_{j,N_T}^{CAE} should be equal; and they are set to the predefined value $S_{j,0}^{CAE}$ by (10).

Eq. (11) defines the minimum $S_{j,min}^{CAE}$ and maximum $S_{j,max}^{CAE}$ air storage capacities of the jth CAES. The variation of stored energy level in the CAES tank as the result of charging/discharging is given in (12). While the formulations (2)-(12) model each of the SCAESs, the total power available P_t^{ACE} for CAES aggregator ACE as a sum of charging/discharging power of CAESs is calculated by (13). The operation cost of a CAES unit OC_t^{CAE} is given in (14) where $VOM_{j,t}^{CAE,Inj}$ and $VOM_{j,t}^{CAE,Dis}$ are the variable operating costs of a CAES during injection and discharge modes, respectively. Considering a gas turbine in discharging procedure as simple cycle mode of CAES, $HR_j^{CAE,Dis}$ refers to fuel heat rate for discharging phase of CAES and H_{NG} is the price of natural gas.

However, considering the small scale and the lack of gas turbine in the presented CAES units, the operating cost of these units is neglected in this study. Therefore, maximizing the revenue of the aggregator Rev^{ACE} is formulated as the sum of hourly profits/costs, which is obtained from selling/purchasing power to/from DSO P_t^{ACE} at the local energy price π_t^{DLP}.

It is assumed that the energy conversion rates for charge and discharge procedures are considered to be a fixed value and $a_j^{Inj} = a_j^{Dis} = 0.85$. Noteworthy, this value is lower than that for large-scale CAESs due to lower thermal efficiency of the heat exchanger in SCAESs.

3.3 Distribution power flow equations:

$$P_l = \sum_{m=1}^{N_{Bus}} V_l V_m Y_{l,m} \cos(\Theta_{l,m} - \delta_l + \delta_m) \tag{16}$$

$$Q_l = -\sum_{m=1}^{N_{Bus}} V_l V_m Y_{l,m} \sin(\Theta_{l,m} - \delta_l + \delta_m) \tag{17}$$

Power flow equations for active and reactive powers are defined in (16) and (17); where P_l and Q_l are the injected active and reactive powers at the l^{th} node. V_l and δ_l are the amplitude and angle of voltage at l^{th} node. $Y_{l,m}$ and $\Theta_{l,m}$ are the amplitude and angle of the $(l,m)^{th}$ entry of bus admittance matrix.

3.4 Operating constraints

1) Bus voltage limit:

$$V_{min} \leq V_i \leq V_{max} \tag{18}$$

The voltage of buses should be limited within the operating range $[V_{min}, V_{max}]$; where V_{min} and V_{max} are the minimum and maximum acceptable voltage value of the i^{th} node, and V_i is the voltage magnitude of the i^{th} node.

2) Distribution line limits:

$$\left|P_{ij}^{line}\right| \leq P_{ij,Max}^{line} \tag{19}$$

Eq. (19) limits the power flow of transmission lines P_{ij}^{line} due to thermal capacity of branches; where $P_{ij,Max}^{line}$ is the maximum power transmitted between nodes i and j.

3) Power balance constraints:

$$\sum_{i=1}^{N_{DG}} P_{i,t}^{DG} + \sum_{p=1}^{N_{PV}} P_{i,t}^{PV} + P_t^{ACE} + P_t^{GRI} = P_t^{Dem} + P_t^{Loss} \quad \forall t \tag{20}$$

The power generation-demand balance of the grid is given by (20); where $P_{i,t}^{DG}$ is the power generation of diesel DGs, $P_{i,t}^{PV}$ is the power generation of solar units, and P_t^{Dem} is the hourly load demand of the grid.

4) DG resources modeling:

In general, DG units in the distribution network are modelled as PV and PQ nodes [36]. Considering DGs as PV model, they can produce reactive power while keeping the voltage amplitudes inside an acceptable range. In this paper, the PQ model is adopted to formulate DGs in the grid.

4. Solution Approach

The flowchart for the solution methodology proposed in this paper is depicted in Fig. 2. As aforementioned, the presented problem is divided into two sub-problems. The first part should be solved by CAES aggregator, which is an optimization problem to maximize the profit of each CAES unit based on DLMP received by DSO. Because the formulations in this part have been linearized, it can be easily solved by an available linear programming toolbox. In this paper, *linprog* package of the Matlab software is used to solve this sub-problem.

After determination of the scheduling for CAES units, the power generation of diesel units as well as the power needed to be purchased from the day-ahead market should be scheduled by DSO in the second sub-problem. In this regard, the bi-objective *swarm robotics search & rescue (SRSR)* optimization algorithm is used to optimize the financial or operational objective functions for DSO. The number of function evaluations (as the stopping criterion) and initial solutions are 10000 and 100, respectively. The number of solutions in Pareto front is limited to 50. While first three controlling parameters (i.e., movement factor, Sigma factor, and Sigma limit) of the algorithm are tuned automatically, and the last controlling parameter (i.e., Mu factor) is considered to be 0.7.

5. Results and Discussion

In this study, simultaneous scheduling of a CAES aggregator as well as generating units of the DSO is investigated. The IEEE 33-bus network (Fig. 3) is considered as a case study [37]. It is assumed that the locations of storage and generating units are predefined as the current problem is operation scheduling. The power generation of solar units located at buses 10, 18, 26, 32 is detailed in Fig. 4.

The hourly active and reactive power demands of the distribution network are portrayed in Fig. 5 and Fig. 6, respectively. The specification of CAES and diesel units are detailed in Table 1 and Table 2, respectively. In this paper, four scenarios with different operating objectives are considered as follows.

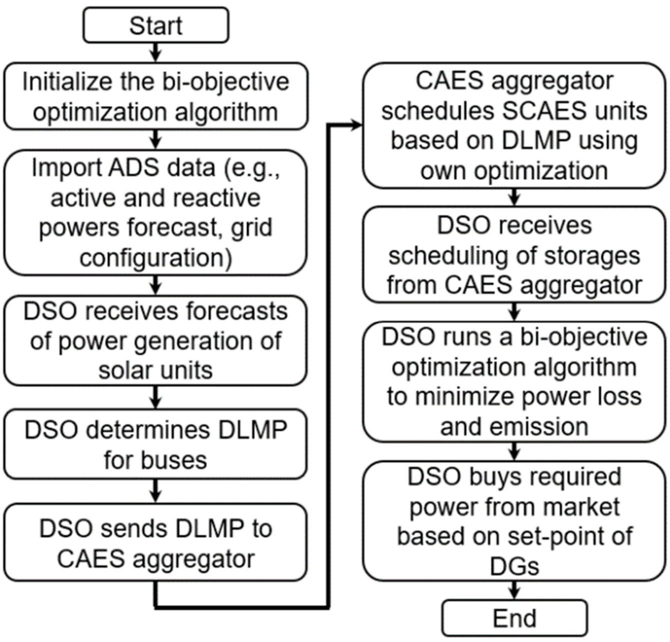

Fig. 2: The flowchart of the aimed methodology.

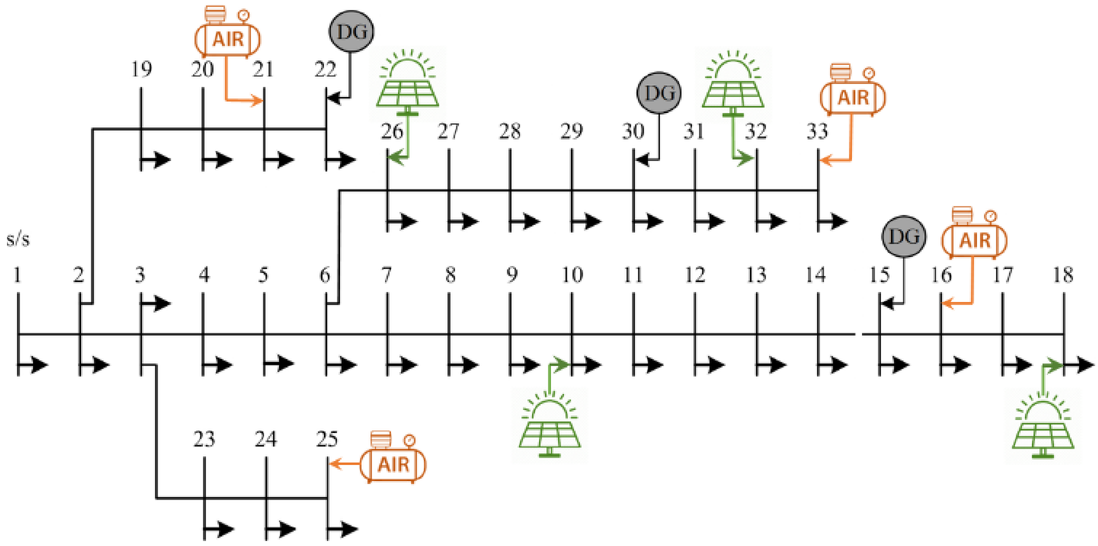

Fig. 3: Configuration of the IEEE 33-bus test system.

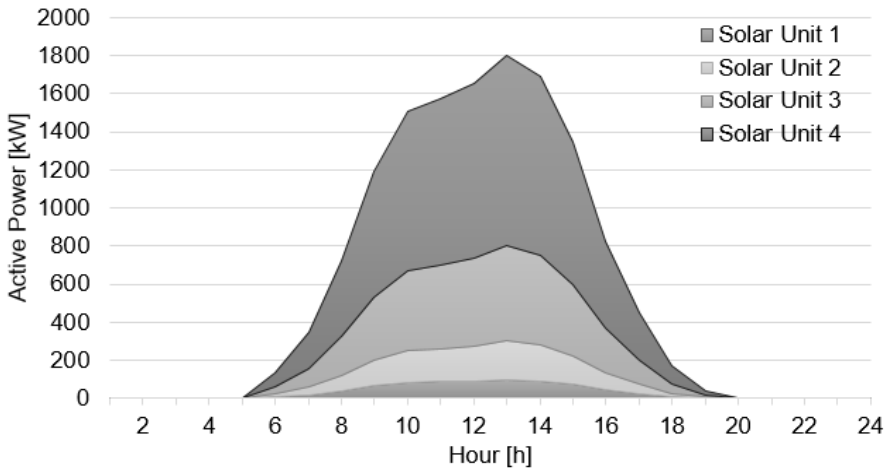

Fig. 4: Power generation of solar units.

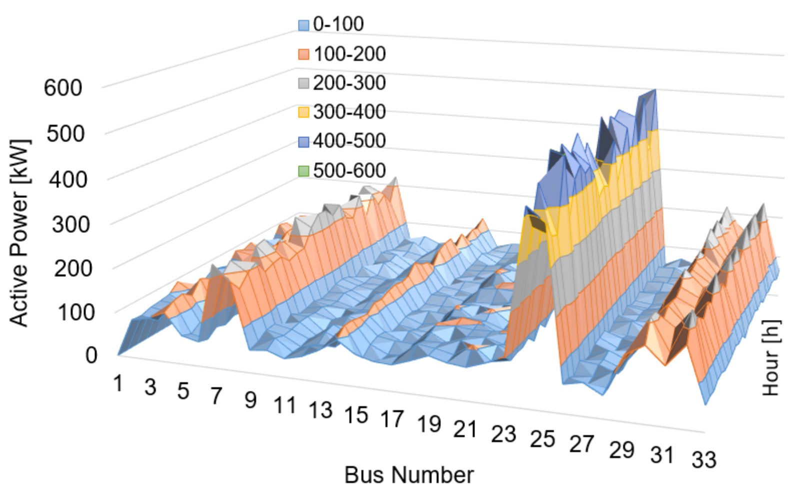

Fig. 5: Active load demand of the grid for a 24h scheduling.

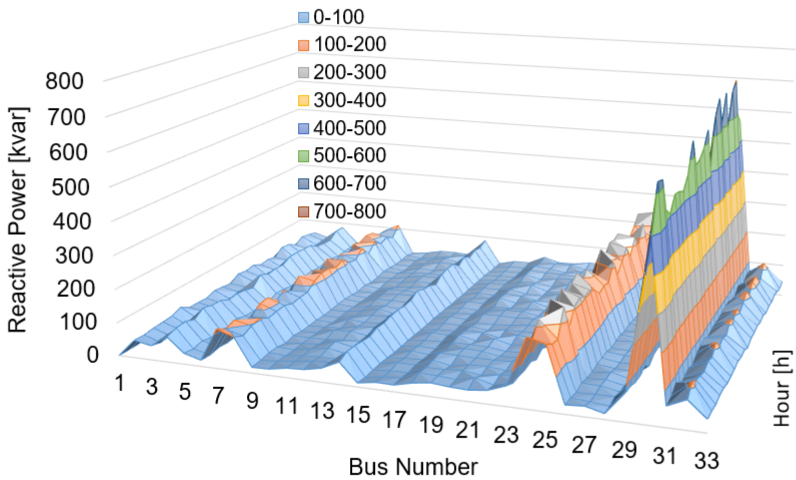

Fig. 6: Reactive load demand of the grid for a 24h scheduling.

Table 1: Specification data for CAES units

	Location [Bus]	Max & Min capacity [kWh]	Initial state [kWh]	Cha/Dis ramp rate [kWh]	Conversion rate
Unit 1	16	750 & 75	75	400	0.85
Unit 2	21	450 & 45	225	250	0.85
Unit 3	25	800 & 80	160	400	0.85
Unit 4	33	550 & 55	165	250	0.85

Table 2: Specification data for diesel units

	Location [Bus]	Max & Min power [kW]	Power factor	a & b fuel consumption factors [L/kWh]	CO_2 emission factor [kg/L]
Unit 1	15	550 &100	0.9	0.116 & 0.08145	2.68
Unit 2	22	800 &150	0.9	0.111 & 0.07932	2.68
Unit 3	30	1000 & 200	0.9	0.107 & 0.07764	2.68

5.1 Scenario 1: Base case

This scenario is to investigate the status of the grid without considering power generation (renewable and conventional) or storage units. In this scenario, the total 24h active power of the grid is 5055.9 kW. Contour and histogram diagrams for voltage profile of the grid and are depicted in Fig. 7.

As can be seen, some of the buses (e.g., 7-18 and 27-33) are located deep voltage point of the grid; where their voltage value violates the acceptable limit [0.95-1.05 p.u.]. Noteworthy, some markets consider 0.9 p.u. as the lower boundary of this acceptable limit and increasing voltage profile regarded as a power quality factor is provided in the ancillary service market.

From the histogram, it is obvious voltage profile of the grid violates the permitted range of [0.95-1.05 p.u.] that more than 450 hours. It should be mentioned that this constraint is valid for the following scenarios, and the algorithm is not permitted to have any voltage violation even if there is a more optimal solution in the case of other objective functions. This means the algorithm, in addition to guaranty acceptable values of the objective functions in different scenarios for CAES aggregator, should offer the system security incorporation with the DSO as a factor for social welfare by shifting the voltage profiles up to 1.05 p.u.

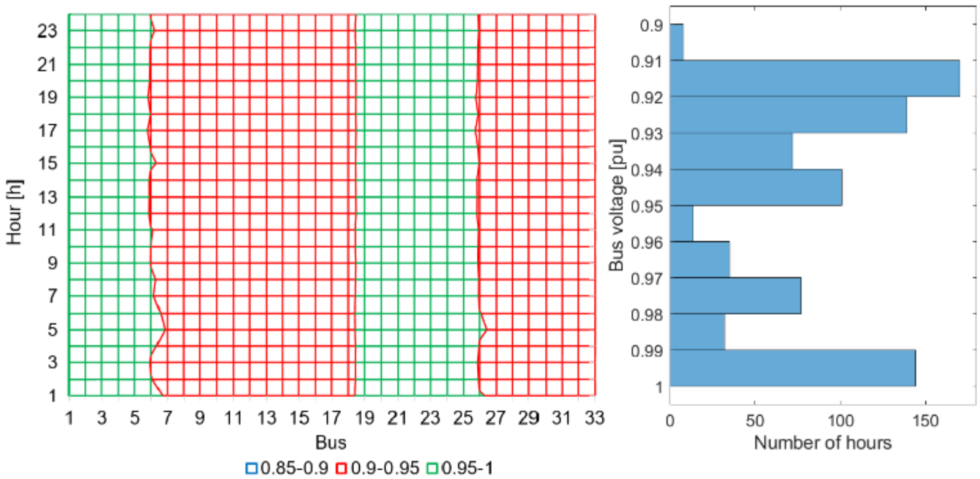

Fig. 7: 24h voltage profile of grid before allocation of DGs and storage units.

5.2 Scenario 2: Emission & Power loss objectives

In the second scenario, two objectives of emission and power loss have been considered for DSO optimization. CO_2 emission per unit of diesel fuel consumption is 2.68 kg [34]. In order to evaluate the impact of CAES aggregator, two sub-scenarios with and without the presence of CAES aggregator are presented. The set of optimal solutions for both cases are shown in Fig. 8.

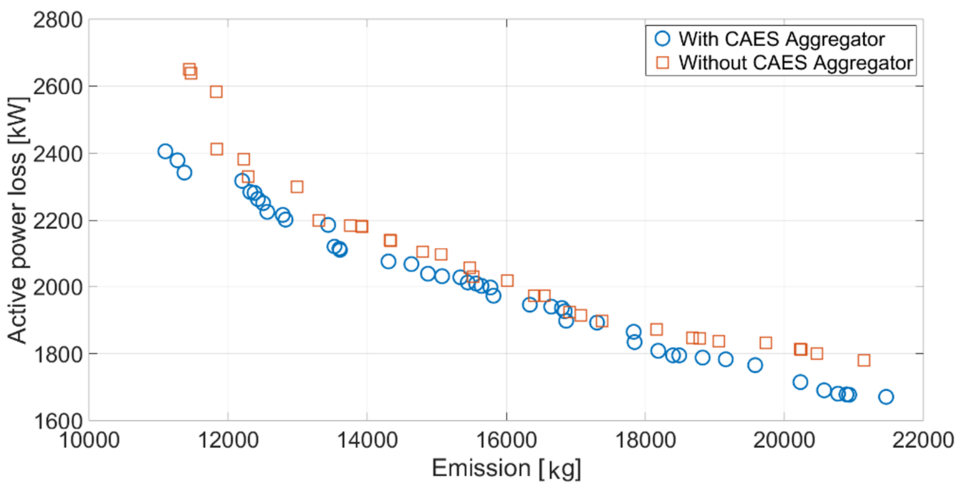

Fig. 8: Bi-objective optimum 24h operation of the grid considering emission and power loss as objective functions (Scenario 2).

As can be seen, an increment in the involvement level of diesel generators results in a reduction of total power loss of the grid; because a major part of local loads can be supplied locally and there is no need to be supplied from the upstream grid. Noteworthy, separate from the operating cost of diesel generators, diesel units should commit in the daily operation to increase voltage profile of the buses during the hours in which solar units cannot supply power due to lack of sun irradiation, even though the operating costs of these diesel generators are highly more than the cost of importing power from the upstream grid. In other words, diesel generators play the role of security guarantee devices. As a result, the share of expensive diesel generators and their corresponding emission is mainly determined by the voltage profile of the grid. As long as the voltage value reaches the permitted limit [0.9-1.05 p.u.] on the buses with voltage drop, the rest of the power is supplied with the upstream grid. Worthy of mentioning that an increase in supply from the upstream grid may increase the voltage drop on ending buses of long feeders, which should be compensated by diesel generators accordingly.

For the second sub-scenario in which the storage aggregator is committed, as can be seen, presence of CAES units could provide a considerable improvement in both terms of emission and active power losses. Evidently, to the amount of emission is directly correlated with amount of generation buy the diesel generators. Therefore, solutions on the left hand-side of the figure are representing lower contributions of diesel generators (i.e., where emission has very low values between 10000-12000 kg). Respect to these solutions, it can be deduced that adding CAES aggregators has a higher impact to decrease power losses; especially when diesel generators are not involved in the operation of the system.

The DLMP determined by DSO considering the CAES aggregator's participation in the grid operation is shown in Fig. 9.

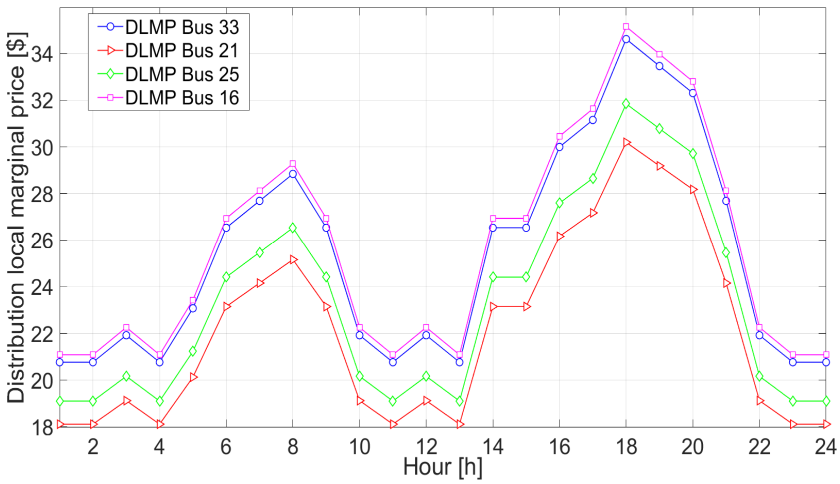

Fig. 9: Distributed marginal price of buses.

It can be deduced that the buses located at the end side have higher DLMP values. Such an approach is adopted by DSO because generators and storage units located at the proximity to the substation have fewer effects on the voltage profile regulation and power loss reduction. Optimal scheduling of the storage units obtained by the CAES aggregator is depicted in Fig. 10.

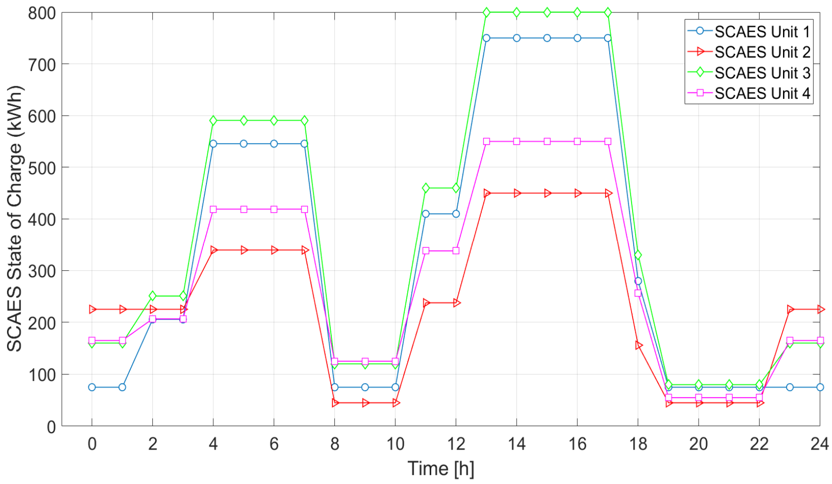

Fig. 10: Energy variations of SCAESs during 24h scheduling

Evidently, the aggregator exploits peaks of the DLMP price to maximize the total profit of CAES owners; and that is the reason charging/discharging pattern of the CAES units follows that of DLMP.

5.3 Scenario 3: Emission & Operating costs objectives

This scenario considers CO_2 emission and operating costs of the grid as the objective functions. Noteworthy, simultaneous minimization of both objectives is a contradictive issue in this scenario; because less usage of diesel units to minimize the emission leads the grid towards more drops on the voltage profile of the network due to more power supply from the upstream grid. On the other hand, the price of energy during the hours in the middle of the day is higher than the cost of running diesel units. Therefore, it necessitates a compromise to reach an optimal schedule of fuel-based units and power purchased from the upstream grid. In this study, the fuel price for diesel units is 0.999 $/L. Fig. 11 shows the set of solutions of the given bi-objective optimization problem with the same sub-scenarios of with/without CAES aggregator.

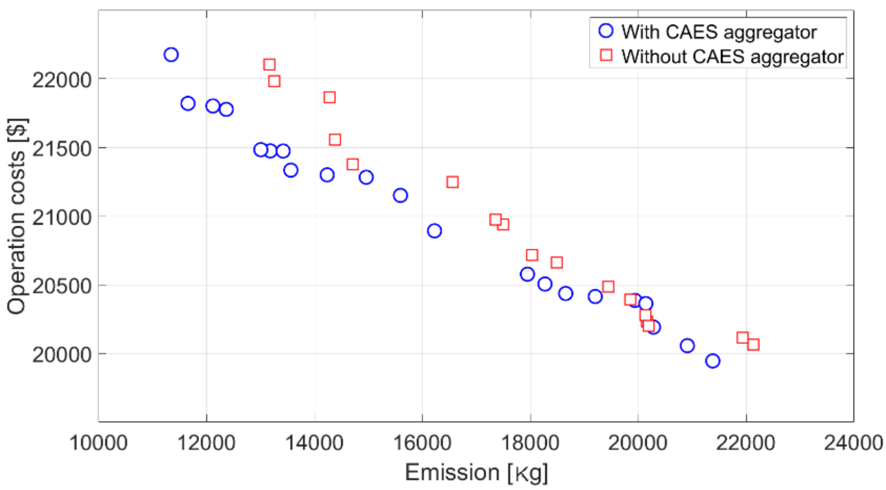

Fig. 11: Bi-objective optimum 24h operation of the grid considering emission and power loss as objective functions (Scenario 3).

It can be seen that CAES aggregator could reduce the cost of operation in a wide range of operation; even though the CAES units are not under control of the DSO anymore and also are scheduled to maximize their own profit. Moreover, it can be seen that considering the same configuration, operating points with lower emission values are available when involving the CAES aggregator. It demonstrates that even having the conflicting objectives of DSO (i.e., to minimize operating costs) and CAES aggregator (i.e., to maximize its own profit), DSO benefits from the private operation of CAES units. Additionally, for the operating points with the least operational costs (e.g., around 20000$), less CO_2 emission means fewer operating hours of diesel units and more utilization of CAESs units. Hence, the extended life cycle is expected for diesel units while CAEs units are more resistant devices (because of having fewer combustion cycles and also the potential of using air turbines for the discharging mode).

5.4 Scenario 4: Power loss & Operating costs objectives

The last scenario, as can be seen in Fig. 12, is to find the optimum operating points of the current configuration with the objective of total active power loss and operating costs. Minimizing the power loss results in an increase in the costs (either from diesel usage or purchasing power from the day-ahead market). Basically, importing power from the upstream grid cannot be an efficient solution for power loss reduction, especially when there are large load demands at the ending buses. It may even make the situation worse in some cases.

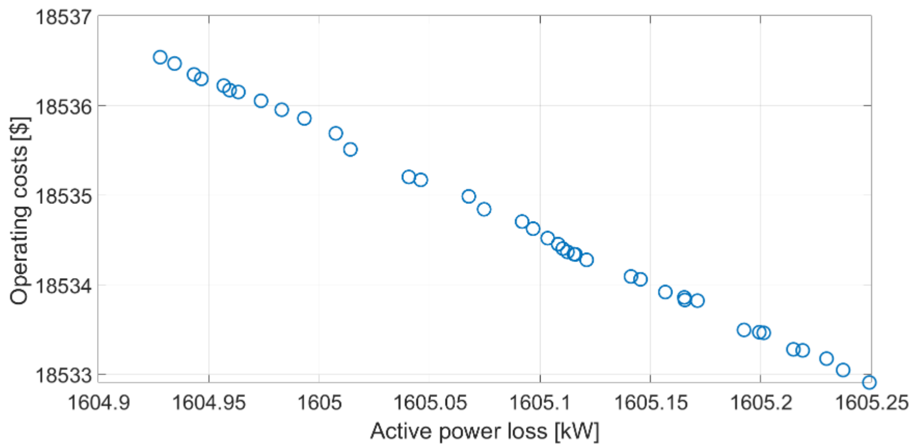

Fig. 12: Energy variations of SCAESs during 24h scheduling.

Therefore, considering the fact that CAES units are individually controlled and cannot significantly increase the voltage profile during the whole scheduling period (because they get the role of loads in some hours), diesel units are the last option; while the optimization algorithm prefers to use them as less as possible, to only meet voltage constraint, trying not to increase operating costs. Finally, all solutions are converged to near marginal points, and a Pareto-front solution limited to a narrow range is created.

6. Conclusions

The paper has proposed the concept of CAES aggregator for active distribution systems. The aggregator scheduled the charging/discharging patterns of storage units using the proposed linear programming to maximize their own profit based on local prices. Considering the results obtained from three bi-objective scenarios, it can be deduced that independent operations of CAES units not only had no adverse outcomes on the financial and technical grid operation, but also it assisted the DSO to optimally exploit the potentials of the grid's assets.

References

[1] M. J. Ghadi, A. Rajabi, S. Ghavidel, A. Azizivahed, L. Li, and J. Zhang, "From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors," *Applied Energy,* vol. 253, p. 113543, 2019.

[2] M. H. Imani, K. Yousefpour, M. J. Ghadi, and M. T. Andani, "Simultaneous presence of wind farm and V2G in security constrained unit commitment problem considering uncertainty of wind generation," in *2018 IEEE Texas Power and Energy Conference (TPEC)*, 2018, pp. 1-6: IEEE.

[3] M. J. Ghadi, S. Ghavidel, A. Rajabi, A. Azizivahed, L. Li, and J. Zhang, "A review on economic and technical operation of active distribution systems," *Renewable and Sustainable Energy Reviews,* vol. 104, pp. 38-53, 2019.

[4] J. I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, and A. Stoppato, "Trends and challenges in the operation of pumped-storage hydropower plants," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 767-784, 2015.

[5] A. Poullikkas, "A comparative overview of large-scale battery systems for electricity storage," *Renewable and Sustainable energy reviews,* vol. 27, pp. 778-788, 2013.

[6] A. Azizivahed *et al.*, "Risk-Oriented Multi-Area Economic Dispatch Solution with High Penetration of Wind Power Generation and Compressed Air Energy Storage System," *IEEE Transactions on Sustainable Energy,* 2019.

[7] G. Venkataramani, P. Parankusam, V. Ramalingam, and J. Wang, "A review on compressed air energy storage–A pathway for smart grid and polygeneration," *Renewable and Sustainable energy reviews,* vol. 62, pp. 895-907, 2016.

[8] S. G. Jirsaraie, M. J. Ghadi, A. A. Vahed, J. Aghaei, L. Li, and J. Zhang, "Risk-Constrained Bidding Strategy for a Joint Operation of Wind Power and Compressed Air Energy Storage Aggregators," *IEEE Transactions on Sustainable Energy,* 2019.

[9] S. Ghavidel *et al.*, "Hybrid power plant bidding strategy including a commercial compressed air energy storage aggregator and a wind power producer," in *2017 Australasian Universities Power Engineering Conference (AUPEC)*, 2017, pp. 1-6: IEEE.

[10] S. Shafiee, H. Zareipour, A. M. Knight, N. Amjady, and B. Mohammadi-Ivatloo, "Risk-constrained bidding and offering strategy for a merchant compressed air energy storage plant," *IEEE Transactions on Power Systems,* vol. 32, no. 2, pp. 946-957, 2016.

[11] A. Attarha, N. Amjady, S. Dehghan, and B. Vatani, "Adaptive robust self-scheduling for a wind producer with compressed air energy storage," *IEEE Transactions on Sustainable Energy,* vol. 9, no. 4, pp. 1659-1671, 2018.

[12] S. Shafiee, H. Zareipour, and A. Knight, "Considering thermodynamic characteristics of a CAES facility in self-scheduling in energy and reserve markets," *IEEE Transactions on Smart Grid,* 2016.

[13] H. S. de Boer, L. Grond, H. Moll, and R. Benders, "The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels," *Energy,* vol. 72, pp. 360-370, 2014.

[14] P. Denholm and R. Sioshansi, "The value of compressed air energy storage with wind in transmission-constrained electric power systems," *Energy Policy,* vol. 37, no. 8, pp. 3149-3158, 2009.

[15] S. Shafiee, H. Zareipour, A. M. Knight, N. Amjady, and B. Mohammadi-Ivatloo, "Risk-constrained bidding and offering strategy for a merchant compressed air energy storage plant," *IEEE Transactions on Power Systems,* vol. 32, no. 2, pp. 946-957, 2017.

[16] J. Cheng, R. Li, F. Choobineh, Q. Hu, and S. Mei, "Dispatchable Generation of a Novel Compressed-Air Assisted Wind Turbine and its Operation Mechanism," *IEEE Transactions on Sustainable Energy,* 2018.

[17] B. Cleary, A. Duffy, A. OConnor, M. Conlon, and V. Fthenakis, "Assessing the economic benefits of compressed air energy storage for mitigating wind curtailment," *IEEE Transactions on Sustainable Energy,* vol. 6, no. 3, pp. 1021-1028, 2015.

[18] H. Lund, G. Salgi, B. Elmegaard, and A. N. Andersen, "Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices," *Applied thermal engineering,* vol. 29, no. 5-6, pp. 799-806, 2009.

[19] Z. Guo, W. Wei, L. Chen, Z. Wang, and S. Mei, "Operation of Distribution Network Considering Compressed Air Energy Storage Unit and Its Reactive Power Support Capability," *IEEE Transactions on Smart Grid,* vol. 11, no. 4, pp. 2954-2965, 2020.

[20] J. Cheng and F. Choobineh, "Microgrid expansion through a compressed air assisted wind energy system," in *2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2016, pp. 1-5: IEEE.

[21] C. Fang, L. Chen, Y. Zhang, C. Wang, and S. Mei, "Operation of low-carbon-emission microgrid considering wind power generation and compressed air energy storage," in *Proceedings of the 33rd Chinese Control Conference*, 2014, pp. 7472-7477: IEEE.

[22] B. Liu, Q. Lin, T. Zheng, L. Chen, and S. Mei, "Low carbon economic dispatch for multi-energy distribution network with compressed air energy storage system as energy hub," in *2017 36th Chinese Control Conference (CCC)*, 2017, pp. 3083-3088: IEEE.

[23] A. Gheiratmand, E. Ayoubi, and M. Sarlak, "Optimal operation of micro-grid in presence of renewable resources and compressed air energy storage," in *2017 Conference on Electrical Power Distribution Networks Conference (EPDC)*, 2017, pp. 131-136: IEEE.

[24] M. Moazzami, M. Ghanbari, H. Shahinzadeh, J. Moradi, and G. B. Gharehpetian, "Application of multi-objective grey wolf algorithm on energy management of microgrids with techno-economic and environmental considerations," in *2018 3rd Conference on Swarm Intelligence and Evolutionary Computation (CSIEC)*, 2018, pp. 1-9: IEEE.

[25] Y. Li, S. Miao, X. Luo, B. Yin, J. Han, and J. Wang, "Dynamic modelling and techno-economic analysis of adiabatic compressed air energy storage for emergency back-up power in supporting microgrid," *Applied Energy,* vol. 261, p. 114448, 2020.

[26] M. J. Ghadi *et al.*, "Day-Ahead Market Participation of an Active Distribution Network Equipped with Small-Scale Compressed Air Energy Storage Systems," *IEEE Transactions on Smart Grid,* 2020.

[27] S. Haghifam, A. Najafi-Ghalelou, K. Zare, M. Shafie-khah, and A. Arefi, "Stochastic bi-level coordination of active distribution network and renewable-based microgrid considering eco-friendly Compressed Air Energy Storage system and Intelligent Parking Lot," *Journal of Cleaner Production,* vol. 278, p. 122808, 2021.

[28] J. Gao, J. Chen, B. Qi, Y. Zhao, K. Peng, and X. Zhang, "A cost-effective two-stage optimization model for microgrid planning and scheduling with compressed air energy storage and preventive maintenance," *International Journal of Electrical Power & Energy Systems,* vol. 125, p. 106547, 2021.

[29] X. Wang, C. Yang, M. Huang, and X. Ma, "Multi-objective optimization of a gas turbine-based CCHP combined with solar and compressed air energy storage system," *Energy conversion and management,* vol. 164, pp. 93-101, 2018.

[30] J. Zhang *et al.*, "A bi-level program for the planning of an islanded microgrid including CAES," *IEEE Transactions on Industry Applications,* vol. 52, no. 4, pp. 2768-2777, 2016.

[31] R. Latha, S. Palanivel, and J. Kanakaraj, "Frequency control of microgrid based on compressed air energy storage system," *Distributed Generation & Alternative Energy Journal,* vol. 27, no. 4, pp. 8-19, 2012.

[32] H. Ibrahim, K. Belmokhtar, and M. Ghandour, "Investigation of usage of compressed air energy storage for power generation system improving-application in a microgrid integrating wind energy," *Energy Procedia,* vol. 73, pp. 305-316, 2015.

[33] Y. Wang, "Renewable electricity in Sweden: an analysis of policy and regulations," *Energy policy,* vol. 34, no. 10, pp. 1209-1220, 2006.

[34] A. Askarzadeh, "Distribution generation by photovoltaic and diesel generator systems: Energy management and size optimization by a new approach for a stand-alone application," *Energy,* vol. 122, pp. 542-551, 2017.

[35] S. H. Gilani, M. J. Ghadi, and H. Afrakhte, "Optimal allocation of wind turbines considering different costs for interruption aiming at power loss reduction and reliability improvement using imperialistic competitive algorithm," *International Review of Electrical Engineering,* vol. 8, no. 1, pp. 284-296, 2013.

[36] A. Azizivahed, S. Ghavidel, M. J. Ghadi, L. Li, and J. Zhang, "New energy management approach in distribution systems considering energy storages," in *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-6: IEEE.

[37] H. Ghoreishi, H. Afrakhte, and M. J. ghadi, "Optimal placement of tie points and sectionalizers in radial distribution network in presence of DGs considering load significance," in *2013 Smart Grid Conference (SGC)*, 2013, pp. 160-165.