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A two-stage optimal mechanism for managing energy and ancillary services markets in renewable-based transmission and distribution networks by participating electric vehicle and demand response aggregators

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ABSTRACT

The growing uncertainties in power operations due to the integration of renewable generations (RGs) and electric vehicles (EVs) into electricity grids have amplified the significance of ancillary services (AS). These services have become essential to ensure the sustainable functioning of the grid. In light of this, we introduce a two-stage optimization framework to manage competitive energy and AS markets at the interface of the transmission system (TS) and distribution system (DS). Our approach takes into account a comprehensive set of economic, technical, and security factors. This mechanism is structured in two stages: the first stage encompasses the energy market, while the second stage encompasses AS markets. Spinning reserve (SR) is supplied by conventional thermal units (TUs), whereas regulation capacity is provided by energy storage systems (ESSs), fast-response generators, electric vehicles (EVs), and demand response (DR) aggregators. We applied this mechanism to a 30-bus transmission network connected to four 10-node DSs and utilized the GUROBI solver in GAMS for solving. The simulation results demonstrate that the engagement of DSs in the SR market reduces the reliance on costly TUs, thereby decreasing system costs by approximately 10%. Furthermore, involving ESSs, EVs, and DR aggregators in the regulation market enhances technical performance and results in a 6.91% reduction in total system costs. This approach provides a robust solution to the evolving challenges posed by RGs and EVs in modern electricity grids.

1. Introduction

1.1. Background and motivation

Transforming DSs from price-taker to price-maker during past decade has led to the definition of new tasks for distribution system operators (DSOs) to enhance their operation flexibility and achieve an optimal market participation strategy [1]. For instance, DS can relieve system congestion or reduce losses in the TS by changing their consumption patterns. It should be noted that the active role of DSs in the energy and AS markets, on the one hand, increases the profitability of these systems and, on the other hand, provides more flexibility for the TS [2,3]. In general, the coordinated operation of TS and DS is a new concept in which various technical, economic and security aspects must be considered.

In recent years, with the increasing influence of uncertain behavior sources such as renewable generations (RGs) and EVs in DSs, the need for coordination between these systems and the TS is felt more than ever, because the operation of the TS must be done take into account all downstream uncertainties [4,5]. Note that equipping TSs and DSs with ESSs can greatly neutralize the impact of operational uncertainties. In addition, DSs can provide significant flexibility for transmission system operator (TSO) by implementing DR programs as well as utilizing electric vehicle-to-grid (V2G) services [6,7]. Abovementioned discussions have encouraged us to design a comprehensive model for managing energy and AS markets among TS and DS, in which DSO provides a significant portion of the flexibility required by TSO through ESSs, DR programs, and V2G services.

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Nomenclature

Sets

D	DS index
E	Energy storage system index
Ev	Electric vehicle index
g,g'	Regular/Fast-Response thermal unit index
i,j	Bids/Offers index
It	Iteration loop index
K	Market player index
L	Line index
n,m	Node index
Pv	PV power plant index
S	Scenario index
T	Time index
W	Wind farm index

Scalar

α^d	EV's charge at departure time (%)
Δt	Scheduling time step (h)
η^{Ch}/η^{Dch}	Charge/Discharge efficiency of storage systems (%)
η^{PV}	PV power plant efficiency (%)
G^{STC}	Sun radiation at standard conditions (W/m^2)
$\lambda^{Reg,ESS}$	ESS cost for regulation market participation ($/MW)
$\lambda^{Reg,EV}$	EV cost for regulation market participation ($/MW)
$\lambda^{Reg,DR}$	DR cost for regulation market participation ($/MW)
$\theta^{Min}/\theta^{Max}$	Minimum/Maximum voltage angle (rad)
$v_{ci}/v_r/v_{co}$	Cut-in/Rated/Cut-out speed (m/s)
V^{Min}/V^{Max}	Minimum/Maximum voltage magnitude (p.u)

Parameters

$\alpha_n^{CL,Min}/\alpha_n^{CL,Max}$	Minimum/Maximum level of curtailable-load (%)
$\alpha_n^{SL,Min}/\alpha_n^{SL,Max}$	Minimum/Maximum rate of the load shifting (%)
E_e^{Min}/E_e^{Max}	Minimum/Maximum energy level of ESS (MWh)
$E_{ev}^{Min}/E_{ev}^{Max}$	Minimum/Maximum energy level of EV (MWh)
$E_e^{Initial}/E_{ev}^{Initial}$	Initial energy of ESS/EV (MWh)
$G_{t,s}^{PV}$	Sun radiation (W/m^2)
$G_l/B_l/r_l$	Conductance/Susceptance/Resistance of line (p.u)
it^{Max}	Maximum iteration in bidding loop
$\kappa_{l,n}$	Flow direction coefficient of line
$\lambda_{k,i=it,t,s}^{Buy}/\lambda_{k,j=it,t,s}^{Sell}$	Bid/Offer price in the market ($/MWh)
$\lambda_g^{Reg}/\lambda_{g'}^{Reg}$	Cost of regular/fast-response thermal unit for regulation market participation ($/MW)
λ_g^{Res}	Cost of regular thermal unit for SR market participation ($/MW)
ω_s	Scenario probability (%)
$\widehat{P}_{k,i=it,t,s}^{Buy}/\widehat{P}_{k,j=it,t,s}^{Sell}$	Bid/Offer power in the market ($/MWh)
$P_e^{Ch,Min}/P_e^{Ch,Max}$	Minimum/Maximum charge power limit of ESS (MW)
$P_e^{Dch,Min}/P_e^{Dch,Max}$	Minimum/Maximum discharge power limit of ESS (MW)
$P_{ev}^{Ch,Min}/P_{ev}^{Ch,Max}$	Minimum/Maximum charge power limit of EV (MW)
$P_{ev}^{Dch,Min}/P_{ev}^{Dch,Max}$	Minimum/Maximum discharge power limit of EV (MW)
$P_{n,t,s}^{Load}/Q_{n,t,s}^{Load}$	Active/Reactive demand (MW/MVAR)
$P_{k,t,s,it}^{Market}$	Market transactions level in each iteration loop (MW)
$P_{pv}^{PV,r}$	Maximum PV power plant capacity (MW)
$P_g^{TU,Min}/P_{g'}^{TU,Min}$	Minimum active power generation of regular/fast-response thermal unit (MW)
$P_g^{TU,Max}/P_{g'}^{TU,Max}$	Maximum active power generation of regular/fast-response thermal unit (MW)
$P_k^{Tie-Line}$	DS tie-line capacity (MW)
$P_w^{W,r}$	Maximum wind farm capacity (MW)
π_{pv}^{PV}	Cost of PV power plant for energy market participation ($/MW)
$\pi_g^{TU}/\pi_{g'}^{TU}$	Cost of regular/fast-response thermal unit for energy market participation ($/MW)
π_w^{W}	Cost of wind farm for energy market participation ($/MW)
$Q_g^{TU,Min}/Q_{g'}^{TU,Min}$	Minimum active power generation of regular/fast-response thermal unit (MVAR)
$Q_g^{TU,Max}/Q_{g'}^{TU,Max}$	Maximum active power generation of regular/fast-response thermal unit (MVAR)
$RU_g/RU_{g'}$	Ramp-Up limit of regular/fast-response thermal unit (MW)
$RD_g/RD_{g'}$	Ramp-Down limit of regular/fast-response thermal unit (MW)
$Reg_{t,s}^{Req}$	Required regulation by transmission system (MW)
$Res_{t,s}^{Req}$	Required SR by transmission system (MW)
$SUC_g/SUC_{g'}$	Start-Up cost of regular/fast-response thermal unit ($)
$SDC_g/SDC_{g'}$	Shut-Down cost of regular/fast-response thermal unit ($)
$S_l^{\max}$	Capacity of line (MVA)
T_{ev}^a/T_{ev}^d	Arrival/Departure time of EV (h)
$v_{t,s}$	Wind speed (m/s)

Variables

$C_{pv,t,s}^{PV}$	Operation cost of PV power plant ($)
$C_{g,t,s}^{TU}/C_{g',t,s}^{TU}$	Operation cost of regular/fast-response thermal unit ($)
$C_{w,t,s}^{W}$	Operation cost of wind farm ($)
$E_{e,t,s}/E_{ev,t,s}$	Energy level of ESS/EV (MWh)
$\lambda_{k,t,s}^{MC}$	Marginal cost of market player in iteration loop ($/MWh)
$P_{k,i,t,s}^{Buy}/P_{k,j,t,s}^{Sell}$	Accepted did/offer power in the market ($/MWh)
$P_{d,t,s}^{DN}/Q_{d,t,s}^{DN}$	Active/Reactive power transaction of DS (MW/MVAR)
$P_{l,t,s}^{Line}/Q_{l,t,s}^{Line}$	Active/Reactive power flow of line (MW/MVAR)
$P_{l,t,s}^{Loss}$	Active power loss (MW)
$P_{k,t,s}^{Market}$	Accepted market transactions level for each player (MW)
$P_{pv,t,s}^{PV}$	PV power plant power generation (MW)
$P_{g,t,s}^{TU}/P_{g',t,s}^{TU}$	Active power generation of regular/fast-response thermal unit (MW)
$P_{w,t,s}^{W}$	Wind farm power generation (MW)
$Q_{g,t,s}^{TU}/Q_{g',t,s}^{TU}$	Reactive power generation of regular/fast-response thermal unit (MVAR)
$Reg_{g,t,s}^{Up}/Reg_{g',t,s}^{Dn}$	Participation rate of regular/fast-response thermal unit in regulation market (MW)
$Reg_{e,t,s}^{Up}/Reg_{e,t,s}^{Dn}$	Participation rate of ESS in regulation market (MW)
$Reg_{ev,t,s}^{Up}/Reg_{ev,t,s}^{Dn}$	Participation rate of EV in regulation market (MW)
$Reg_{n,t,s}^{Up,SL}/Reg_{n,t,s}^{Dn,SL}$	Amount of shifting-load in regulation market (MW)
$Reg_{n,t,s}^{Up,CL}$	Amount of curtailable-load in regulation market (MW)
$Res_{g,t,s}$	Participation rate of regular thermal units in SR market (MW)
$\theta_{n,t,s}$	Voltage angle (rad)
$V_{n,t,s}$	Voltage magnitude (p.u)

Binary Variables

$I_{k,i,t,s}^{Buy}/I_{k,j,t,s}^{Sell}$	Status of accepted bid/offer in the energy market
$I_{e,t,s}^{Ch}/I_{e,t,s}^{Dch}$	Charging/discharging status of ESS
$I_{ev,t,s}^{Ch}/I_{ev,t,s}^{Dch}$	Charging/discharging status of EV
$I_{n,t,s}^{CL}$	Status of curtailable-load
$I_{n,t,s}^{SL-}/I_{n,t,s}^{SL+}$	Decreasing/Increasing status of load shifting DR

$I_{g,t,s}/I_{g',t,s}$	Status of regular/fast-response thermal unit	$I^{SD}_{g,t,s}/I^{SD}_{g',t,s}$	Shut-Down status of regular/fast-response thermal unit
$I^{SU}_{g,t,s}/I^{SU}_{g',t,s}$	Start-Up status of regular/fast-response thermal unit		

Table 1
Comparison of the proposed mechanism in this paper with recent models in the current literature.

Refs.	Power Flow Program	TS	DS	DR Programs	EV Fleets	EES	RESs	Energy Market	Reservation Market	Regulation Market	Uncertainties
[24]	✓	✓	×	×	×	×	✓	✓	×	×	✓
[14]	×	✓	✓	×	×	✓	✓	×	×	✓	✓
[25]	×	✓	×	×	×	✓	✓	×	✓	×	×
[26]	×	✓	✓	×	×	✓	×	×	×	✓	✓
[27]	✓	✓	×	×	×	×	×	✓	×	×	×
[28]	✓	✓	×	×	×	×	×	✓	×	×	×
[29]	✓	✓	×	×	×	✓	×	×	×	✓	×
[30]	✓	✓	×	×	×	✓	×	✓	×	×	×
[5]	✓	✓	✓	×	×	✓	✓	×	✓	×	✓
[7]	✓	×	✓	✓	×	✓	✓	✓	×	×	✓
[21]	✓	×	✓	✓	×	✓	✓	✓	×	×	✓
[31]	✓	×	×	✓	✓	✓	✓	×	×	✓	✓
[32]	✓	✓	✓	✓	×	✓	✓	×	×	✓	✓
[33]	✓	×	✓	✓	×	✓	✓	✓	×	×	✓
[34]	✓	✓	×	×	×	×	✓	✓	×	×	✓
[35]	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
[36]	✓	×	✓	✓	×	✓	✓	×	×	✓	✓
[37]	✓	✓	✓	✓	×	✓	×	×	×	✓	✓
This Paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

1.2. Literature review

The proliferation of RGs in recent years, despite their many benefits such as reducing emissions, reducing operating costs and reducing system losses, has posed many challenges to coordination between TS and DS due to their intermittent output. Therefore, many researchers have investigated the impact of RGs on the coordinated operation of TS and DS [8]. In this light, [9] proposes a second order cone programming (SOCP) framework for managing energy and SR markets among TS and DS where RGs uncertainties are included in the problem via stochastic method. The model is designed in two levels, in the first level the TS planning problem, and in the second level the DS planning problem are modeled. The simulation results reflect that the inclusion of uncertainties in the model leads to a more realistic and reliable programming. In order to perform expansion planning of TS and DS in [10], a stochastic strategy is proposed where RGs uncertainties are embedded in the problem through a scenario-based method. TS operational uncertainties are also included through a robust method. The expansion planning problem is formulated in a two-level format and the iteration solution algorithm is used to solve it. Simulation outputs demonstrate that providing a coordinated model for the expansion of TS and DS has led to a reduction in the daily cost. [11] proposes an optimal strategy for the coordinated operation of TS and DS in day-ahead and real-time markets where stochastic technique is adopted to model the operational uncertainties. Fast-response generation units located in the DSs are provided required flexibility of the system. The proposed strategy is modelled by the Benders decomposition approach in two levels, and the research outputs illustrate the positive effect of the above-mentioned strategy on the promotion of social welfare index.

Designing competitive energy and AS markets for TS and DS is another issue that has been considered by researchers in the last decade [12]. The authors in [13] formulate energy and AS markets as a bi-level problem, in the first level energy and flexibility markets of the TS are modeled while in the second level the energy market of the DS is modeled. Karush-Kuhn-Tucker (KKT) conditions are applied to convert two-stage formulation to one-stage formulation, and the simulation results mirror that the behavior of prosumers directly affects the market-clearing price (MPC). In [14], the authors have introduced a coordinated model for holding the energy market of TS and DS. In the proposed model, DS provides the balance required by the system, and the simulation results illustrate the significant impact of the generation units' flexibility on reducing network congestion. In [15] a hierarchical framework is introduced to form a coordinated market for TS and DS. In this model, the DSO does its generation scheduling aiming at maximizing profits and sends its market strategy to the TSO. Then, the TSO performs the final scheduling of the system according to the DSO' strategy. The outputs of simulation substantiate that the introduced model has led to achieving an optimal equilibrium point in the market. [16] shows that the coordinated operation of TS and DS leads to more cost-effective use of generation units. This study also shows that increasing the flexibility of prosumers reduces the MCP of DS. [17] proves that the coordinated scheduling of TS and DS leads to the more optimal allocation of AS and thus reduces costs.

Recently, several studies have shown that the potential of grid-connected EVs, ESSs, and DR programs can be harnessed to enhance operation flexibility and reduce lines' congestion. In this light, the authors of [18] have used DR programs and compressed air energy storage (CAES) systems to manage the TS congestion. A two-level framework is presented for network scheduling in which uncertainties arising from RGs are included in the problem by chance-constrained technique. Simulation outputs reveal that CAES and DR programs not only reduce network congestion but also improve the social welfare index. The authors in [19] use the re-scheduling of generation units and ESSs to alleviate the congestion of a 30-bus TS. The model is designed in a mixed-integer linear programming (MILP) format, and its objective is to minimize system congestion. Simulation outputs demonstrate that ESSs in addition to reducing system congestion have led to improved reliability index.

In [20], real-time scheduling of a 118-bus DS is performed by a multi-stage optimization method, in which EVs and incentive-based DR programs are considered. The service area of microgrid is specified in stage 1 with the aim of maximizing system resilience. In stage 2, the market strategies of microgrid are created and in stage 3, the network planning is done by considering the submitted strategies. Simulation outputs mirror that the above-mentioned model, using V2G services and DR programs, improves operating flexibility. [21] Provides a stochastic

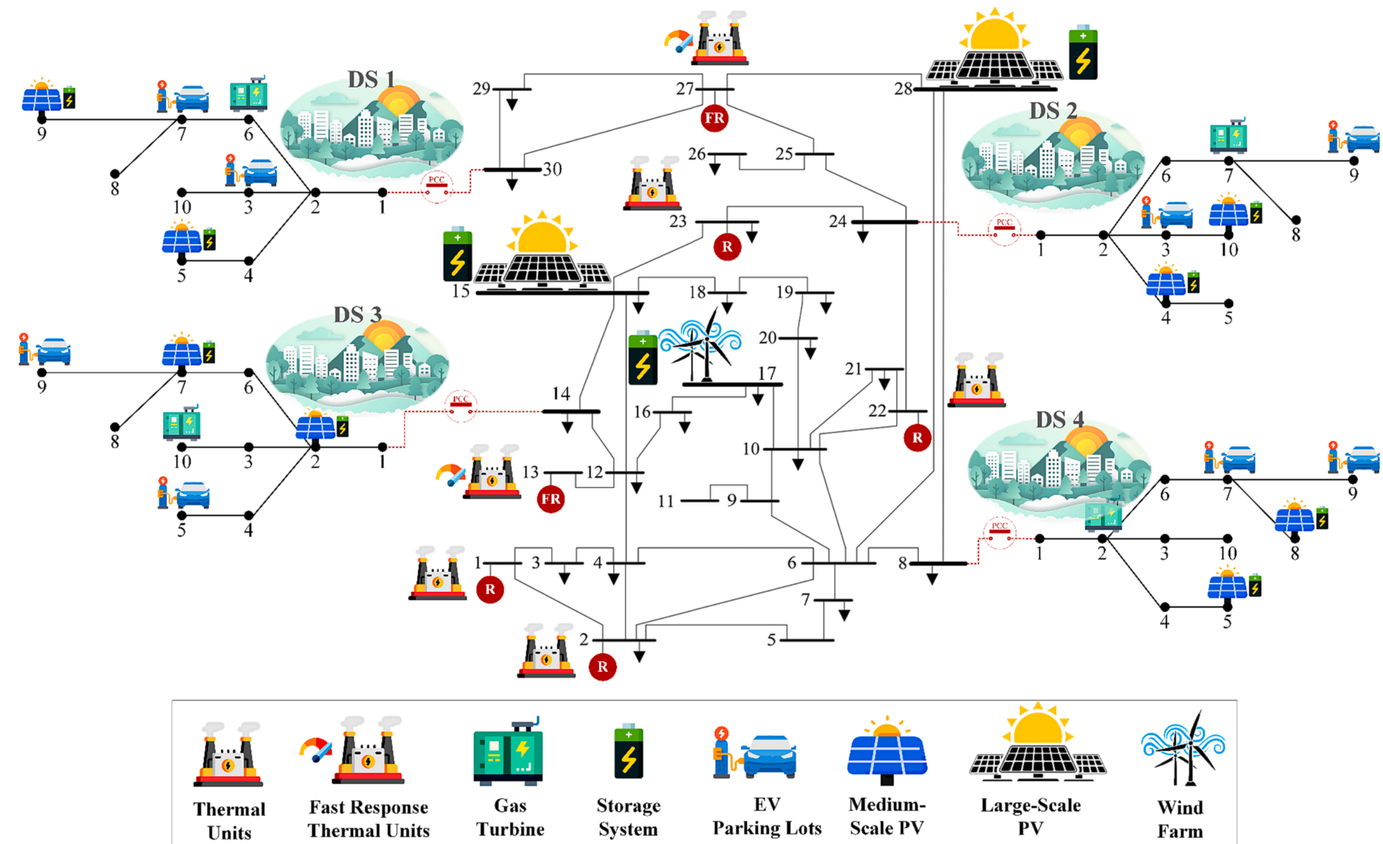


Fig. 1. The overview of the interconnected TS and DSs.

MILP strategy for DS planning, in which ESSs and flexible loa provide the flexibility required by the DS. The introduced strategy is simulated in GAMS and the outputs mirror that flexible loads and ESSs improve the consumption pattern of the system and thus increase the flexibility of operation.

The authors of [7] show the impact of DR programs and ESSs on promoting flexibility and reducing costs. This research also shows that the coordination of DR programs and ESSs leads to a considerable reduction in DS daily costs. [22] presents a scenario-based strategy for the optimal operation of DSs in which ESSs and DR programs are considered. This strategy is implemented on 33-bus and 118-bus DSs and GUROBI solver is used to solve it. Simulation outputs declare that ESSs and DR programs alleviate network congestion and reduce the locational marginal price (LMP). [23] presents a centralized model for the optimal operation of a DS in the presence of energy hubs. In the proposed model, EVs and ESSs reduce system load demand during peak hours by changing their charge/discharge schedule, thereby improving network flexibility.

1.3. Research gap and contributions

Table 1 is provided for comparing various aspects of this paper with recent literature in the same field. As evident from the existing literature, most papers tend to concentrate on a single market, offering limited exploration of the interplay between various markets within a single model. Notably, there is a conspicuous gap in research regarding the combined impact of V2G services, DR programs, and EESs on the reservation and regulation markets at the interface of transmission and distribution systems. This area demands more in-depth investigation. Furthermore, to the best of the authors' knowledge, there is a scarcity of models designed for the sequential settlement of energy, reservation, and regulation markets, each encompassing distinct implementation periods. The overarching conclusion drawn from the literature review underscores the pressing necessity for the development of innovative models that are in tune with modern networks. These models are pivotal for unlocking and harnessing the latent potential of flexible demand-side capacities within ancillary service markets.

In response to the identified gaps, the authors of this paper put forth a groundbreaking two-stage optimization mechanism designed to effectively oversee the energy, reservation and regulation markets at the interface of TSO and DSO. This mechanism thoroughly assesses the influence of the aforementioned variables on both economic and technical facets. The following pioneering innovations are unveiled within the pages of this paper:

- Presenting a multi-stage MIQCP mechanism for managing coordinated TSO-DSO energy and AS markets.
- Executing AS and regulation markets in day-ahead and intraday horizons, respectively, for more accurate resource allocation.
- Assessing the technical and economic effects of the DSs participation in the SR market.
- Evaluating the impact of ESSs, DR aggregators and V2G services on reducing regulation market costs.
- Reducing system LMP and improving voltage profiles during peak period through the participation of DR aggregators, EV users and ESSs in the regulation market.

2. System description

Fig. 1 shows the architecture of interconnected TS and DSs. As can be seen, the studied system is a 30-bus TS connected to four 10-bus DSs. The information on 30-bus TS is extracted from [38] whereas the information on 10-bus DSs is in accordance with [39]. According to the Fig. 1 six TUs are located on the TS, two of which are fast-response units. In

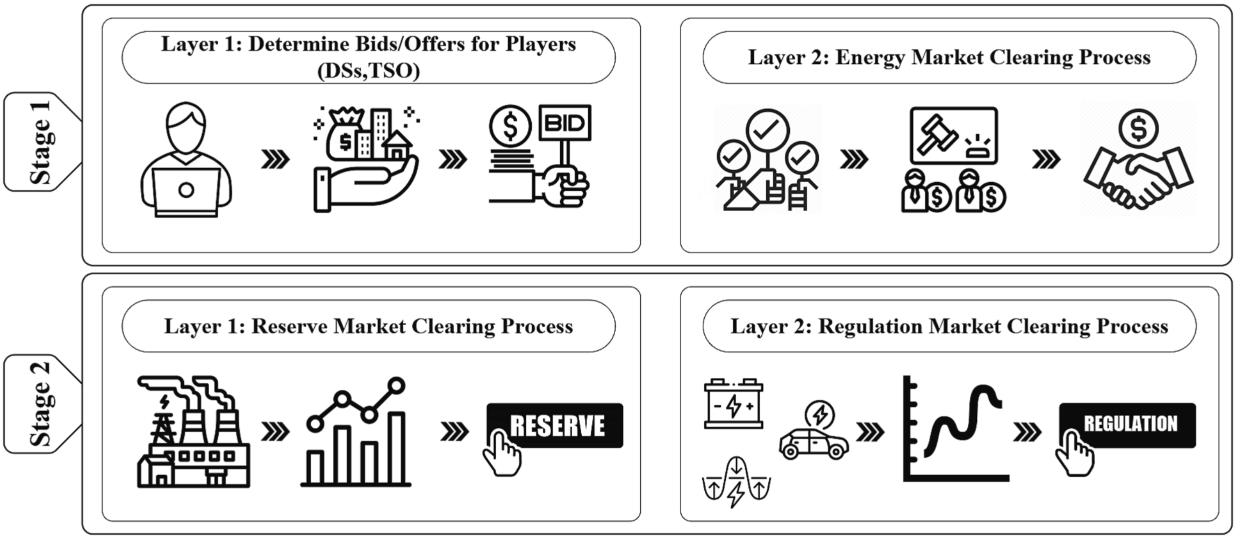


Fig. 2. Overview of the proposed two-stage mechanism.

addition, a wind farm, two large-scale photovoltaic (PV) power plants and two large-scale ESSs are located on the TS. DSs are equipped with gas turbines, medium-scale PV power plants and medium-scale ESSs. As can be observed, each DS has equipped with two parking lots to aggregate EVs that can have the bi-directional power transaction with the grid. In the proposed concept, the participants in the energy and SR markets consist of generating units in both the transmission and distribution systems. On the other hand, the regulation market encompasses players such as fast-response thermal units (FRTUs), as well as DR and EV aggregators. Fig. 2.

3. Mathematical formulation

The overview of the proposed two-stage model is shown in Fig. 1. According to the figure, this model is structured as a two-level problem, with each level also comprising two layers. The first stage models the day-ahead energy market, while the second stage models ancillary service markets, including day-ahead spinning reserve and intraday regulation. In this proposed concept, all three markets for energy, spinning reserve, and regulation are settled sequentially. In this regard, in the first layer of stage 1, energy market players, which are TUs within transmission and distribution networks, submit their bids to participate in the market. Then, in the second layer of stage 1, the day-ahead energy market settlement is determined based on the received bids with the goal of maximizing social welfare, and the MCP is determined.

Following this, in the first layer of stage 2, the day-ahead reservation market takes place, with the participants being the thermal units in the transmission and distribution systems. The objective of this market is to minimize the costs of system reservation provision. Finally, in the second layer of stage 2, the intraday regulation market is conducted, with the participation of FRTUs, EESs, and EV and DR aggregators. The aim of this market is to minimize the system's costs for providing regulation capacities. It should be highlighted that to ensure the sustainability of the proposed model, uncertainties in load demand, radiation, and wind speed are incorporated into the model using a scenario-based stochastic method.

3.1. Stage 1

3.1.1. Layer 1

Eqs. (1) to (4) model the first layer of the first stage of the proposed mechanism. In this layer, each player determines their offers/bids for the day-ahead market and sends them to the energy market. Eq. (1) proposes the objective function of the first layer, in which the operational cost of each player is minimized. It should be noted that Eq. (1) is solved from the point of view of each market player, including TS and DSs; k, t and s are the indicators of players, time and scenarios, respectively. $C^{TU}_{g,t,s}$ and $C^{TU}_{g',t,s}$ are the operating costs of regular and fast-response TUs, respectively; $C^{PV}_{pv,t,s}$ and $C^{W}_{w,t,s}$ are respectively the operating costs of PV power plants and wind farms. In Eq. (2), the power balance of TS and DSs is calculated. $P^{Market}_{k,t,s}$ is a variable related to the power exchange of each player. Note that Eq. (2) is solved in 20 repetitions for 20 $P^{Market}_{k,t,s}$, and its marginal value is equal to the marginal cost of each player. So, each actor makes 20 offers/bids with 20 different marginal cost per hour. The amount of $P^{Market}_{k,t,s}$ in each step is determined by Eq. (3). Through Eq. (4), $P^{Market}_{k,t,s}$ variable is stored in one of the $\widehat{P}^{Buy}_{k,i=it,t,s}$ or $\widehat{P}^{Sell}_{k,j=iter,t,s}$ parameters according to its symbol.

$$\min OC_{k,s} = \sum_{t}\left(\sum_{g\in\Delta_k^g} C^{TU}_{g,t,s} + \sum_{g'\in\Delta_k^{g'}} C^{TU}_{g',t,s} + \sum_{pv\in\Delta_k^{pv}} C^{PV}_{pv,t,s} + \sum_{w\in\Delta_k^{w}} C^{W}_{w,t,s}\right) \tag{1}$$

$$\sum_{g\in\Delta_k^g} P^{TU}_{g,t,s} + \sum_{g'\in\Delta_k^{g'}} P^{TU}_{g',t,s} + \sum_{pv\in\Delta_k^{pv}} P^{PV}_{pv,t,s} + \sum_{w\in\Delta_k^{w}} P^{W}_{w,t,s} = P^{Market}_{k,t,s} + \sum_{n\in\Delta_k^{n}} P^{Load}_{n,t,s} \;,\; \lambda^{MC}_{k,t,s} \tag{2}$$

$$P^{Market}_{k,t,s,it} = -P^{Tie-Line}_{k} + \left(\frac{it-1}{it^{Max}-1}\right)\left(2P^{Tie-Line}_{k}\right) \tag{3}$$

$$if\, P^{Market}_{k,t,s} \leqslant 0 \rightarrow \begin{cases} \widehat{P}^{Buy}_{k,i=it,t,s} = \left|P^{Market}_{k,t,s,iter}\right| \\ \lambda^{Buy}_{k,i=it,t,s} = \lambda^{MC}_{k,t,s} \end{cases}$$

$$if\, P^{Market}_{k,t,s} \geqslant 0 \rightarrow \begin{cases} \widehat{P}^{Sell}_{k,j=it,t,s} = P^{Market}_{k,t,s,it} \\ \lambda^{Sell}_{k,j=it,t,s} = \lambda^{MC}_{k,t,s} \end{cases} \tag{4}$$

3.1.2. Layer 2

Second layer of the first stage determines the MCP by considering the offers/bids of market players. In this regard, Eq. (5) calculates the MCP aiming at maximizing the social welfare index [40]. Eq. (6) states that $P^{Market}_{k,t,s}$ is the difference between the sales and purchases of each market player. Constraints (7) and (8) limit the final contracts to the offers/bids submitted by the market players. Constraint (9) prohibits the

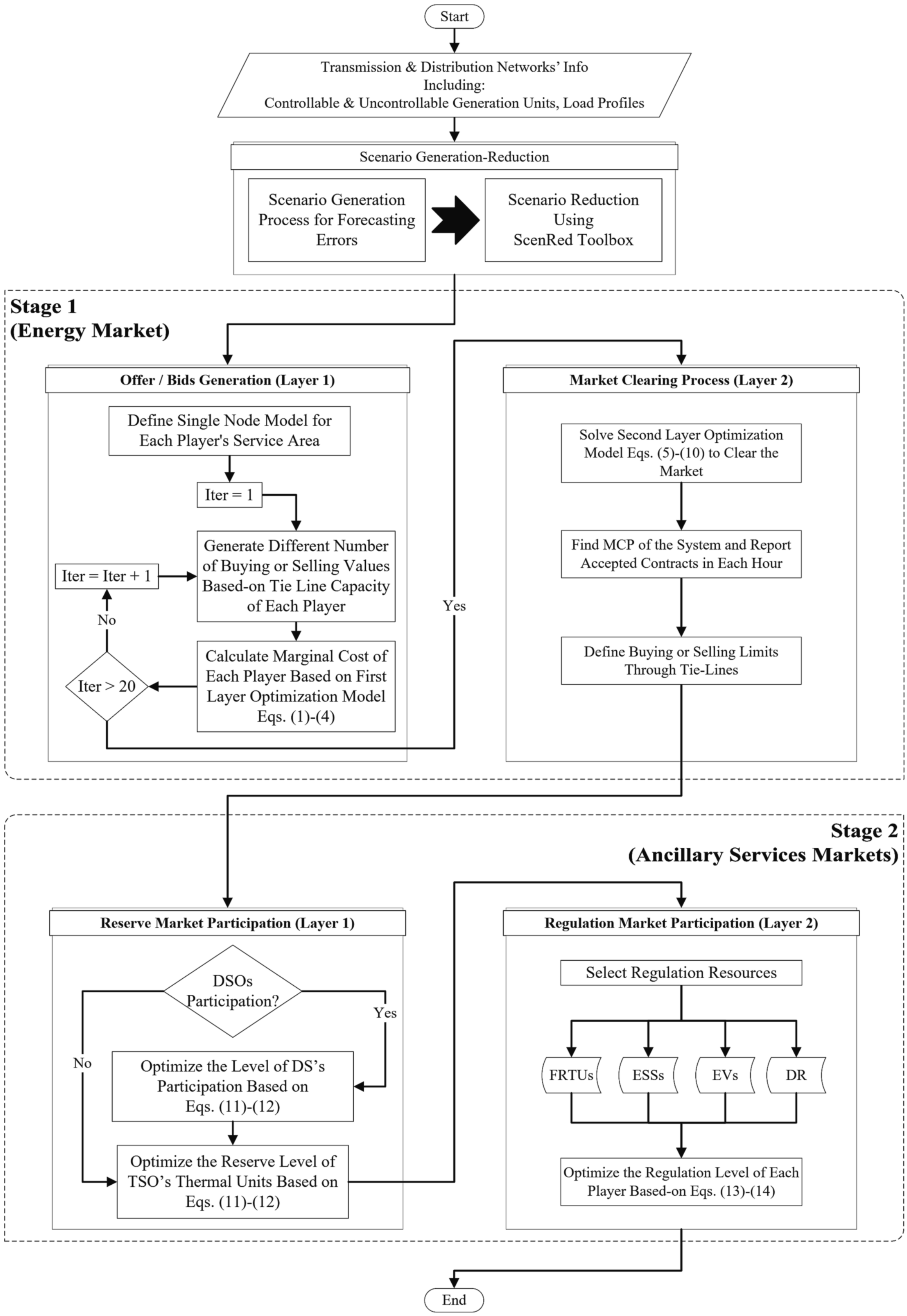


Fig. 3. Steps of implementing the proposed two-stage mechanism.

simultaneous approval of offers and bids for a market player. Ultimately, the balance between buying and selling in the pool market is established through Eq. (10).

$$\max \text{ SW} = \sum_s \omega_s \sum_t \sum_k \left(\sum_i \lambda^{Buy}_{k,i,t,s} P^{Buy}_{k,i,t,s} - \sum_j \lambda^{Sell}_{k,j,t,s} P^{Sell}_{k,j,t,s} \right) \tag{5}$$

$$\sum_j P^{Sell}_{k,j,t,s} - \sum_i P^{Buy}_{k,i,t,s} = P^{Market}_{k,t,s} \tag{6}$$

$$P^{Sell}_{k,j,t,s} \leqslant \widehat{P}^{Sell}_{k,j,t,s} I^{Sell}_{k,j,t,s} \tag{7}$$

$$P^{Buy}_{k,i,t,s} \leqslant \widehat{P}^{Buy}_{k,i,t,s} I^{Buy}_{k,i,t,s} \tag{8}$$

$$\sum_j I^{Sell}_{k,j,t,s} + \sum_i I^{Buy}_{k,i,t,s} \leqslant 1 \tag{9}$$

$$\sum_k P^{Market}_{k,t,s} = 0 \tag{10}$$

3.2. Stage 2

3.2.1. Layer 1

The first layer of the second stage is modeled through Eqs. (11) and (12). It should be pointed out that the SR and regulation markets are respectively held in the first and second layers of this stage [41]. First layer objective function is provided in Eq. (11), which is the minimization of SR market costs. Condition (12) explains that all SR capacities must be provided through regular TUs. Note that the day-ahead scheduling problem of each player is solved in day-ahead horizon with a time step of one hour ($\Delta t = 1$).

$$\min TC^{Res} = \sum_s \omega_s \sum_t \left(\sum_g \lambda^{Res}_g Res_{g,t,s} \right) \tag{11}$$

$$\sum_g Res_{g,t,s} = Res^{Req}_{t,s} \tag{12}$$

3.2.2. Layer 2

Eqs. (13) and (14) model the second layer of the second stage of the mechanism. At this layer, the problem of regulation market is solved. Eq. (13) shows the objective function of the second layer of stage 2, which is to minimize the costs of the regulation market. This market is solved for the present day, and its participants are FRTUs, EESs, and EV and DR aggregators. Eq. (14) guarantees the balance of the regulation market.

$$\min TC^{Reg} = \sum_s \omega_s \sum_t \left(\begin{array}{c} \sum_{g'} \left[\lambda^{Reg}_{g'} \left(Reg^{Up}_{g',t,s} + Reg^{Dn}_{g',t,s} \right) \right] + \lambda^{Reg,ESS} \sum_e \left(Reg^{Up}_{e,t,s} + Reg^{Dn}_{e,t,s} \right) \\ + \lambda^{Reg,EV} \sum_{ev} \left(Reg^{Up}_{ev,t,s} + Reg^{Dn}_{ev,t,s} \right) \\ + \lambda^{Reg,DR} \sum_n \left(Reg^{Up,CL}_{n,t,s} + Reg^{Up,SL}_{n,t,s} + Reg^{DN,SL}_{n,t,s} \right) \end{array} \right) \tag{13}$$

Table 2
Hypotheses of the studied cases.

Case	SR Provider		Responsible Resources to Supply Regulation Capacities			
	TS	DSs	TS	DSs		
			FRTUs	ESSs	EV Aggregators	DR Aggregators
1	✓	×	✓	×	×	×
2	✓	✓	✓	×	×	×
3	✓	✓	✓	✓	×	×
4	✓	✓	✓	✓	✓	×
5	✓	✓	✓	✓	✓	✓

$$\sum_{g' \in \Delta^{g'}_k} \left(Reg^{Up}_{g',t,s} - Reg^{DN}_{g',t,s} \right) + \sum_{e \in \Delta^e_k} \left(Reg^{Up}_{e,t,s} - Reg^{DN}_{e,t,s} \right) + \sum_{ev \in \Delta^{ev}_k} \left(Reg^{Up}_{ev,t,s} - Reg^{DN}_{ev,t,s} \right) + \sum_{n \in \Delta^n_k} \left(Reg^{Up,CL}_{n,t,s} + Reg^{Up,SL}_{n,t,s} - Reg^{DN,SL}_{n,t,s} \right) = Reg^{Req}_{t,s} \tag{14}$$

3.3. Generation units

The operation of TUs is done through Eqs. (a1)-(a8) [42]. g and g' are the indices of ordinary and fast-response TUs, respectively. Constraints (a1) and (a2) state that the sum of power generation and capacity allocated to the SR/regulation market must be within the allowable range of the thermal unit. Constraint (a3) limits the reactive power to the capacity of the thermal unit. Constraints (a4) and (a5), respectively, apply limitations on the ramp-up and ramp-down of TUs. Start-up and Shut-down flags of the TU at hour t is specified via Eq. (a6). Constraint (a7) is presented to avoid start-up and shut-down of the TU at the same time. Finally, the operating cost of the TU is computed using Eq. (a8), taking into account the rate of generated power, start-up and shut-down costs, and generation coefficients.

Eq. (a9) shows that the power generation of wind farms is computed through a three-part function with respect to the hourly wind speed. The operating cost of wind farm is obtained by Eq. (a10). The power generation of PV power plants is calculated using Eq. (a11), taking into account the hourly radiation. Ultimately, the operating cost of PV power plants is obtained via Eq. (a12).

$$P^{TU}_{\{g,g'\},t,s} + Reg^{Up}_{g',t,s} + Res_{g,t,s} \leqslant P^{TU,Max}_{\{g,g'\}} I_{\{g,g'\},t,s} \tag{a1}$$

$$P^{TU}_{\{g,g'\},t,s} - Reg^{Dn}_{g',t,s} \geqslant P^{TU,Min}_{\{g,g'\}} I_{\{g,g'\},t,s} \tag{a2}$$

$$Q^{TU,Min}_{\{g,g'\}} I_{\{g,g'\},t,s} \leqslant Q^{TU}_{\{g,g'\},t,s} \leqslant Q^{TU,Max}_{\{g,g'\}} I_{\{g,g'\},t,s} \tag{a3}$$

$$P^{TU}_{\{g,g'\},t,s} - P^{TU}_{\{g,g'\},t-1,s} + Reg^{Up}_{g',t,s} + Res_{g,t,s} \leqslant RU_{\{g,g'\}} \left(1 - I^{TU}_{\{g,g'\},t,s} \right) + P^{TU,Min}_{\{g,g'\}} I^{SU}_{\{g,g'\},t,s} \tag{a4}$$

Table 3
Equipment specifications and locations.

Thermal Units

Number	Locations	Q^{max} (MVAR)	P^{max} (MW)	Energy ($/MW)	SR ($/MW)	Regulation ($/MW)	Owner
1	1	20	80	21	–	2.1	TS
2	2	20	80	20	–	2	TS
3	22	15	50	20	–	2	TS
4	27	15	55	22	28	–	TS
5	23	10	30	21	–	2.1	TS
6	13	15	40	21	28	–	TS
7	36	1.5	5	16	–	1.6	1
8	47	1	3.75	14	–	1.4	2
9	60	1.5	5	17	–	1.7	3
10	62	1.5	6.25	16	–	1.6	4

Renewable Generations

Number	Locations	P^{max} (MW)	Energy ($/MW)	Type	Owner
1	15	40	15	PV	TS
2	17	60	19	Wind	TS
3	28	40	17	PV	TS
4	35	2.5	13	PV	1
5	39	2	11	PV	1
6	44	2.5	9	PV	2
7	50	3	10	PV	2
8	52	2.5	11	PV	3
9	57	2.5	12	PV	3
10	65	4	13	PV	4
11	68	1	11	PV	4

Table 4
Input parameters values [21].

Parameter	Value	Parameter	Value	Parameter	Value
η_e^{ch}	95 %	E_e^{min}	30 %	it^{Max}	20
η_e^{dch}	95 %	E_e^{max}	95 %	θ^{Min}	$-\pi$
$E_e^{initial}$	50 %	v_i	4 m/s	θ^{Max}	π
V^{Min}	0.9p.u.	v_r	14 m/s	η^{PV}	95 %
V^{Max}	1.1p.u.	v_o	20 m/s	G_{std}	1000 W/m^2

$$P^{TU}_{\{g,g'\},t-1,s} - P^{TU}_{\{g,g'\},t,s} + Reg^{Dn}_{g',t,s} \leqslant RD_{\{g,g'\}}\left(1 - I^{SD}_{\{g,g'\},t,s}\right) + P^{TU,Min}_{\{g,g'\}} I^{SD}_{\{g,g'\},t,s} \quad \text{(a5)}$$

$$I^{SU}_{\{g,g'\},t,s} - I^{SD}_{\{g,g'\},t,s} = I_{\{g,g'\},t,s} - I_{\{g,g'\},t-1,s} \quad \text{(a6)}$$

$$I^{SU}_{\{g,g'\},t,s} + I^{SD}_{\{g,g'\},t,s} \leqslant 1 \quad \text{(a7)}$$

$$C^{TU}_{\{g,g'\},t,s} = \pi^{TU}_{\{g,g'\}} P^{TU}_{\{g,g'\},t,s} + SUC_{\{g,g'\}} I^{SU}_{\{g,g'\},t,s} + SDC_{\{g,g'\}} I^{SD}_{\{g,g'\},t,s} \quad \text{(a8)}$$

$$P^{W}_{w,t,s} = \begin{cases} 0\ , & v_{t,s} < v_{ci} \text{ Or } v_{t,s} \geqslant v_{co} \\ P^{W,r}_{w} \dfrac{v_{t,s} - v_{ci}}{v_r - v_{ci}}\ , & v_{ci} \leqslant v_{t,s} < v_r \\ P^{W,r}_{w}\ , & v_r \leqslant v_{t,s} < v_{co} \end{cases} \quad \text{(a9)}$$

$$C^{W}_{w,t,s} = \pi^{W}_{w} P^{W}_{w,t,s} \quad \text{10)}$$

$$P^{PV}_{pv,t,s} = \frac{\eta^{PV} P^{PV,r}_{pv} G^{PV}_{t,s}}{G^{STC}} \quad \text{11)}$$

$$C^{PV}_{pv,t,s} = \pi^{PV}_{pv} P^{PV}_{pv,t,s} \quad \text{12)}$$

3.4. Transmission system power flow

A linear AC power flow program (b1)-(b9) is executed on both TS and DS in the proposed mechanism [43]. In this regard, constraints (b1) and (b2), respectively, guarantee the nodal equilibrium of active and reactive powers. LHS of these equations are related to production while RHSs are related to consumption. $P^{TU}_{g,t,s}$, $P^{W}_{w,t,s}$ and $P^{PV}_{pv,t,s}$ are the power generated by thermal unit, wind farms and PV power plants, respectively; $P^{Line}_{l,t,s}$ is the power injected into line l; $P^{Load}_{n,t,s}$ and $P^{DN}_{d,t,s}$ are the load demand of bus n and the load demand of DS d, respectively. $Q^{TU}_{g,t,s}$ is the reactive power generated by the unit g; $Q^{Line}_{l,t,s}$, $Q^{Load}_{n,t,s}$ and $Q^{DN}_{d,t,s}$ are the reactive power injected in line l, the reactive power demand of node n, and the reactive power required by the DS d.

Eqs. (b3) and (b4) calculate the active and reactive powers of line l at time t, respectively. According to these equations, the flow of active and reactive powers depends on the voltage magnitude and its angle at both ends of the line l. Constraint (b5) restricts the apparent power flow at line l. Power losses ($P^{Loss}_{l,t,s}$) are calculated using Eq. (b6). Eq. (b7) calculates the amount of power demand at buses connected to DSs. Constraints (b8) and (b9) are provided to confine magnitude and angle of the voltage.

$$\sum_{g\in\Delta^{g}_{TSO}} P^{TU}_{g,t,s} + \sum_{w\in\Delta^{w}_{TSO}} P^{W}_{w,t,s} + \sum_{pv\in\Delta^{pv}_{TSO}} P^{PV}_{pv,t,s} = \sum_{l\in\Delta^{l}_{n}} \kappa_{l,n} P^{Line}_{l,t,s} + P^{Load}_{n,t,s} + \sum_{d\in\Delta^{d}_{n}} P^{DN}_{d,t,s} \quad \text{(b1)}$$

$$\sum_{g\in\Delta^{g}_{TSO}} Q^{TU}_{g,t,s} = \sum_{l\in\Delta^{l}_{n}} \kappa_{l,n} Q^{Line}_{l,t,s} + Q^{Load}_{n,t,s} + \sum_{d\in\Delta^{d}_{n}} Q^{DN}_{d,t,s} \quad \text{(b2)}$$

$$P^{Line}_{l,t,s} = G_l\left(V_{n,t,s} - V_{m,t,s}\right) + B_l\left(\theta_{n,t,s} - \theta_{m,t,s}\right) + \frac{P^{Loss}_{l,t,s}}{2} \quad \text{(b3)}$$

$$Q^{Line}_{l,t,s} = B_l\left(V_{n,t,s} - V_{m,t,s}\right) - G_l\left(\theta_{n,t,s} - \theta_{m,t,s}\right) \quad \text{(b4)}$$

$$\left(P^{Line}_{l,t,s}\right)^2 + \left(Q^{Line}_{l,t,s}\right)^2 \leqslant \left(S^{\max}_{l}\right)^2 \quad \text{(b5)}$$

$$P^{Loss}_{l,t,s} = r_l\left(\left(P^{Line}_{l,t,s}\right)^2 + \left(Q^{Line}_{l,t,s}\right)^2\right) \quad \text{(b6)}$$

$$P^{DN}_{d,t,s} = \sum_{i} P^{Buy}_{d,i,t,s} - \sum_{j} P^{Sell}_{d,j,t,s} \quad \text{(b7)}$$

$$V^{Min} \leqslant V_{n,t,s} \leqslant V^{Max} \quad \text{(b8)}$$

$$\theta^{Min} \leqslant \theta_{n,t,s} \leqslant \theta^{Max} \quad \text{(b9)}$$

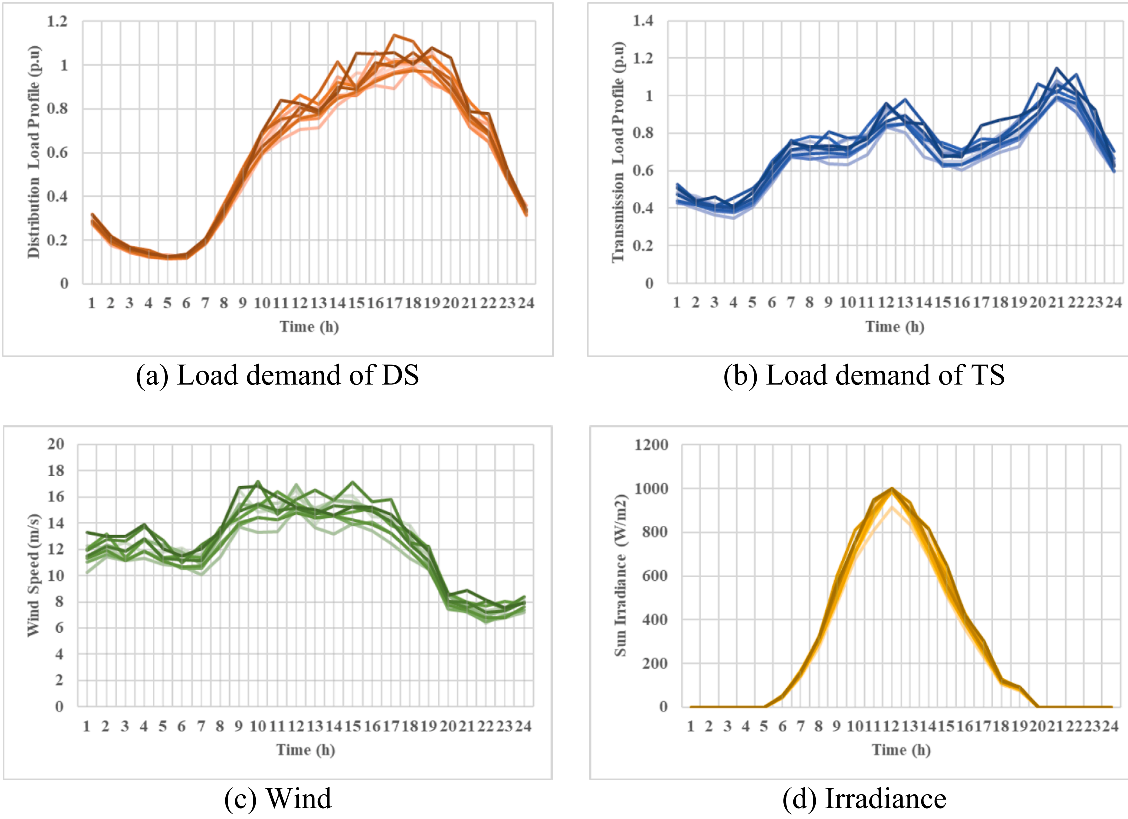


Fig. 4. Scenarios obtained using ScenRed.

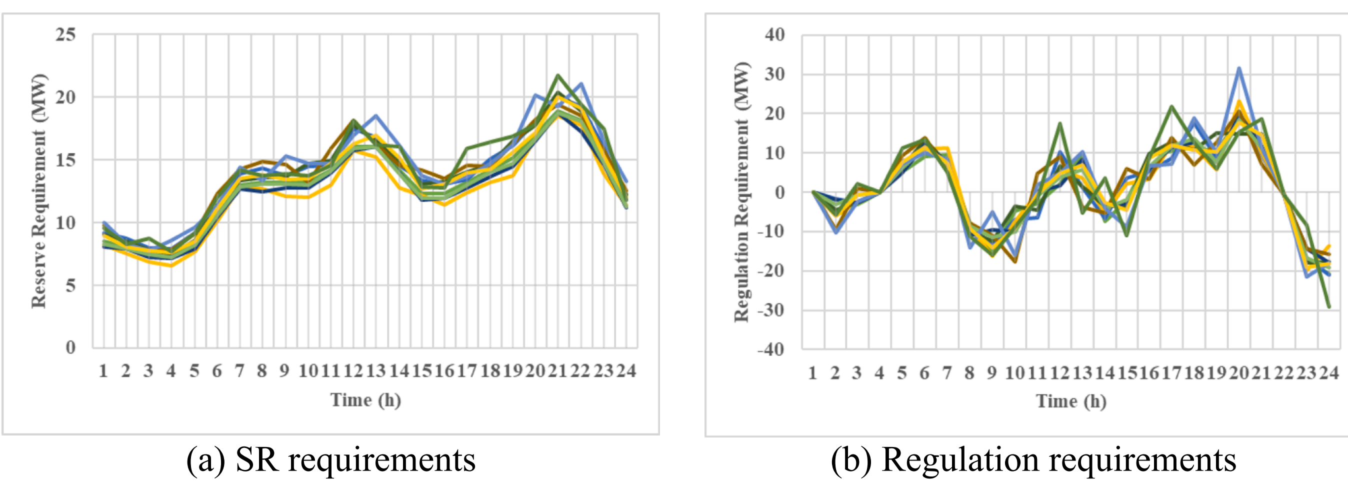


Fig. 5. Ancillary service requirements of TS.

Table 5
Numerical results obtained from Case 1.

Market Actors	Equipment' OC ($)	Transactions ($)			Sum.
		Energy Market	SR Market	Regulation Market	
TS	66217.42	−2036.18	627.77	5473.88	70282.89
DS 1	1496.56	517.84	0	0	2014.4
DS 2	904.34	334.4	0	0	1238.74
DS 3	1543.83	502.81	0	0	2046.64
DS 4	1929.83	681.13	0	0	2610.96
Total ($)	72091.98	0	627.77	5473.88	78193.63

Table 6
Numerical results obtained from Case 2.

Market Actors	Equipment' OC ($)	Transactions ($)			Sum.
		Energy Market	SR Market	Regulation Market	
TS	66154.49	−2036.18	614.09	5473.88	70206.28
DS 1	1508.87	517.84	−12.32	0	2014.39
DS 2	912.94	334.4	−8.61	0	1238.73
DS 3	1556.91	502.81	−13.09	0	2046.63
DS 4	1945.05	681.13	−15.23	0	2610.95
Total ($)	72078.26	0	564.84	5473.88	78116.98

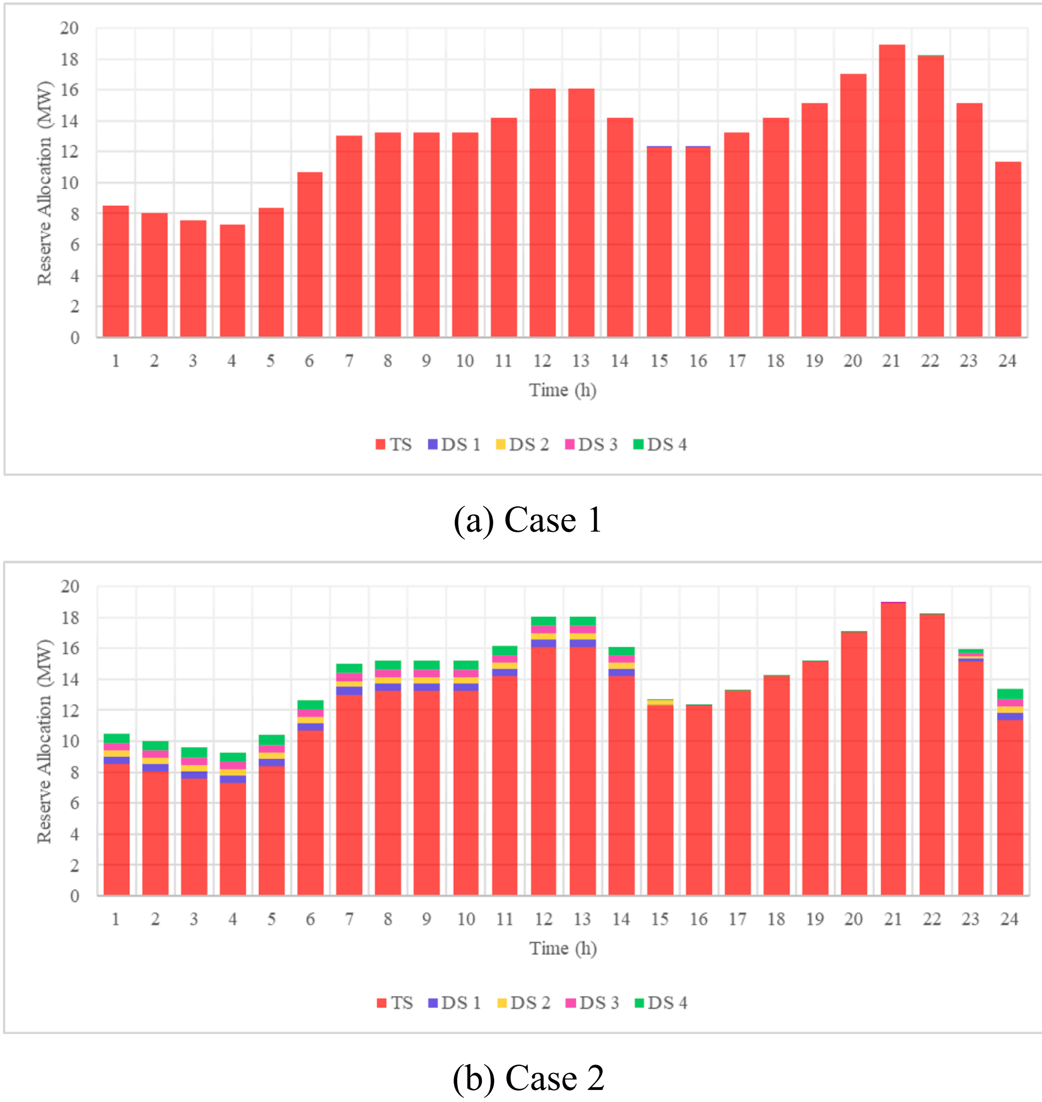


Fig. 6. SR providers in Cases 1 & 2.

3.5. Distribution system power flow

As mentioned, a linear AC power flow program is also executed on the DSs [44]. It should be noted that the formulation of this program is similar to the executed program on the TS, except that the equilibrium equations of active and reactive powers are updated. Eqs. (c1) and (c2) respectively represent the nodal equilibrium constraints for active and reactive powers within the DS.

$$P^{DN}_{d,t,s}\Big|_{n=1}+\sum_{g\in\Delta^{g}_{d,n}}P^{TU}_{g,t,s}+\sum_{pv\in\Delta^{pv}_{d,n}}P^{PV}_{pv,t,s}=\sum_{l\in\Delta^{l}_{d,n}}\kappa_{l,n}P^{line}_{l,t,s}+P^{load}_{n,t,s} \tag{c1}$$

$$Q^{DN}_{d,t,s}\Big|_{n=1}+\sum_{g\in\Delta^{g}_{d,n}}Q^{GT}_{g,t,s}=\sum_{l\in\Delta^{l}_{d,n}}\kappa_{l,n}Q^{line}_{l,t,s}+Q^{load}_{n,t,s} \tag{c2}$$

3.6. Energy storage system

ESSs are formulated through Eqs. (d1)-(d6) [45]. Eq. (d1) computes the energy level of the ESS. $E_{e,t-1,s}$ is the ESS energy level in the previous hour. $P^{Ch}_{e,t,s}$ and $P^{Dch}_{e,t,s}$ are respectively the charged and discharged powers per hour. $Reg^{Up}_{e,t,s}$ and $Reg^{Dn}_{e,t,s}$ are the capacities allocated to the up and down regulation markets. Constraint (d2) models the allowable energy range of the ESS. Eq. (d3) states that the total capacity allocated to charging and down-regulation must be less than a permissible value. Similarly, constraint (d4) applies this restriction to discharged power and up-regulation capacity. $I^{Ch}_{e,t,s}$ and $I^{Dch}_{e,t,s}$ are decision variables that determine the charge and discharge status, respectively. Eq. (d5) fixes the ESS energy level in the first and last hours on the $E^{Initial}_{e}$ parameter. Constraint (d6) makes it impossible to charge and discharge the ESS at the same time.

$$E_{e,t,s}=E_{e,t-1,s}+\left(\eta^{Ch}Reg^{Dn}_{e,t,s}-\frac{Reg^{Up}_{e,t,s}}{\eta^{Dch}}\right)\Delta t \tag{d1}$$

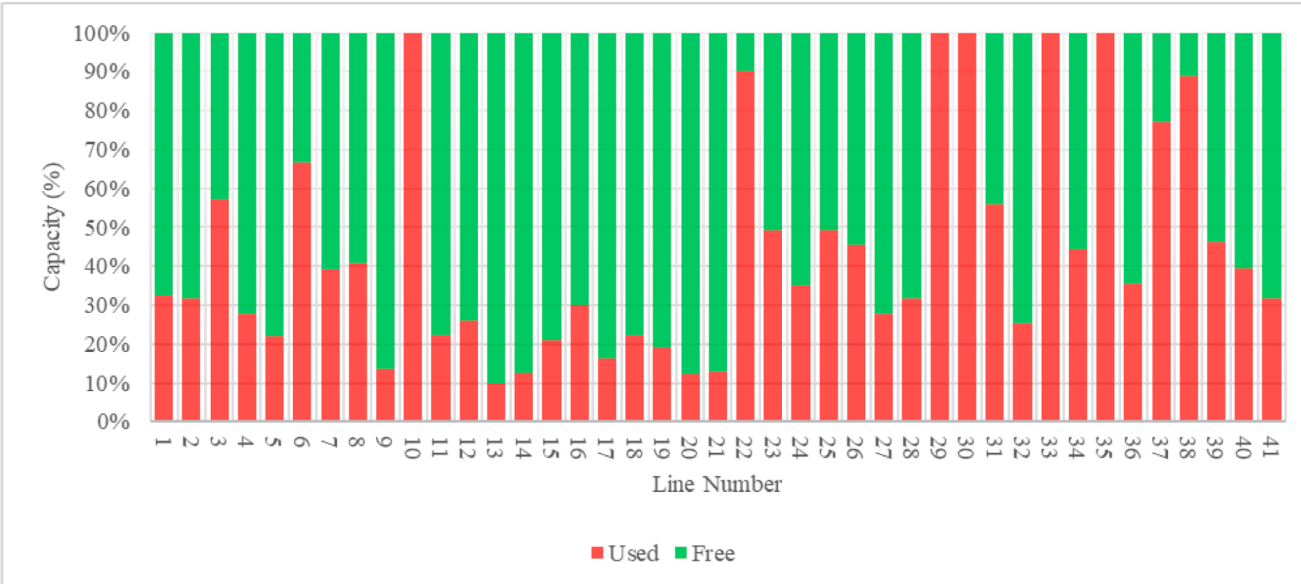
$$E^{Min}_{e}\leqslant E_{e,t,s}\leqslant E^{Max}_{e} \tag{d2}$$

$$P^{Ch,Min}_{e}I^{Ch}_{e,t,s}\leqslant Reg^{Dn}_{e,t,s}\leqslant P^{Ch,Max}_{e}I^{Ch}_{e,t,s} \tag{d3}$$

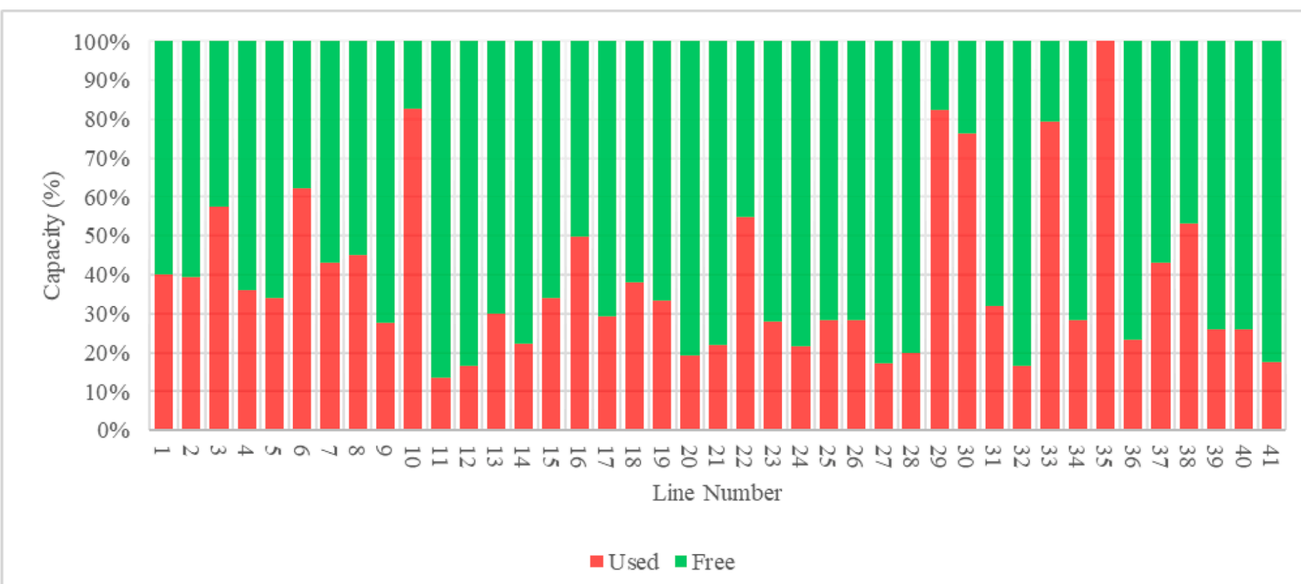
$$P^{Dch,Min}_{e}I^{Dch}_{e,t,s}\leqslant Reg^{Up}_{e,t,s}\leqslant P^{Dch,Max}_{e}I^{Dch}_{e,t,s} \tag{d4}$$

$$E_{e,t=0,s}=E_{e,t=24,s}=E^{Initial}_{e} \tag{d5}$$

$$0\leqslant I^{Ch}_{e,t,s}+I^{Dch}_{e,t,s}\leqslant 1 \tag{d6}$$



(a) Without regulation market



(b) With regulation market

Fig. 7. Impact of the regulation market on TS congestion in Case 2.

3.7. Electric vehicle parking lots

The relations required to model EV parking lots are provided in Eqs. (e1)-(e7) [46]. Note that parking lots can participate in the regulation market. Eq. (e1) restricts the energy level of the EV battery. The energy level of each EV is computed via Eq. (e2). Constraints (e3) and (e4) model the restrictions on charge/discharge and power allocation to the up-/down-regulation. Eq. (e5) states that the energy level of each EV at arrival time is in accordance with the input scenarios [23]. Constraint (e6) expresses that the energy level of EVs at departure time should be equal to a predetermined value [47]. Constraint (e7) prevents EV from simultaneously charging and discharging.

$$E_{ev}^{Min} \leqslant E_{ev,t,s} \leqslant E_{ev}^{Max} \tag{e1}$$

$$E_{ev,t,s} = E_{ev,t-1,s} + \left(\eta^{Ch} Reg_{ev,t,s}^{Dn} - \frac{Reg_{ev,t,s}^{Up}}{\eta^{Dch}} \right) \Delta t \tag{e2}$$

$$P_{ev}^{Ch,Min} I_{ev,t,s}^{Ch} \leqslant Reg_{ev,t,s}^{Dn} \leqslant P_{ev}^{Ch,Max} I_{ev,t,s}^{Ch} \tag{e3}$$

$$P_{ev}^{Dch,Min} I_{ev,t,s}^{Dch} \leqslant Reg_{ev,t,s}^{Up} \leqslant P_{ev}^{Dch,Max} I_{ev,t,s}^{Dch} \tag{e4}$$

$$E_{ev,t=T_{ev}^{a},s} = E_{e,s}^{Initial} \tag{e5}$$

$$E_{ev,t=T_{ev}^{d},s} = \alpha^{d} E_{ev}^{Max} \tag{e6}$$

$$0 \leqslant I_{ev,t,s}^{Ch} + I_{ev,t,s}^{Dch} \leqslant 1 \Big|_{\left(t \geqslant T_{ev}^{a} \text{ and } t < T_{ev}^{d}\right)} \tag{e7}$$

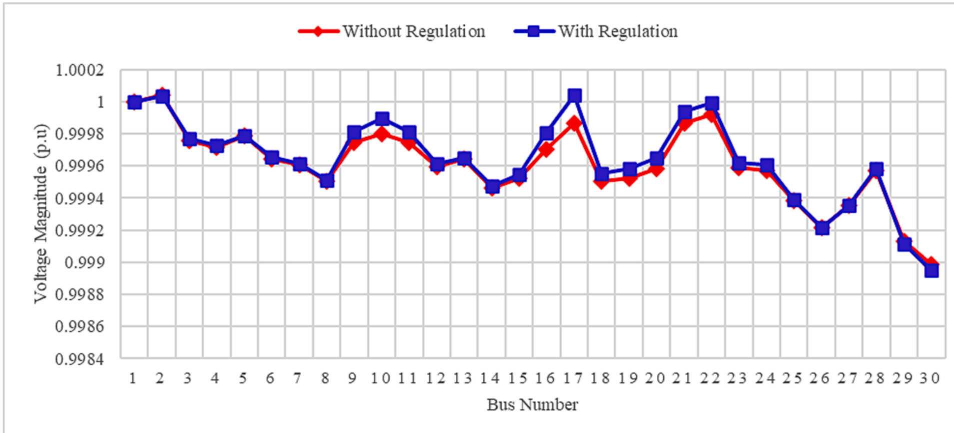


Fig. 8. Impact of the regulation market on voltage profile at 21 o'clock.

Table 7
Numerical results obtained from Case 3.

Market Actors	Equipment' OC ($)	Transactions ($)			Sum.
		Energy Market	SR Market	Regulation Market	
TS	65052.51	−2036.18	614.09	5150.19	68780.61
DS 1	1534.08	517.84	−12.32	−67.84	1971.76
DS 2	971.93	334.4	−8.61	−183.63	1114.09
DS 3	1621.52	502.81	−13.09	−166.95	1944.29
DS 4	2015.84	681.13	−15.23	−166.88	2514.86
Total ($)	71195.88	0	564.84	4564.89	76325.61

3.8. DR aggregators

Eqs. (f1) – (f6) model DR aggregators [48]. It is assumed in the proposed mechanism that DR aggregators only participate in the regulation market. For this purpose, through the implementation of two demand response programs, shifting-load and curtailable-load, they buy part of the consumers' load and sell it at a higher price in the regulation market. Eq. (f1) confines participation in the regulation market through the curtailable-load program. $I^{CL}_{n,t,s}$ is a binary variable whose value is equal to 1 if the curtailable-load program is executed on node n. Constraint (f2) states that the curtailable-load DR program is applied to each node only once during the operation period. Constraints (f3) and (f4), respectively, confine the participation in the up and down regulation markets through the shifting-load program. Constraint (f5) indicates the prohibition of simultaneous increase and decrease of load. Constraint (f6) balances the load increase and decrease [49].

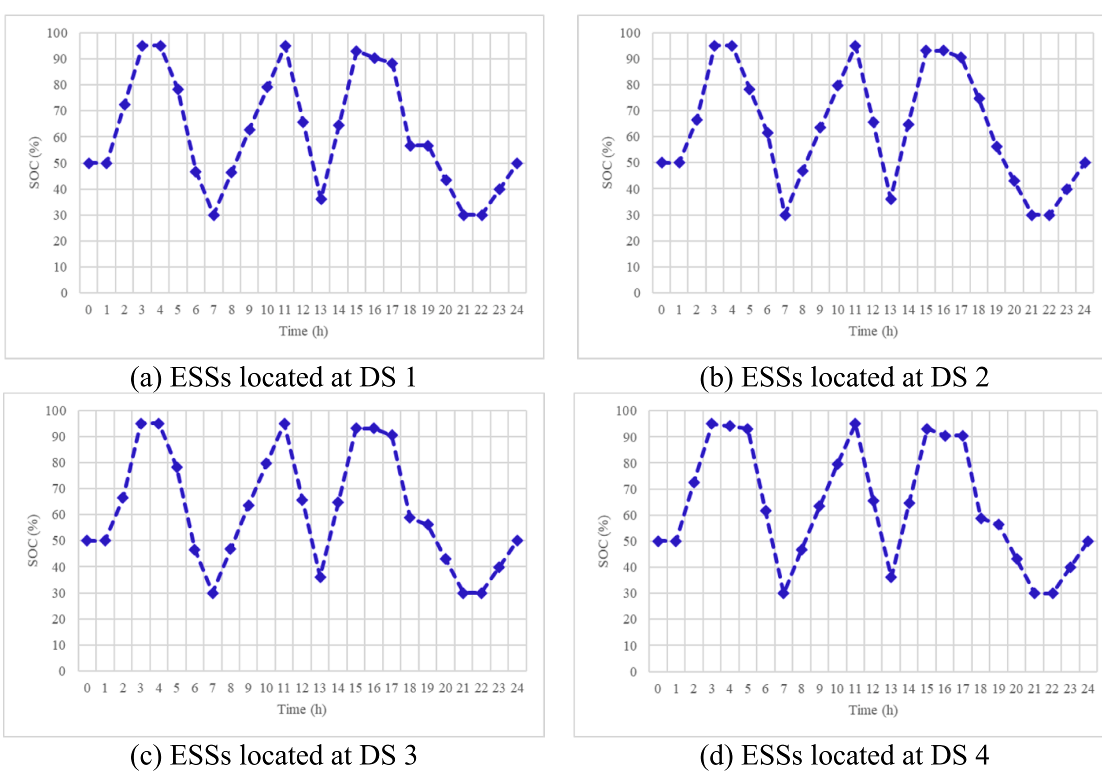
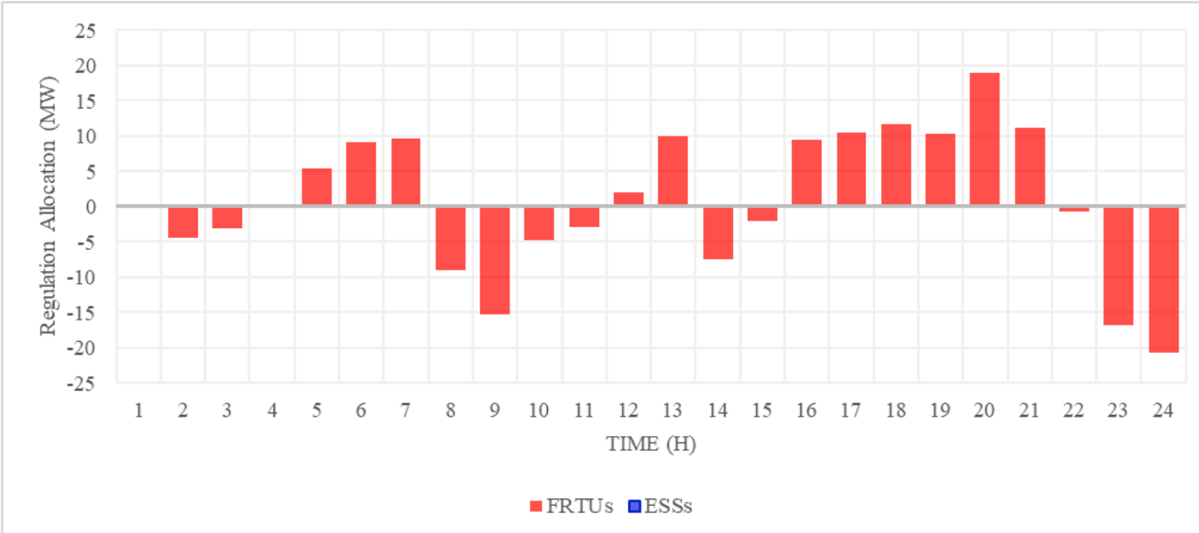
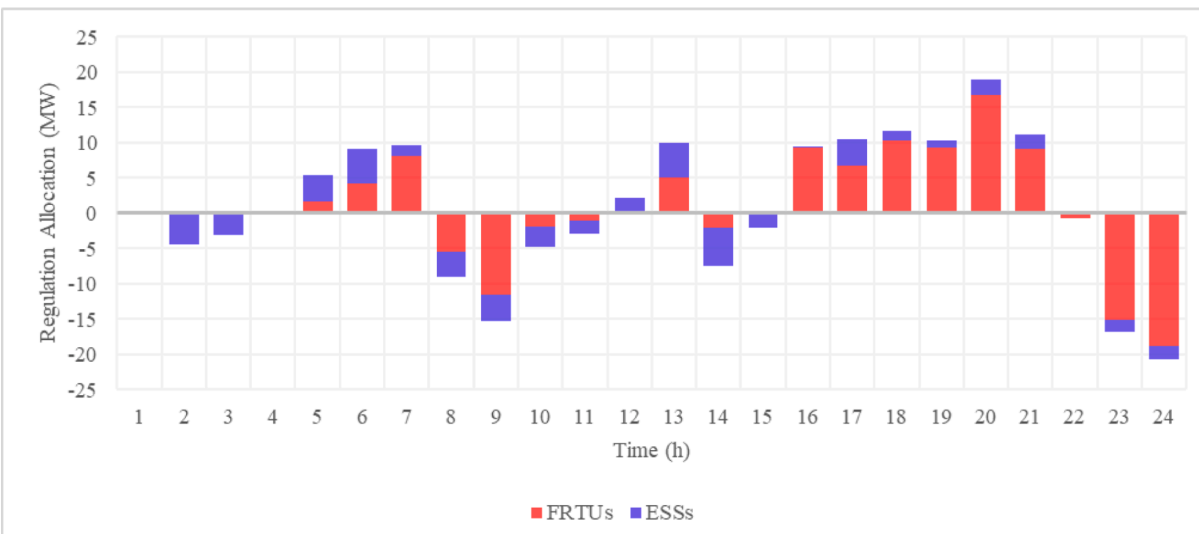


Fig. 9. Performance of ESSs in Case 3.



(a) Case 2



(b) Case 3

Fig. 10. Regulation capacity providers in Cases 2 & 3.

$$\alpha_n^{CL,Min} P_{n,t,s}^{Load} I_{n,t,s}^{CL} \leqslant Reg_{n,t,s}^{Up,CL} \leqslant \alpha_n^{CL,Max} P_{n,t,s}^{Load} I_{n,t,s}^{CL} \tag{f1}$$

$$\sum_t I_{n,t,s}^{CL} \leqslant 1 \tag{f2}$$

$$\alpha_n^{SL,\min} P_{n,t,s}^{Load} I_{n,t,s}^{SL+} \leqslant Reg_{n,t,s}^{Dn,SL} \leqslant \alpha_n^{SL,Max} P_{n,t,s}^{Load} I_{n,t,s}^{SL+} \tag{f3}$$

$$\alpha_n^{SL,Min} P_{n,t,s}^{Load} I_{n,t,s}^{SL-} \leqslant Reg_{n,t,s}^{Up,SL} \leqslant \alpha_n^{SL,Max} P_{n,t,s}^{Load} I_{n,t,s}^{SL-} \tag{f4}$$

$$I_{n,t,s}^{SL+} + I_{n,t,s}^{SL-} \leqslant 1 \tag{f5}$$

$$\sum_t Reg_{n,t,s}^{Up,SL} = \sum_t Reg_{n,t,s}^{Dn,SL} \tag{f6}$$

4. Methodology

The proposed two-stage mechanism is executed as depicted in Fig. 3. As shown in the flowchart, the process initiates with scenario generation in the first step. To accomplish this, a total of 1000 scenarios for wind, radiation, and load demand are created using the Weibull, Beta, and Normal probability distribution functions, respectively. Subsequently, the ScenRed algorithm is applied to select 10 scenarios for these parameters from the initial scenario pool, resulting in 4 scenarios for wind patterns, 3 scenarios for load demand, and 3 scenarios for solar irradiance. The scenarios are then structured in a composite manner ($A \times B \times C$), yielding a total of 36 scenarios. The optimization problem for each layer is subsequently solved using these 36 scenarios.

Moving on to the next step, the first stage of the proposed mechanism is initiated. In the initial layer of this stage, each market participant formulates their day-ahead offers/bids for the energy market and submits them to the pool market. Following this, in the second layer of the first stage, the day-ahead MCP is determined based on the offers and bids submitted by the market players. Upon establishing the MCP in the first stage, the AS markets, encompassing SR and regulation markets, are conducted in the second stage. As evident, the first layer of the second stage involves the day-ahead market. Finally, in the second layer of the

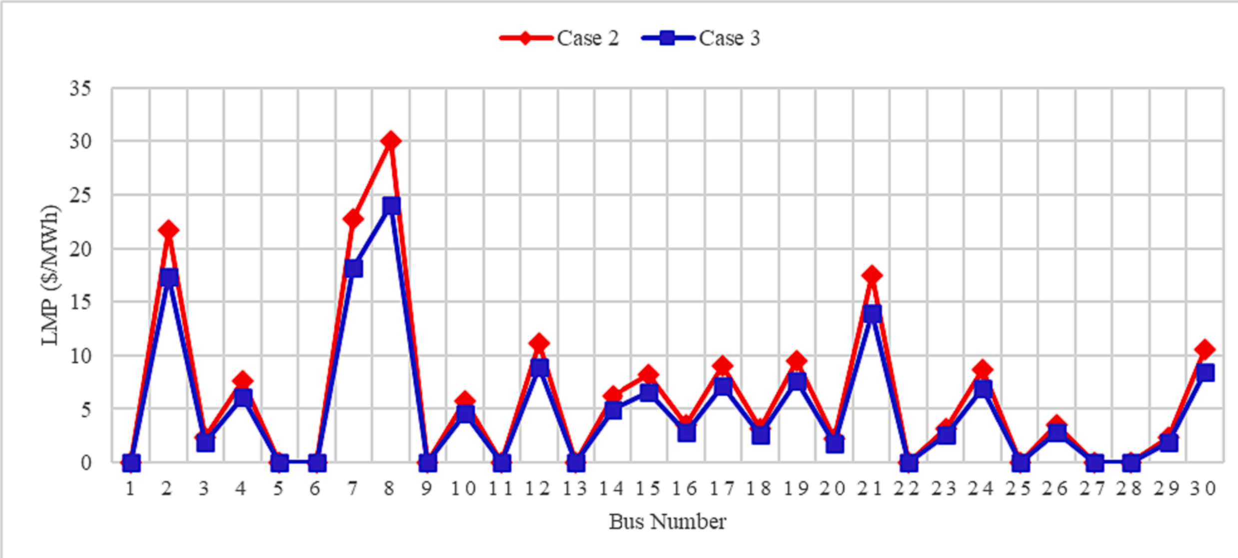


Fig. 11. System LMP in Cases 2 & 3.

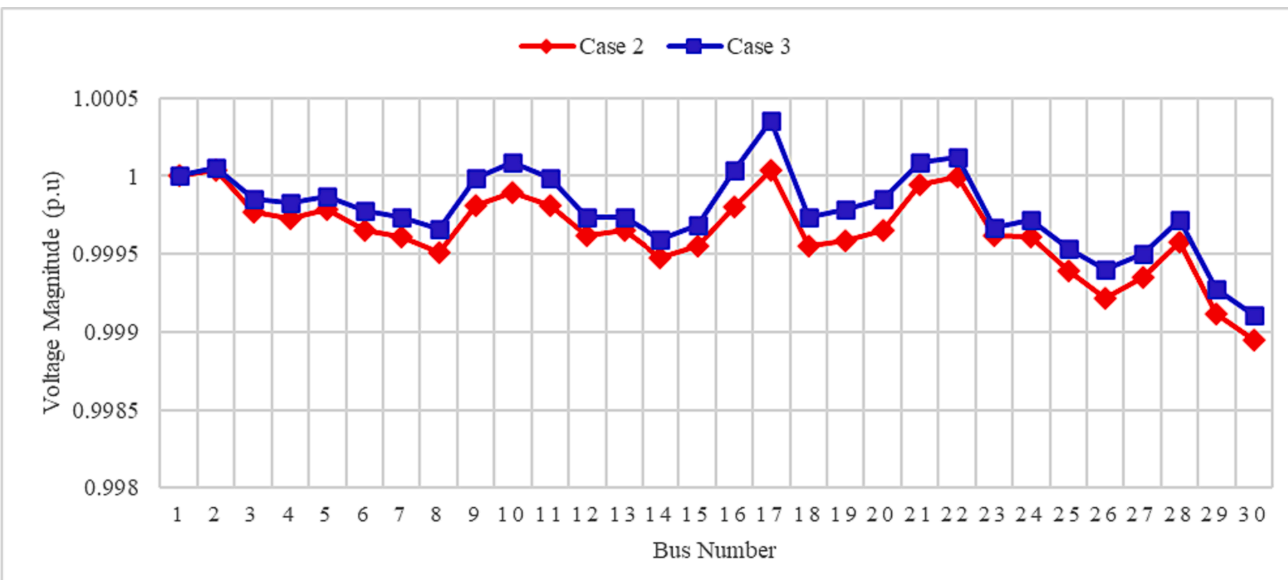


Fig. 12. Voltage profile in Cases 2 & 3.

Table 8
Numerical results obtained from Case 4.

Market Actors	Equipment' OC ($)	Transactions ($)			Sum.
		Energy Market	SR Market	Regulation Market	
TS	64120.36	−2036.19	614.09	4763.36	67461.62
DS 1	1565.29	517.85	−12.32	−152	1918.82
DS 2	1050.57	334.4	−8.61	−427.69	948.67
DS 3	1694.08	502.81	−13.09	−355.33	1828.47
DS 4	2087.72	681.13	−15.23	−337.48	2416.14
Total ($)	70518.02	0	564.84	3490.86	74573.72

second stage, the system's intraday scheduling is executed, giving due consideration to the regulation market. The objective functions and constraints required to solve each layer are presented below:

The first layer of stage 1: Minimization of (1) subject to (2)-(4) and (a1)-(a12).

The second layer of stage 1: Maximization of (5) subject to (6)-(10).

The first layer of stage 2: Minimization of (11) subject to (12), (a1)-(a8), (b1)-(b9) and (c1)-(c2).

The second layer of stage 2: Minimization of (13) subject to (14), (a1)-(a8), (b1)-(b9), (c1)-(c2), (d1)-(d6), (e1)-(e7) and (f1)-(f6).

5. Simulation results

5.1. Input data

Five distinct case studies have been meticulously crafted to assess the efficacy of the proposed two-stage mechanism in enhancing both the economic and technical metrics of TSO-DSO coordination. Comprehensive insights into the particulars of these studied cases can be found

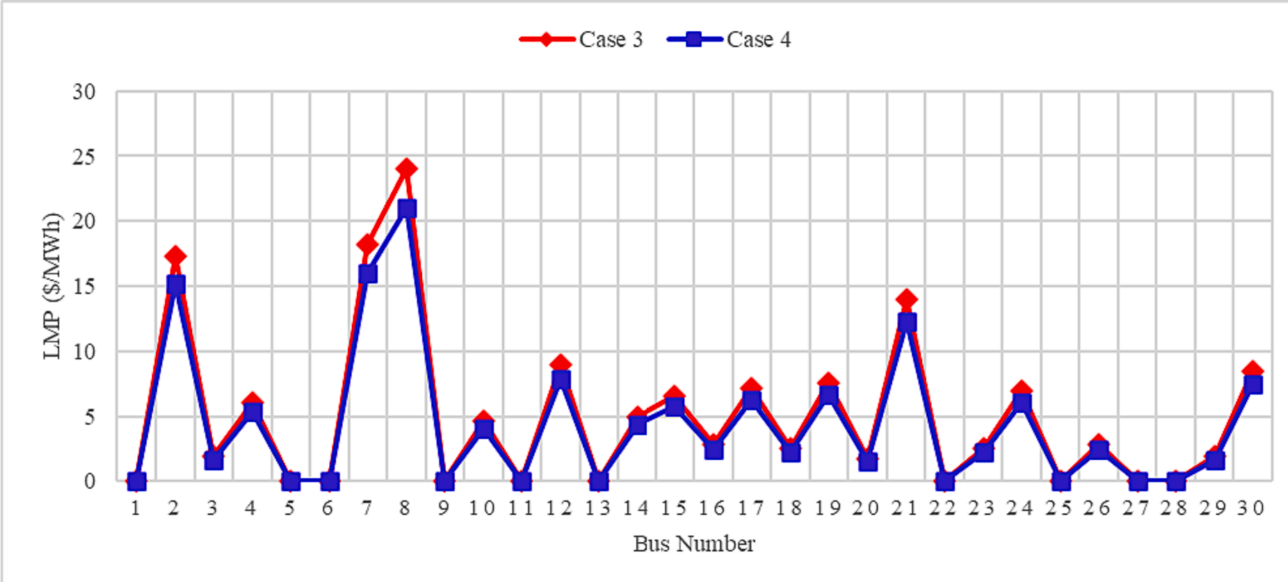


Fig. 13. System LMP in Cases 3 & 4.

in Table 2. It is worth noting that these case studies offer an in-depth analysis of how various market participants influence the SR and regulation markets, providing valuable insights into the intricate dynamics of these essential components. Table 3 provides information on components of TS and DSs. Table 4 gives the values of the problem parameters. Fig. 4a – d present load, wind speed and radiation scenarios. Note that scenarios related to the presence/absence status of EVs are in accordance with Ref. [23]. The scenarios related to the required SR and regulation capacities of the system are displayed in Fig. 5a and b, respectively.

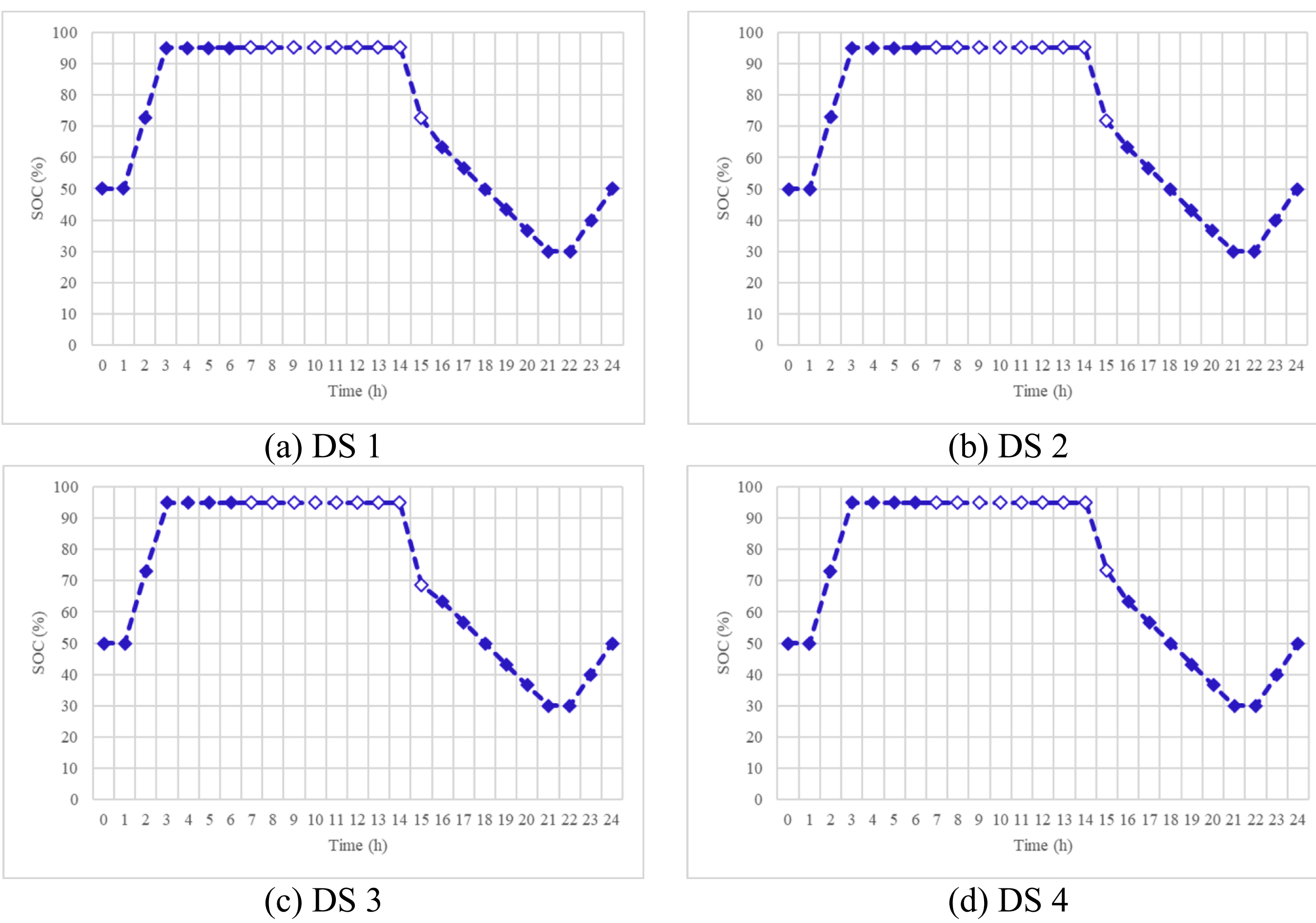


Fig. 14. The performance curve of parking lots.

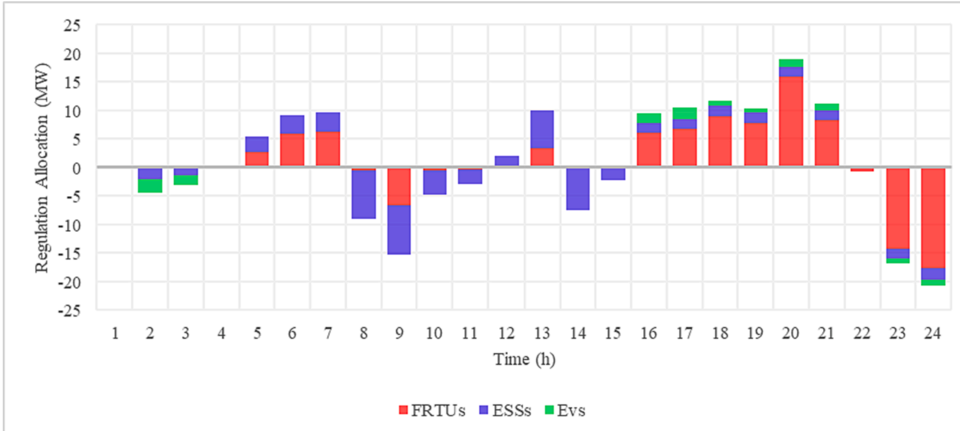


Fig. 15. Regulation capacity providers in Case 4.

Table 9
Numerical results obtained from Case 5.

Market Actors	Equipment' OC ($)	Transactions ($)			Sum.
		Energy Market	SR Market	Regulation Market	
TS	62939.65	−1625.2	614.98	4645.42	66574.85
DS 1	1736.72	413.3	−11.24	−463.83	1674.95
DS 2	1182.33	237.45	−8.37	−673.23	738.18
DS 3	1854.56	407.88	−12.55	−640.35	1609.54
DS 4	2284.39	566.57	−14	−717.64	2119.32
Total ($)	69997.65	0	568.82	2150.37	72716.84

5.2. Results of Cases 1 & 2

In this subsection, numerical results obtained from Cases 1 and 2 are presented. In Case 1, only the TUs located on TS provide the SR of the system, while in Case 2 the DSs also participate in the SR market. The results obtained from Cases 1 and 2 are presented in Tables 5 and 6, respectively. According to these results, the participation of DSs in the SR market has led to an increase in their revenue, and thus a reduction in their total costs. In addition, the numerical outputs illustrate that the total cost of the SR market in Case 2 is reduced by about 10 % over Case 1, which is due to the lower operation cost of TUs located on DSs compared to TUs located on the TS. Fig. 6a and b show the SR providers in Cases 1 and 2, the analysis of which demonstrates that the participation rate of expensive TUs of TS in Case 2 has decreased significantly over Case 1, and on the other hand, a part of SR capacities has been supplied by TUs of DSs. In order to investigate the effect of the regulation market on the TS congestion, the operation problem is solved once without considering the regulation market and once with considering this market, and the results are presented in Fig. 7a and b. It should be noted that the regulation capacity providers in this case are FRTUs located in the TS. The evaluation of Fig. 7a and b illustrates that neglecting the regulation market has led to the congestion of lines 10, 29, 30, 33 and 35 at peak hours (21 o'clock) and, in contrast, considering the regulation market has led to a significant reduction in the congestion in mentioned lines. Fig. 8 also depicts the effect of the regulation market on the TS voltage profile at peak hour. As can be seen, the regulation market leads to an increase in the voltage level in peak hour, and as a result, improves the technical and security aspects of the system.

5.3. Results of Cases 3 to 5

The results of Cases 3 to 5 are discussed in this subsection. In Case 3, the proposed mechanism is solved, taking into account the participation of ESSs in the regulation market. The results of Case 3 are tabulated in Table 7. The numbers of the table indicate that the total costs of the regulation market in Case 3 have decreased by about 16.06 % compared to Case 2, which is due to the participation of ESSs in the regulation market. The performance of ESSs is illustrated in Fig. 9a – d, which clear that these systems exactly correspond to the signal of up and down regulation markets. It can be clearly seen that ESSs are discharged during the regulation up period while they are charged during the regulation down period.

In addition, analysis of the operating point of ESSs reveals that by storing energy in the early hours of the day and injecting it into the grid during peak hours, flexibility is increased while operating costs are minimized. Fig. 10a and b respectively depict the regulation capacity providers in Cases 2 and 3. These figures show that in Case 2, all regulation capacity is provided by fast-response TUs, while in Case 3, a considerable portion of the regulation capacity is provided by ESSs. In this regard, Fig. 11 presents the LMP of TS in Cases 2 and 3. Comparison of LMPs in this figure reveals that ESSs participation in the regulation market has made LMP smoother in Case 3, which is due to the lower operating cost of these systems over fast-response TUs. It should be noted that LMP is zero in the no-load points of the network. Finally, Fig. 12 depicts the effects of ESSs participation in the regulation market on the voltage profile at peak hour. Evaluation of this figure shows that ESSs have increased the voltage level at their connection points to the grid.

In Case 4, in addition to fast-response generators and ESSs, EV parking lots also participate in the regulation market. Table 8 provides the output numbers of the simulation of Case 4. Numerical results obtained from Case 4 show that the participation of EVs in the regulation market has led to a 1074.03$ reduction in regulation market costs compared to Case 3. In addition, a comparison of the LMPs obtained for Cases 3 and 4 in Fig. 13 shows that EVs' participation in the regulation market resulted in a relative decrease in LMPs during peak hour (21:00). Fig. 14a – d depict the operating point of parking lots placed in DSs. As per Fig. 14a – d, EVs have been discharged between the hours of 16:00 and 21:00, which is the period of up-regulation demand. As it is clear from Fig. 14a – d, there was no charging or discharging in the parking lots between the hours of 7:00 and 15:00, since there are no EVs in the parking lot during these hours. Fig. 15 depicts the regulation capacity providers in Case 4. According to this figure, fast-response generators have the largest share in the regulation market, which is due to the large capacity of these units. This figure also shows that about 43.01 % of the regulation capacity is provided by ESSs and Parking lots.

In Case 5, in addition to fast-response generators and EV parking lots, DR aggregators also participate in the regulation market. To this end, DR aggregators purchase part of the consumers load through two programs,

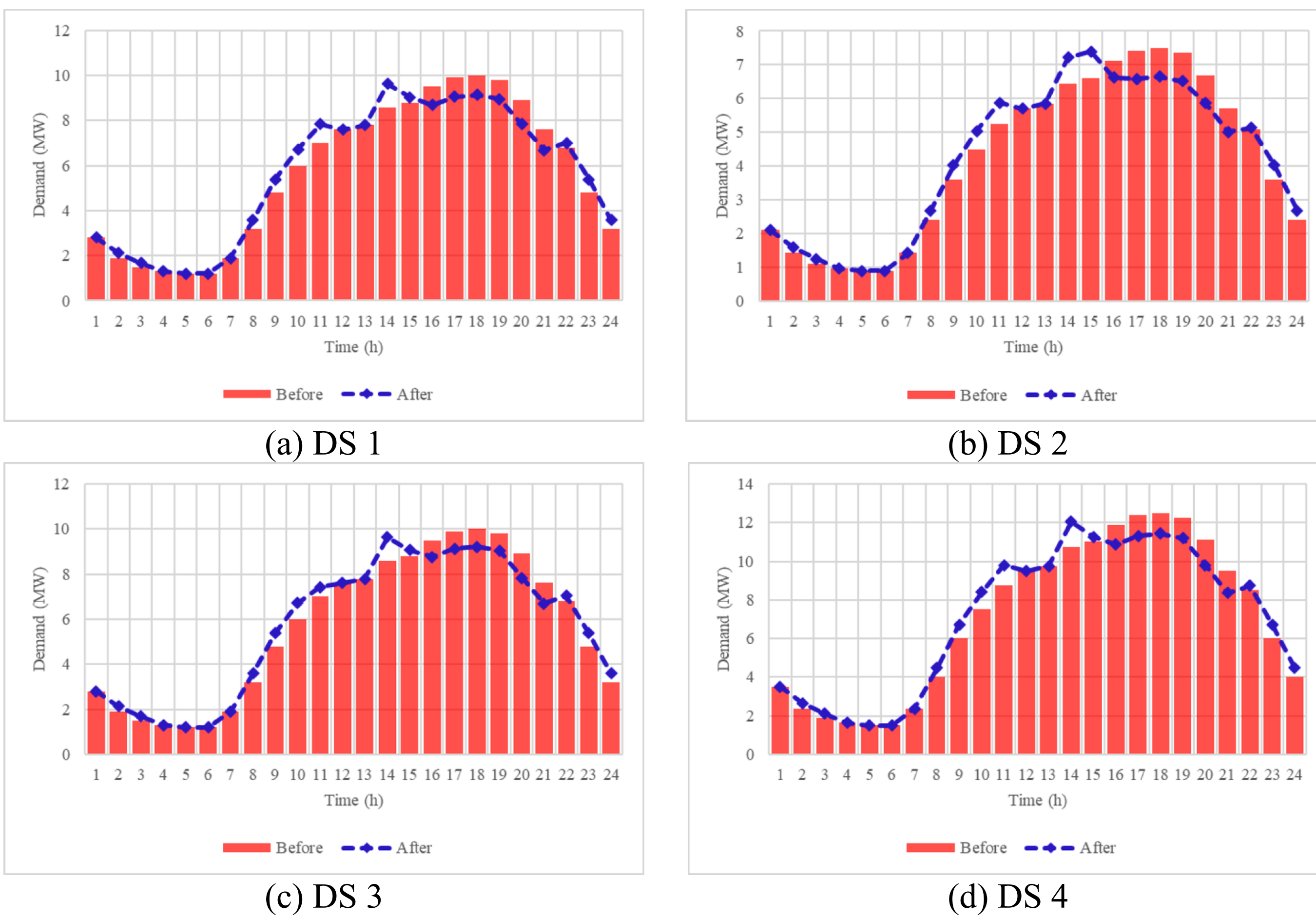


Fig. 16. Impact of DR programs on demand curves of DSs.

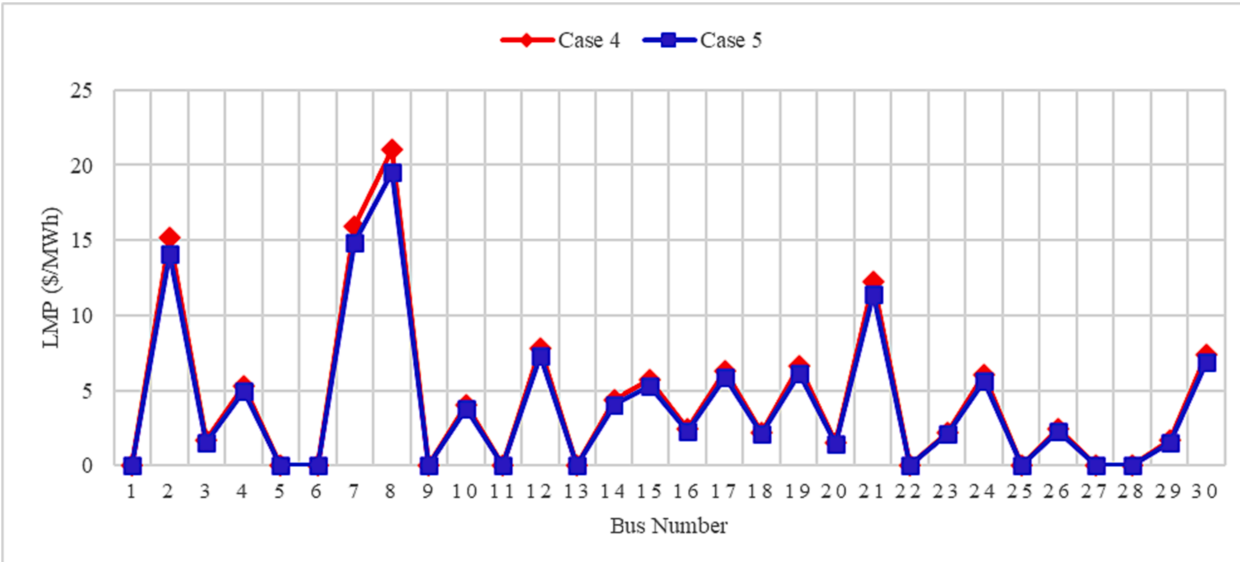


Fig. 17. System LMP in Cases 4 & 5.

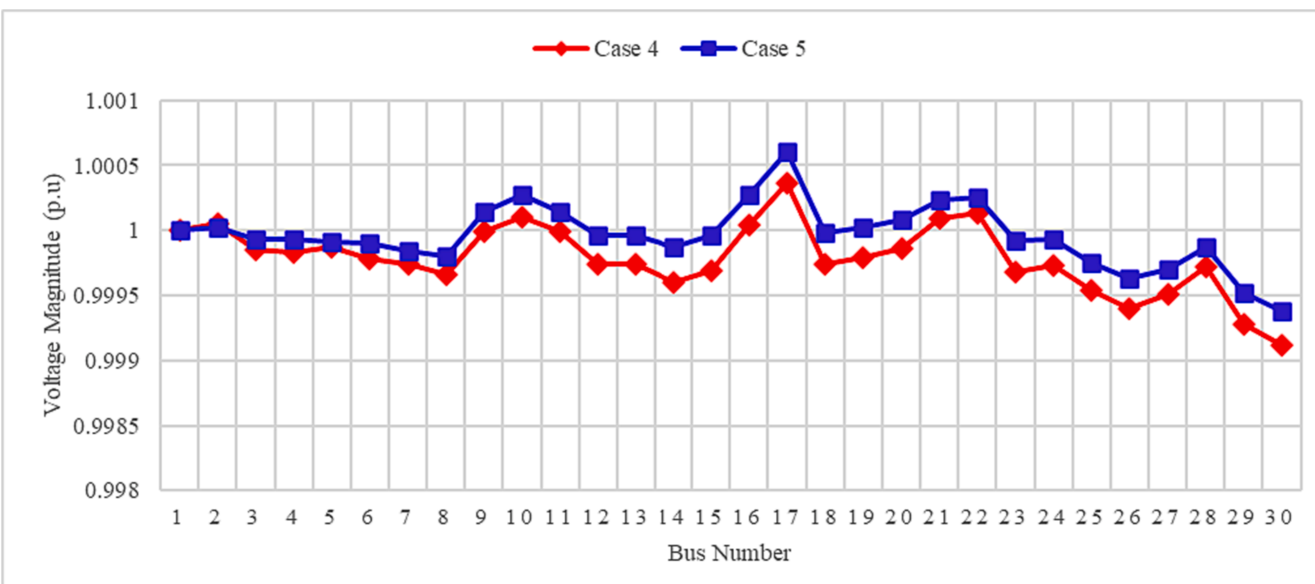


Fig. 18. Voltage profile in Cases 4 & 5.

curtailable-load and shifting-load, and offer it at a higher price in the regulation market. The results of Table 9 reveal that the regulation market costs in Case 5 decreased by 1340.49$ over Case 4, due to the participation of DR aggregators in the regulation market. Fig. 16a – d depict the demand curve for DSs before and after the participation of end-users in DR programs, the evaluation of which shows a significant decrease in demand during the peak period of the up-regulation market (from 16:00 to 21:00). Fig. 17 shows that in Case 5 the LMP of the TS during the peak period is reduced over Case 4, which is due to the decrease in network' load demand in this period. Comparison of numerical results illustrates that the simultaneous participation of ESSs, EVs and DR aggregators in the regulation market in Case 5 has led to a 38.4 % reduction in regulation market costs over Case 4. In Fig. 18, the voltage profiles in Cases 4 and 5 are compared, the analysis of which shows the high impact of the implementation of DR programs on increasing the network voltage level during peak hours.

In Fig. 19, a comparative analysis of system losses in Cases 2 to 5 sheds light on the influence of distribution-level resource participation in the regulation market on the transmission losses. The depicted trends in Fig. 19 unveil a noteworthy correlation: as the engagement of distribution-level resources intensifies in the regulation market, the losses within the transmission system diminish. This observation underscores the pivotal role played by distribution-level resources in optimizing system performance. It's crucial to emphasize that when a substantial portion of the required regulation capacities for the system is sourced from distribution-level providers, it triggers a cascading effect. This, in turn, has led to a reduction in the production level of transmission-level TUs and, consequently, a notable decrease in transmission system losses. This finding reinforces the importance of leveraging distribution-level resources in enhancing the overall efficiency of the transmission network. Overall, the results definitively establish that the engagement of diverse distribution-level resources in

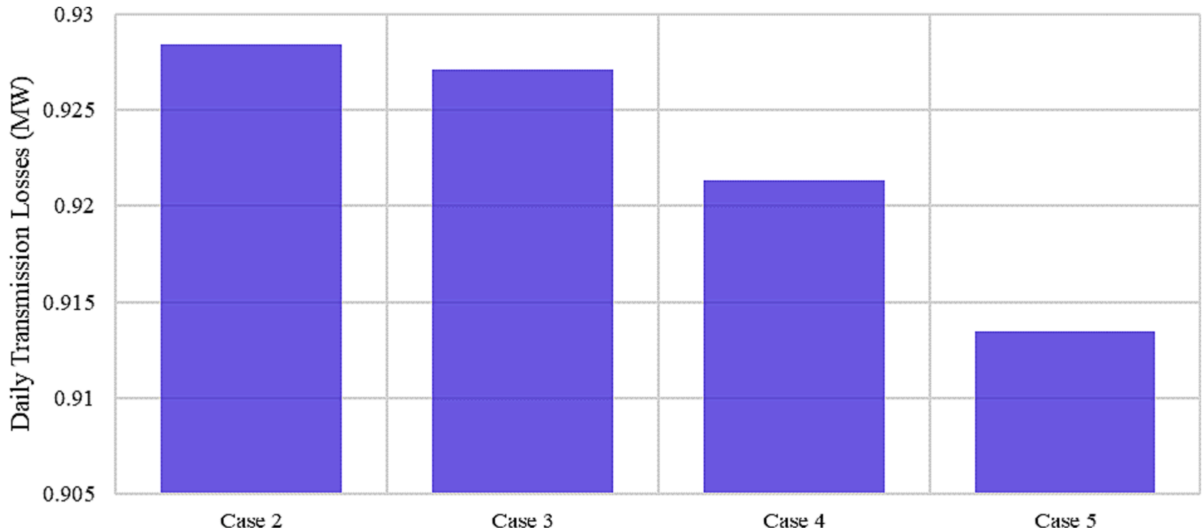


Fig. 19. Daily transmission losses in Cases 2–5.

the regulation market not only amplifies operational flexibility but also culminates in reduced market costs and diminished losses.

6. Conclusion

A two-stage optimization mechanism for coordinated scheduling of TSO-DSO energy and AS markets in the presence of RGs, EVs, EESs, and DR aggregators was presented in this work. The introduced mechanism was modeled in a two-stage format, in the first and second stages of which energy and AS markets were held, respectively. This mechanism was implemented on a 30-bus TS connected to four 10-node DSs, and the highlights are listed below:

- The simulation outputs revealed that DSs participation in the SR market reduced the share of expensive TUs in the market and thus reduced market costs by 10 %. The results also showed that capacity regulation market not only significantly reduced system congestion but also improved the voltage profile. The results also mirrored that holding the regulation market resulted in LMP reduction during the peak period.
- The simulation outputs mirrored that the participation of ESSs and EVs in the regulation market led to the supply of part of the regulation capacity by these resources and reduced the share of expensive fast-response generators in the market. In addition, the results proved the great effect of these resources on reducing the LMP and improving the voltage profile.
- The results showed that implementation of curtailable-load and shifting-load DR programs significantly improved the consumption pattern of consumers. The numerical outputs also revealed that the participation of DR aggregators in the regulation market not only reduced the LMP during the peak period, but also reduced total system costs by 2.48 %.

Totally, the results proved that the introduced two-stage optimization mechanism used the potential of ESSs, EVs and DR programs to improve the technical, security and economic aspects of the coordinated TS and DS.

CRediT authorship contribution statement

XiaoPei Nie: Conceptualization, Methodology, Software, Writing – original draft. **Seyed Amir Mansouri:** Methodology, Software, Writing – original draft. **Ahmad Rezaee Jordehi:** Validation. **Marcos Tostado-Véliz:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Lezama F, Soares J, Canizes B, Vale Z. Flexibility management model of home appliances to support DSO requests in smart grids. Sustain Cities Soc 2020;55:102048. https://doi.org/10.1016/j.scs.2020.102048.

[2] Villanueva-Rosario JA, Santos-García F, Aybar-Mejía ME, Mendoza-Araya P, Molina-García A. Coordinated ancillary services, market participation and communication of multi-microgrids: A review. Appl Energy 2022;308:118332. https://doi.org/10.1016/j.apenergy.2021.118332.

[3] Tostado-Véliz M, Kamel S, Hasanien HM, Turky RA, Jurado F. Optimal energy management of cooperative energy communities considering flexible demand, storage and vehicle-to-grid under uncertainties. Sustain Cities Soc 2022;84:104019. https://doi.org/10.1016/j.scs.2022.104019.

[4] Kumar R, Channi HK. A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: Design, optimization and techno-economic-environmental analysis. J Clean Prod 2022;349:131347. https://doi.org/10.1016/j.jclepro.2022.131347.

[5] Chen H, Wang D, Zhang R, Jiang T, Li X. Optimal participation of ADN in energy and reserve markets considering TSO-DSO interface and DERs uncertainties. Appl Energy 2022;308:118319. https://doi.org/10.1016/j.apenergy.2021.118319.

[6] Kucukvar M, Onat NC, Kutty AA, Abdella GM, Bulak ME, Ansari F, et al. Environmental efficiency of electric vehicles in Europe under various electricity production mix scenarios. J Clean Prod 2022;335:130291. https://doi.org/10.1016/j.jclepro.2021.130291.

[7] Mansouri SA, Ahmarinejad A, Nematbakhsh E, Javadi MS, Jordehi AR, Catalão JPS. Energy management in microgrids including smart homes: A multi-objective approach. Sustain Cities Soc 2021;69:102852. https://doi.org/10.1016/j.scs.2021.102852.

[8] Mansouri SA, Javadi MS. A robust optimisation framework in composite generation and transmission expansion planning considering inherent uncertainties. J Exp Theor Artif Intell 2017;29:717–30. https://doi.org/10.1080/0952813X.2016.1259262.

[9] Habibi M, Vahidinasab V, Sepasian MS. A privacy-preserving approach to day-ahead TSO-DSO coordinated stochastic scheduling for energy and reserve. IET Gener Transm Distrib 2022;16:163–80. https://doi.org/10.1049/gtd2.12286.

[10] Liu J, Tang Z, Zeng PP, Li Y, Wu Q. Distributed adaptive expansion approach for transmission and distribution networks incorporating source-contingency-load uncertainties. Int J Electr Power Energy Syst 2022;136:107711. https://doi.org/10.1016/j.ijepes.2021.107711.

[11] Hermann A, Jensen TV, Østergaard J, Kazempour J. A complementarity model for electric power transmission-distribution coordination under uncertainty. Eur J Oper Res 2022;299:313–29. https://doi.org/10.1016/j.ejor.2021.08.018.

[12] El-Meligy MA, Sharaf M, Soliman AT. A coordinated scheme for transmission and distribution expansion planning: A Tri-level approach. Electr Power Syst Res 2021; 196:107274. https://doi.org/10.1016/j.epsr.2021.107274.

[13] Jiang T, Wu C, Zhang R, Li X, Chen H, Li G. Flexibility Clearing in Joint Energy and Flexibility Markets Considering TSO-DSO Coordination. IEEE Trans Smart Grid 2022::1. https://doi.org/10.1109/TSG.2022.3153634.

[14] Vagropoulos SI, Biskas PN, Bakirtzis AG. Market-based TSO-DSO coordination for enhanced flexibility services provision. Electr Power Syst Res 2022;208:107883. https://doi.org/10.1016/j.epsr.2022.107883.

[15] Papalexopoulos A, Frowd R, Birbas A. On the development of organized nodal local energy markets and a framework for the TSO-DSO coordination. Electr Power Syst Res 2020;189:106810. https://doi.org/10.1016/j.epsr.2020.106810.

[16] Betancourt-Paulino P, Chamorro HR, Soleimani M, Gonzalez-Longatt F, Sood VK, Martinez W. On the perspective of grid architecture model with high TSO-DSO interaction. IET Energy Syst Integr 2021;3:1–12. https://doi.org/10.1049/esi2.12003.

[17] Rossi M, Migliavacca G, Viganò G, Siface D, Madina C, Gomez I, et al. TSO-DSO coordination to acquire services from distribution grids: Simulations, cost-benefit analysis and regulatory conclusions from the SmartNet project. Electr Power Syst Res 2020;189:106700. https://doi.org/10.1016/j.epsr.2020.106700.

[18] Abdolahi A, Gazijahani FS, Alizadeh A, Kalantari NT. Chance-constrained CAES and DRP scheduling to maximize wind power harvesting in congested transmission systems considering operational flexibility. Sustain Cities Soc 2019;51:101792. https://doi.org/10.1016/j.scs.2019.101792.

[19] Dehnavi E, Aminifar F, Afsharnia S. Congestion management through distributed generations and energy storage systems. Int Trans Electr Energy Syst 2019;29:e12018.

[20] Sheidaei F, Ahmarinejad A. Multi-stage stochastic framework for energy management of virtual power plants considering electric vehicles and demand response programs. Int J Electr Power Energy Syst 2020;120:106047. https://doi.org/10.1016/j.ijepes.2020.106047.

[21] Mansouri SA, Ahmarinejad A, Nematbakhsh E, Javadi MS, Esmaeel Nezhad A, Catalão JPS. A sustainable framework for multi-microgrids energy management in automated distribution network by considering smart homes and high penetration of renewable energy resources. Energy 2022::123228. https://doi.org/10.1016/j.energy.2022.123228.

[22] Sheidaei F, Ahmarinejad A, Tabrizian M, Babaei M. A stochastic multi-objective optimization framework for distribution feeder reconfiguration in the presence of renewable energy sources and energy storages. J Energy Storage 2021;40:102775. https://doi.org/10.1016/j.est.2021.102775.

[23] Amir Mansouri S, Javadi MS, Ahmarinejad A, Nematbakhsh E, Zare A, Catalão JPS. A coordinated energy management framework for industrial, residential and commercial energy hubs considering demand response programs. Sustain Energy Technol Assessments 2021;47:101376. https://doi.org/10.1016/j.seta.2021.101376.

[24] Ahmad S. Review for "Interactive <scp>FACTS</scp> and demand response program as an incremental welfare consensus for maximizing wind power penetration" 2020. https://doi.org/10.1002/2050-7038.12526/v1/review3.

[25] Wang X, Xu T, Mu Y, Wang Z, Deng Y, Zhang T, et al. Congestion management under peer-to-peer energy trading scheme among microgrids through cooperative game. Energy Rep 2022;8:59–66. https://doi.org/10.1016/j.egyr.2021.11.130.

[26] Wang L, Kwon J, Schulz N, Zhou Z. Evaluation of Aggregated EV Flexibility With TSO-DSO Coordination. IEEE Trans Sustain Energy 2022:1–12. https://doi.org/10.1109/TSTE.2022.3190199.

[27] Roustaei M, Letafat A, Sheikh M, chabok A, Sadoughi R, Ardeshiri M. A cost-effective voltage security constrained congestion management approach for transmission system operation improvement. Electr Power Syst Res 2022;203:107674. https://doi.org/10.1016/j.epsr.2021.107674.

[28] Chen Y, Casto A, Wang F, Wang Q, Wang X, Wan J. Improving Large Scale Day-Ahead Security Constrained Unit Commitment Performance. IEEE Trans Power Syst 2016;31:4732–43. https://doi.org/10.1109/TPWRS.2016.2530811.

[29] Wang X, Zhao T, Parisio A. Frequency regulation and congestion management by Virtual Storage Plants. Sustain Energy, Grids Networks 2022;29:100586. https://doi.org/10.1016/j.segan.2021.100586.

[30] Tarashandeh N, Karimi A. Utilization of energy storage systems in congestion management of transmission networks with incentive-based approach for investors. J Energy Storage 2021;33:102034. https://doi.org/10.1016/j.est.2020.102034.

[31] Saberi H, Zhang C, Dong ZY. Capacity of Virtual Energy Storage System for Frequency Regulation Services Via a Data-Driven Distributionally Robust Optimization Method. IEEE Trans Power Syst 2022:1–13. https://doi.org/10.1109/tpwrs.2022.3193899.

[32] Garcia-Torres F, Bordons C, Tobajas J, Real-Calvo R, Santiago I, Grieu S. Stochastic Optimization of Microgrids With Hybrid Energy Storage Systems for Grid Flexibility Services Considering Energy Forecast Uncertainties. IEEE Trans Power Syst 2021;36:5537–47. https://doi.org/10.1109/tpwrs.2021.3071867.

[33] Safaie AA, Alizadeh Bidgoli M, Javadi S. A multi-objective optimization framework for integrated electricity and natural gas networks considering smart homes in downward under uncertainties. Energy 2022;239:122214. https://doi.org/10.1016/j.energy.2021.122214.

[34] Paul K. Modified grey wolf optimization approach for power system transmission line congestion management based on the influence of solar photovoltaic system. Int J Energy Environ Eng 2022. https://doi.org/10.1007/s40095-021-00457-2.

[35] Javanmard B, Tabrizian M, Ansarian M, Ahmarinejad A. Energy management of multi-microgrids based on game theory approach in the presence of demand response programs, energy storage systems and renewable energy resources. J Energy Storage 2021;42:102971. https://doi.org/10.1016/j.est.2021.102971.

[36] Paredes Á, Aguado JA, Rodrí-guez P. Uncertainty-Aware Trading of Congestion and Imbalance Mitigation Services for Multi-DSO Local Flexibility Markets. IEEE Trans Sustain Energy 2023:1–13. https://doi.org/10.1109/tste.2023.3257405.

[37] Kara G, Pisciella P, Tomasgard A, Farahmand H, Crespo del Granado P. Stochastic local flexibility market design, bidding, and dispatch for distribution grid operations. Energy 2022;253:123989. https://doi.org/https://doi.org/10.1016/j.energy.2022.123989.

[38] Braga Flôr VB, Do Coutto Filho MB, Stachinni de Souza JC, Satoru Ochi L. Strategic observation of power grids for reliable monitoring. Int J Electr Power Energy Syst 2022;138:107959. https://doi.org/https://doi.org/10.1016/j.ijepes.2022.107959.

[39] Grisales-Noreña LF, Montoya OD, Gil-González WJ, Perea-Moreno A-J, Perea-Moreno M-A. A Comparative Study on Power Flow Methods for Direct-Current Networks Considering Processing Time and Numerical Convergence Errors. Electronics 2020;9. https://doi.org/10.3390/electronics9122062.

[40] Chen Y, Wang H, Yan Z, Xu X, Zeng D, Ma B. A two-phase market clearing framework for inter-provincial electricity trading in Chinese power grids. Sustain Cities Soc 2022;85:104057. https://doi.org/10.1016/j.scs.2022.104057.

[41] Ruwaida Y, Chaves-Avila JP, Etherden N, Gomez-Arriola I, Gürses-Tran G, Kessels K, et al. TSO-DSO-Customer coordination for purchasing flexibility system services: Challenges and lessons learned from a demonstration in Sweden. IEEE Trans Power Syst 2022:1–13. https://doi.org/10.1109/TPWRS.2022.3188261.

[42] Yamujala S, Jain A, Sreekumar S, Bhakar R, Mathur J. Enhancing power systems operational flexibility with ramp products from flexible resources. Electr Power Syst Res 2022;202:107599. https://doi.org/10.1016/j.epsr.2021.107599.

[43] Mansouri SA, Nematbakhsh E, Jordehi AR, Marzband M, Tostado-Véliz M, Jurado F. An interval-based nested optimization framework for deriving flexibility from smart buildings and electric vehicle fleets in the TSO-DSO coordination. Appl Energy 2023;341:121062. https://doi.org/10.1016/j.apenergy.2023.121062.

[44] Nanou SI, Psarros GN, Papathanassiou SA. Network-constrained unit commitment with piecewise linear AC power flow constraints. Electr Power Syst Res 2021;195:107125. https://doi.org/10.1016/j.epsr.2021.107125.

[45] Chaudhary G, Lamb JJ, Burheim OS, Austbø B. Review of Energy Storage and Energy Management System Control Strategies in Microgrids. Energies 2021;14. https://doi.org/10.3390/en14164929.

[46] Zheng Y, Shao Z, Lei X, Shi Y, Jian L. The economic analysis of electric vehicle aggregators participating in energy and regulation markets considering battery degradation. J Energy Storage 2022;45:103770. https://doi.org/10.1016/j.est.2021.103770.

[47] Makeen P, Memon S, Elkasrawy MA, Abdullatif SO, Ghali HA. Smart green charging scheme of centralized electric vehicle stations. Int J Green Energy 2022;19:490–8. https://doi.org/10.1080/15435075.2021.1947822.

[48] Liu X, Li Y, Lin X, Guo J, Shi Y, Shen Y. Dynamic bidding strategy for a demand response aggregator in the frequency regulation market. Appl Energy 2022;314:118998. https://doi.org/10.1016/j.apenergy.2022.118998.

[49] Balasubramanian S, Balachandra P. Effectiveness of demand response in achieving supply-demand matching in a renewables dominated electricity system: A modelling approach. Renew Sustain Energy Rev 2021;147:111245. https://doi.org/10.1016/j.rser.2021.111245.