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ORIGINAL RESEARCH PAPER

A two-stage stochastic bilevel programming approach for offering strategy of DER aggregators in local and wholesale electricity markets

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Abstract
A two-stage stochastic programming scheme is proposed in order to evaluate the offering strategy of a distributed energy resource aggregator in both wholesale and local electricity markets and appropriately cope with uncertainties associated with its decision-making problem. In this regard, the aggregator combines a broad range of virtual and real distributed energy resources to simultaneously participate in the local electricity market as a price-maker or strategic player and the wholesale electricity market as a price-taker or non-strategic player. To model the studied aggregator as a strategic entity in the local market, a bilevel programming approach is exploited in this work. Accordingly, at the upper level of the raised problem, the aggregator tends to promote its expected profit through taking part in the wholesale and local electricity markets, while at the lower level, the considered local market is cleared in a way to maximise the social welfare. In the end, the effectiveness of the proposed framework for the simultaneous participation of the distributed energy resource aggregator in these two markets has been explored utilising a case study.

KEYWORDS
local electricity market, offering strategy, strategic DER aggregator, two-stage stochastic bilevel approach

1 | INTRODUCTION

By and large, distributed energy resources (DERs) are real or virtual generation units that are directly connected to the distribution systems. Depending on their nature and characteristics, these resources are divided into three different categories, including generation units like wind turbines (WTs) and photovoltaics (PVs), energy storage systems like battery storage units (BSUs), and finally, controllable loads such as demand response programmes (DRPs) [1]. Real DERs refer to resources that convert energy from different sources into electricity, such as WTs and PVs. On the contrary, virtual DERs refer to various sources that only exchange electricity or flexibility with the grid, like BSUs and DRPs. Recently, to organise a variety of DERs at the distribution level and get benefit from their provided advantages, including improvement of voltage profile, flexibility, and reliability, peak shaving etc., a concept named the aggregator (AG) platform for integrating the generation as well as the storage capacity of them has been presented [2]. This concept allows DERs' provided energy services to be aggregated to move upward from the local distribution level to the system-wide or transmission system operator (TSO) level. Also, this platform causes easier control and operation of DERs at the distribution level. Accordingly, multiple decentralised sources cooperate with each other in the form of a coalition to not only present valuable services to the distribution system operator (DSO) but also to participate in various electricity markets as an independent financial entity. It is worth noting that the DER AG is a software-based digital platform so it is not necessary for the entire units to be physically integrated within a specific area, and they must be only connected to the AG operator by information and communication technologies (ICTs). In general, the operator of the DER AG acts as an intermediary between customers and varied stakeholders such as the DSO, retailer, and microgrid [3]. Accordingly, its energy trading process is summarised in the following two layers. At the first layer, the AG interacts with its customers by designing appropriate contracts or sending incentive signals. Implementation of this layer requires secure ICT infrastructures, including software, hardware, firmware, and networks at the distribution level that could be achieved in developed countries in the coming years. At the second layer, this agent interacts with different markets to exchange energy or flexibility services. At this stage, the AG makes decisions regarding its optimal participation, namely bids/offers, in different markets. According to the capacity and type of aggregated resources within the DER AG, technical specifications of the distribution and transmission systems, as well as the structure and regulations of the existing electricity markets, this emerging entity is able to take part in varied markets, i.e. the wholesale electricity market (WEM) and local electricity market (LEM), as a price-maker or price-taker player [4]. It is noteworthy that nowadays, even in developed countries, including Nordic countries, energy exchanges between various AGs, customers, and system operators are based on long-term price signals and contracts [5]. Unlike a price-taker DER AG that has only an impact on market outcomes, a price-maker AG has an adequate share of the market to exercise market power and alter market prices for its own benefit. Nonetheless, to implement the decision-making process of a strategic AG, the comprehensive view concerning its objective function, operational constraints of aggregated DERs, technical constraints of networks, uncertainty modelling, and the behaviour of the AG's competitors in markets should be obtained. On the other hand, since the DER AG is an autonomous financial player, it has the opportunity to simultaneously take part in distinct electricity markets such as the WEM and LEM. Nevertheless, this matter requires an appropriate model that can assess several key factors, including the impact of two markets on the optimal offering strategy of the DER AG, the way of interaction among markets, the effect of each markets' uncertainties on the decision-making procedure of the AG, the impact of available participants' behaviour in each market etc.

In recent years, numerous research works have been conducted on the optimal participation of DER AGs in different electricity markets, consisting of the WEM and LEM, some of which are highlighted as follows:

For participation of multiple DERs in the virtual power plant (VPP) platform in the WEM, a two-stage programming scheme has been suggested in [6]. At the first stage of this model, the day-ahead (DA) scheduling of the VPP, as a price-taker player, is optimised in a way to maximise its daily profit. At the second stage, the real-time (RT) imbalance cost of this agent is minimised through adjusting operating points of integrated units within the VPP. A stochastic mixed-integer linear programming method has been utilised in [7] to model the offering strategy of a DER AG in the DA WEM. In this regard, the AG is responsible for managing the energy and financial interactions between DERs and the WEM. This scheduling has been executed from a price-taker AG's point of view aimed at maximising its expected profit. The offering strategy of one DER AG as a price-taker entity in the DA LEM is evaluated in [8]. In this regard, the daily profit of this player has been maximised using a risk-based mathematical optimisation model. For the simultaneous participation of a microgrid in WEM and LEM, a two-stage programming approach has been employed in [9]. Accordingly, at the first stage, offers of this price-taker actor to the DA markets and the optimal operating points of generation units are determined. At the second stage, the optimal operating points of flexible units are achieved. The objective function of this problem is to minimise the total operating costs of the studied microgrid. A robust optimisation model has been utilised in [10], in which a DER AG can simultaneously take part in the DA and RT WEM and LEM as a price-taker agent. Accordingly, the considered AG trades power with the operator of the mentioned markets to minimise its total operating costs. A robust optimisation model has been suggested in [11] to study the bidding strategy of the AG of real and virtual DERs in the DA and RT WEM. The objective function of this price-taker entity is to promote its profits from the involvement in the considered markets. In order to optimise the bidding strategy of several microgrids in the DA LEM, a bilevel competitive model has been suggested in [12]. At the upper level (UL) of this framework, microgrid owners seek to reduce their operating costs by submitting offers to the DSO as the LEM operator. While, at the lower level (LL), the LEM operator clears the market via getting offers from these strategic players. To enhance the participation of DERs in the form of an independent AG in the DA LEM, a bilevel scheme has been provided in [13]. Accordingly, at the UL of the problem, the operating cost of this price-maker entity is minimised, and at the LL, the total welfare of LEM participants is maximised. A linear programming approach has been presented in [14] to optimise the offering strategy of an AG of DERs in the DA reserve market. The main purpose of this price-taker agent is to maximise its expected profit through adjusting the operating points of integrated sources. An optimal bidding strategy according to information gap decision theory has been used in [15] to model the participation of a price-taker DER AG with a wide range of uncertainties in its decision-making process in the WEM. The optimisation problem has been conducted from the AG's viewpoint with the aim of maximising its daily profit. A novel offering strategy has been suggested in [16], in which DER AGs offer price-elastic bids based on the technical constraints of the distribution system to the WEM. This research's objective is to promote the expected profit of the studied AG as well. A stochastic bilevel programming approach has been presented in [17] for investigating the optimal participation of a strategic VPP in the energy and reserve WEM. Accordingly, at the UL of the problem, the VPP, which has aggregated several real and virtual DERs, maximises its expected profit. On the contrary, at the LL of the problem, energy and reserve markets are settled in a way to enhance social welfare. A distributed optimisation method has been suggested in [18] to enable the network-secure bidding strategy of a price-taker DER AG in the RT energy and reserve WEM. In this context, the DER AG interacts and negotiates with the DSO in order to present offers to the WEM that perfectly satisfy the technical as well as operational constraints of the distribution system. In the end, a risk-based bi-objective optimisation framework has been utilised in [19] to study the bidding strategy of a price-taker VPP in the DA WEM. The primary purpose of this work is to not only maximise the profit of the studied VPP but also to minimise the emission of the aggregated units within the VPP.

Analysing the reviewed papers reveals that, normally, in the offering strategy of the DER AG, this entity has been taken into account as a non-strategic player. Considering this simplification, the AG's submitted bids and offers to different markets cannot perfectly reflect the flexible and optimal behaviour of the integrated DERs within the coalition. As a result, this agent is unable to gain the highest possible amount of profit via taking part in electricity markets. For another, it is seen that in most studies, the DER AG has got the opportunity to simultaneously participate in two separate markets, namely WEM and LEM. Hence, these articles have not been able to properly examine the impact of these two markets on the optimal performance of this independent actor as well as the impact of the WEM conditions on the LEM clearing conditions. Aiming to fill the mentioned research gaps, two primary contributions of this study are:

1. Proposing a novel bilevel optimisation model for the offering strategy of a DER AG as a strategic or price-maker player in the LEM considering the behaviour of competitors.
2. Presenting a novel two-stage programming framework to enable the simultaneous involvement of the DER AG in both LEM and WEM.

The remainder of the article is organised as follows: the general overview of the problem, its mathematical formulations, and the utilised solution approach are described in Section 2. The implementation of a typical case study and its discussions are presented in Section 3. Finally, the conclusion is provided in Section 4.

2 | METHODS AND MATERIALS

As mentioned earlier, the main purpose of this study is to investigate the offering strategy of DER AGs in the LEM and the WEM as price-maker and price-taker actors, respectively. In this regard, it is presumed that an independent financial entity aggregates a wide range of DERs located at the distribution level to have more effective and simultaneous participation in both WEM and LEM. In this context, several real and virtual DERs collaborate as a coalition to not only trade energy with one another but also to supply/compensate for their excess/shortage through simultaneous involvement in the mentioned markets. In this case, since a considerable amount of generation and storage capacities is integrated, AGs have the chance to exercise market power via taking part in the LEM as strategic players. To model the behaviour of a strategic AG in the LEM, a bilevel programming approach is executed in this study. At the UL of it, the DER AG's offering strategy in both considered markets is determined, and at the LL, the LEM is cleared by the DSO as the market operator and in the presence of the AG's non-strategic competitors. The described bilevel framework is based on the Stackelberg game-theoretic since the AG as the leader of the game, has the opportunity to obtain local market power, and other participants, as followers of the game, have non-strategic behaviour in this market. In other words, according to the strategic decisions of the DER AG, its competitors compete with one another in a non-cooperative manner. Considering the AG as a price-maker agent allows it to alter LEM clearing prices for its own interests through adjusting the submitted offers/bids. Moreover, enabling the AG's simultaneous participation in both markets increases its flexibility in the decision-making process. On the other hand, to overcome the stochastic nature of uncertain variables, including the RT WEM price, wind speed, and solar irradiance, a scenario-based two-stage stochastic programming scheme has been implemented in this problem. Accordingly, the DER AG's accepted offers in the DA LEM and WEM, as well as operating points of the available dispatchable generators (DGs) within the coalition, are determined at the first stage. At the second stage, after the realisation of random parameters, the AG's traded power with the RT WEM, as well as upward/downward adjustment power of DGs and charge/discharge power of BSUs, are specified. It should be mentioned that, for the realisation of the existing stochastic factors in the raised decision-making process, a high number of scenarios are generated by the Monte Carlo simulation technique and reduced to an adequate number by utilising the fast backward/forward scenario reduction algorithm [20].

The general overview of the raised scheme for the DER AG's offering strategy in both electricity markets is illustrated in more detail in Figure 1.

As shown in Figure 1, the UL's objective function is to increase the expected profit of the considered DER AG through a two-stage stochastic optimisation approach. In contrast, the LL is associated with the LEM clearing process with the aim of social welfare maximisation. By maximising the social welfare, each consumer's surplus and each producer's surplus is increased, which leads to the improvement of the LEM's efficiency. The submitted and accepted offers of the AG in the LEM act as linking variables of these two levels.

2.1 | Problem formulation

Referring to the previous explanations, in the following subsections, objective functions and constraints of the bilevel optimisation problem are formulated from a mathematical viewpoint.

2.1.1 | Upper level problem: offering strategy of DER AG

At the UL of the suggested bilevel framework, the offering strategy of the DER AG as a price-maker player in the LEM and as a price-taker player in the WEM is assessed. This level's

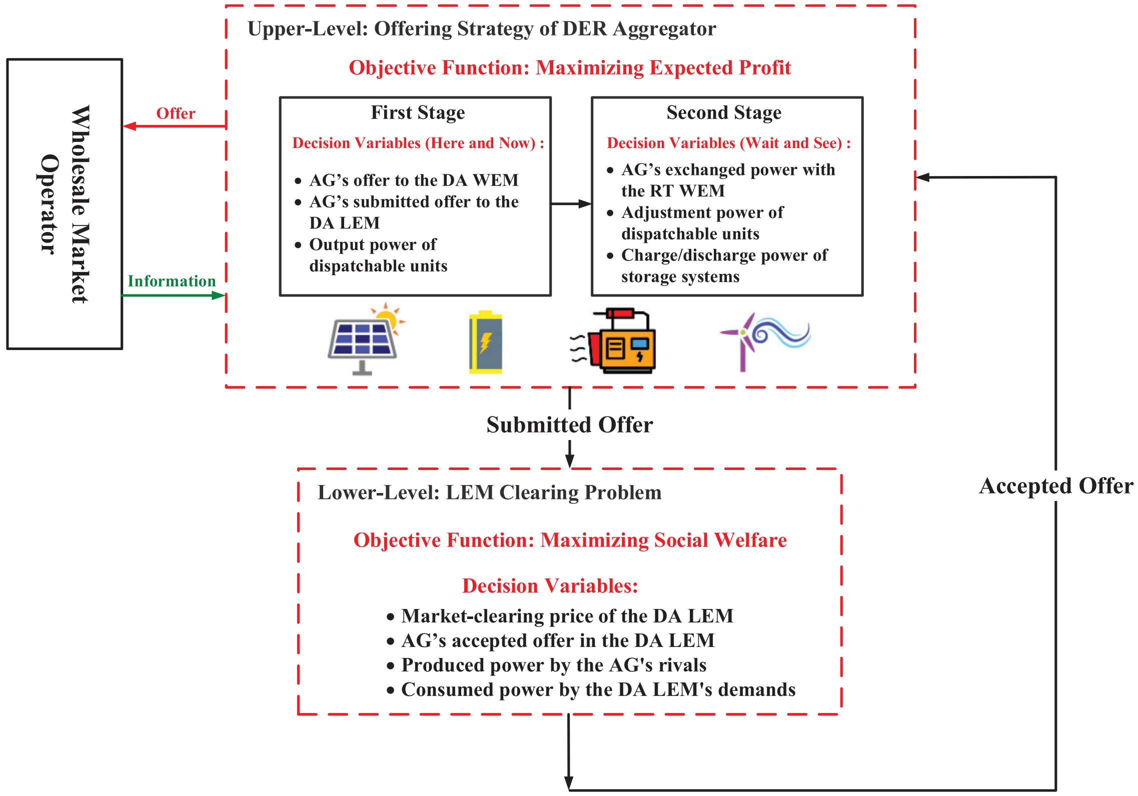

FIGURE 1 Overview of the suggested framework

objective function is to maximise the expected profit of the AG through a two-stage stochastic technique. This objective function is defined as the difference between its income and expenses and includes three main parts, namely income from participation in the DA and RT WEM, income from participation in the DA LEM, and finally, operating costs of DERs integrated within the AG, see Equation (1):

$$\begin{aligned}\mathrm{ObjFun}^{\mathrm{UL}}_{\Omega^{\mathrm{UL}}} = \mathrm{Max} \sum_{h=1}^{H} \Big\{ & q^{\mathrm{AG}}_{\mathrm{WEM,DA}}(h) \cdot \lambda_{\mathrm{WEM,DA}}(h) \\ & + q^{\mathrm{AG}}_{\mathrm{LEM,DA}}(h) \cdot \lambda_{\mathrm{LEM,DA}}(h) \\ & - \sum_{j=1}^{J} P_{\mathrm{DG}}(j,h) \cdot \lambda_{\mathrm{DG}}(j) \\ & + \sum_{s=1}^{S} \varphi(s) \cdot \Big[q^{\mathrm{AG}}_{\mathrm{WEM,RT}}(h,s) \cdot \lambda_{\mathrm{LEM,RT}}(h,s) \\ & - \sum_{j=1}^{J} \big(R_{\mathrm{DG,up}}(j,h,s) \cdot \lambda_{\mathrm{DG,up}}(j) \\ & - R_{\mathrm{DG,dn}}(j,h,s) \cdot \lambda_{\mathrm{DG,up}}(j) \big) \Big] \Big\} \end{aligned} \tag{1}$$

The first and second lines of Equation (1) are related to the first stage of the two-stage stochastic scheme. The first and second terms represent the obtained revenue from taking part in the DA WEM and DA LEM, respectively, and the third term indicates the marginal generation cost of DGs. In turn, the third and fourth lines of this equation are associated with the second stage of the two-stage stochastic scheme. The fourth term represents the AG's revenue/expense from involvement in the RT WEM, and the fifth expression shows the power adjustment costs of DGs. The introduced objective function is subject to a set of technical and operational constraints, as follows:

1. *Constraints of the DA and RT power balance*

Clearly, the amount of power offered by the AG to both DA markets should be equal to the generation capacity of its own units, i.e. DGs, WTs, and PVs, as shown in Equation (2):

$$\begin{aligned} & q^{\mathrm{AG}}_{\mathrm{WEM,DA}}(h) + q^{\mathrm{AG}}_{\mathrm{LEM,DA,Of}}(h) \\ & = \sum_{j=1}^{J} P_{\mathrm{DG}}(j,h) + \sum_{w=1}^{W} P^{F}_{\mathrm{WT}}(w,h) + \sum_{p=1}^{P} P^{F}_{\mathrm{PV}}(p,h), \quad \forall h \end{aligned} \tag{2}$$

After the realisation of stochastic factors, the DER AG must compensate for its shortage or supply its excess by involvement in the RT WEM. This issue is demonstrated in more detail in Equation (3). As shown in this expression, the studied AG exploits the storage capacity of BSUs and the upward/downward adjustment power of DGs to trade its surplus or shortage in the RT WEM.

$$q_{\text{WEM,RT}}^{\text{AG}}(h,s)=\sum_{w=1}^{W}\left(P_{\text{WT}}(w,h,s)-P_{\text{WT}}^{F}(w,h)\right)+\sum_{p=1}^{P}\left(P_{\text{PV}}(p,h,s)-P_{\text{PV}}^{F}(p,h)\right)+\sum_{j=1}^{J}\left(R_{\text{DG,up}}(j,h,s)-R_{\text{DG,dn}}(j,h,s)\right)+\sum_{b=1}^{B}\left(P_{\text{BSU,dch}}(b,h,s)-P_{\text{BSU,ch}}(b,h,s)\right),\quad \forall h,s \tag{3}$$

2. *Constraints of offers to the DA LEM and WEM*

In general, offers of the DER AG to both DA markets are non-negative decision variables that are depicted by Equations (4) and (5).

$$q_{\text{WEM,DA}}^{\text{AG}}(h)\geq 0,\quad \forall h \tag{4}$$

$$q_{\text{LEM,DA,Of}}^{\text{AG}}(h)\geq 0,\quad \forall h \tag{5}$$

Since the pricing mechanism in the DA WEM is uniform, it is presumed that the DER AG submits its offers to the independent system operator at zero price in order to guarantee their acceptance. In the uniform pricing mechanism, the entire suppliers are paid at the same market-clearing price regardless of their presented offers, which is set at the offer price of the most expensive source selected to provide service [21]. On the contrary, offers of the AG to the DSO as the operator of the DA LEM are submitted with $\lambda_{\text{LEM,DA,Of}}^{\text{AG}}(h)$, which is a non-negative variable.

3. *Constraints of generation units*

The generation and adjustment power of DGs integrated within the DER AG are limited by Equations (6) to (9). Additionally, operational constraints of these units are modelled by Equations (10) and (11) [22]:

$$P_{\text{DG}}(j,h)+R_{\text{DG,up}}(j,h,s)\leq P_{\text{DG}}^{\max}(j),\quad \forall j,h,s \tag{6}$$

$$P_{\text{DG}}(j,h)-R_{\text{DG,dn}}(j,h,s)\geq P_{\text{DG}}^{\min}(j),\quad \forall j,h,s \tag{7}$$

$$R_{\text{DG,up}}^{\min}(j)\leq R_{\text{DG,up}}(j,h,s)\leq R_{\text{DG,up}}^{\max}(j),\quad \forall j,h,s \tag{8}$$

$$R_{\text{DG,dn}}^{\min}(j)\leq R_{\text{DG,dn}}(j,h,s)\leq R_{\text{DG,dn}}^{\max}(j),\quad \forall j,h,s \tag{9}$$

$$P_{\text{DG}}(j,h)-P_{\text{DG}}(j,h-1)\leq RU_{\text{DG}}(j),\ \forall j,h \tag{10}$$

$$P_{\text{DG}}(j,h-1)-P_{\text{DG}}(j,h)\leq RD_{\text{DG}}(j),\quad \forall j,h \tag{11}$$

According to the forecasted amount of wind speed and solar radiation, the generation power of WTs and PVs in the first DA stage is calculated by expressions that are obtained from [23]. Notably, these equations are valid for the second RT stage as well.

4. *Constraints of energy storage units*

Mathematical models as well as operational constraints of BSUs are stated by Equations (12) to (18) [20]. In this regard, the charge and discharge power of these systems is limited by Equations (12) and (13), respectively. Equation (14) is also used to prevent simultaneous charge and discharge of BSUs. Furthermore, the amount of energy stored in BSUs and their related limitations are expressed by Equations (15) to (18):

$$P_{\text{BSU,ch}}^{\min}(b)\cdot U_{\text{BSU,ch}}(b,h,s)\leq P_{\text{BSU,ch}}(b,h,s)\leq P_{\text{BSU,ch}}^{\max}(b)\cdot U_{\text{BSU,ch}}(b,h,s),\quad \forall b,h,s \tag{12}$$

$$P_{\text{BSU,dch}}^{\min}(b)\cdot U_{\text{BSU,dch}}(b,h,s)\leq P_{\text{BSU,dch}}(b,h,s)\leq P_{\text{BSU,dch}}^{\max}(b)\cdot U_{\text{BSU,dch}}(b,h,s),\quad \forall b,h,s \tag{13}$$

$$U_{\text{BSU,ch}}(b,h,s)+U_{\text{BSU,dch}}(b,h,s)\leq 1,\quad \forall b,h,s \tag{14}$$

$$SOC_{\text{BSU}}(b,h,s)=SOC_{\text{BSU}}^{\text{ini}}(b),\quad \forall b,h=1,s \tag{15}$$

$$SOC_{\text{BSU}}(b,h+1,s)=SOC_{\text{BSU}}(b,h,s)+P_{\text{BSU,ch}}(b,h,s)\cdot\eta_{\text{BSU,ch}}(b)-P_{\text{BSU,dch}}(b,h,s)/\eta_{\text{BSU,dch}}(b),\quad \forall b,h<24,s \tag{16}$$

$$SOC_{\text{BSU}}^{\text{fin}}(b)=SOC_{\text{BSU}}(b,h,s)+P_{\text{BSU,ch}}(b,h,s)\cdot\eta_{\text{BSU,ch}}(b)-P_{\text{BSU,dch}}(b,h,s)/\eta_{\text{BSU,dch}}(b),\quad \forall b,h=24,s \tag{17}$$

$$SOC_{\text{BSU}}^{\min}(b)\leq SOC_{\text{BSU}}(b,h,s)\leq SOC_{\text{BSU}}^{\max}(b),\quad \forall b,h,s \tag{18}$$

Accordingly, the initial/final amount of energy stored at the start/end of the first/last time period is modelled by Equations (15) and (17), respectively. Additionally, the energy stored and its limitations at each time interval are expressed by Equations (16) and (18), respectively. In the end, decision variables of the UL problem are listed as the following set:

$$\Omega^{\text{UL}}=\left\{\begin{array}{l} q_{\text{WEM,DA}}^{\text{AG}}(h)\ ,\ q_{\text{LEM,DA,Of}}^{\text{AG}}(h)\ ,\ \lambda_{\text{LEM,DA,Of}}^{\text{AG}}(h)\\ P_{\text{DG}}(j,h)\ ,\ R_{\text{DG,up}}(j,h,s)\ ,\ R_{\text{DG,dn}}(j,h,s)\\ P_{\text{BSU,ch}}(b,h,s),\ P_{\text{BSU,dch}}(b,h,s),\ SOC_{\text{BSU}}(b,h,s),\\ U_{\text{BSU,ch}}(b,h,s)\ ,\ U_{\text{BSU,dch}}(b,h,s)\end{array}\right\}$$

2.1.2 | Lower level problem - LEM clearing process

At the LL of the suggested bilevel framework, the DSO, as the LEM operator, collects offers and bids of the entire market participants at the distribution level to settle the DA LEM with the aim of social welfare maximisation. As previously stated, in this situation, all market participants' surplus is increased, which leads to the improvement of the LEM efficiency [24]. This objective function is defined as the difference between the utility of buyers and the cost of sellers who take part in the market [25]. Equation (19) mathematically models the desired objective function:

$$\mathrm{ObjFun}_{\Omega^{\mathrm{LL}}}^{\mathrm{LL}} = \mathrm{Max} \sum_{h=1}^{H} \left\{ \sum_{d=1}^{D} P_{\mathrm{d}}(d,h) \cdot \lambda_{\mathrm{d}}(d,h) - \sum_{c=1}^{C} P_{\mathrm{com}}(c,h) \cdot \lambda_{\mathrm{com}}(c,h) - q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h) \cdot \lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h) \right\} \quad (19)$$

In the above expression, the first, second, and third terms demonstrate the utility of all consumers, the cost of producers who are the AG's non-strategic competitors, and the cost of the studied DER AG, respectively. The introduced objective function is subject to a set of technical and operational constraints, as follows:

1. *Constraint of the LEM power balance*

Generally, the accepted offers of all market producers, namely the DER AG and its rival, have to meet bids of all market consumers, as stated in Equation (20):

$$q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h) + \sum_{c=1}^{C} P_{\mathrm{com}}(c,h) = \sum_{d=1}^{D} P_{\mathrm{d}}(d,h);\ \lambda_{\mathrm{LEM,DA}}(h), \quad \forall h \quad (20)$$

2. *Constraints of the LEM offers and bids*

In the clearing process of the DA LEM, accepted offers of the DER AG, which is a non-negative variable, should be limited by the submitted offer of this player to the market. This matter is well illustrated in Equation (21):

$$0 \le q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h) \le q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h);\ \underline{\mu}(h), \bar{\mu}(h), \quad \forall h \quad (21)$$

In addition, offers of DER AG's competitors and bids of consumers in the LEM are limited by Equations (22) and (23), respectively:

$$P_{\mathrm{com}}^{\min}(c,h) \le P_{\mathrm{com}}(c,h) \le P_{\mathrm{com}}^{\max}(c,h);\ \underline{\alpha}(c,h), \bar{\alpha}(c,h), \quad \forall c,h \quad (22)$$

$$P_{\mathrm{d}}^{\min}(d,h) \le P_{\mathrm{d}}(d,h) \le P_{\mathrm{d}}^{\max}(d,h);\ \underline{\beta}(d,h), \bar{\beta}(d,h), \quad \forall d,h \quad (23)$$

It is worth noting that in Equations (20) to (23), the dual variables of constraints are shown after the semicolon. In the end, decision variables of the LL problem are listed as the following set:

$$\Omega^{\mathrm{LL}} = \left\{ \begin{array}{l} q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h), P_{\mathrm{com}}(c,h), P_{\mathrm{d}}(d,h) \\ \lambda_{\mathrm{LEM,DA}}(h), \underline{\mu}(h), \bar{\mu}(h), \underline{\alpha}(c,h), \bar{\alpha}(c,h), \underline{\beta}(d,h), \\ \bar{\beta}(d,h) \end{array} \right\}$$

2.1.3 | Outline of the raised bilevel problem

To further clarify the suggested bilevel programming problem in this article, the UL and LL's linking, as well as non-linking decision variables, are displayed in Figure 2.

As it is clear in Figure 2, the DER AG submits $q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}$ and $\lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}$ as the offer and its related price to the LEM operator. Based on this offer as well as received offers and bids from other producers and consumers, the operator settles the DA LEM and makes optimal decisions as for market-clearing points, i.e. $q_{\mathrm{LEM,DA}}^{\mathrm{AG}}$, $\lambda_{\mathrm{LEM,DA}}$, P_{com}, and P_{d}. Afterwards, the LL's linking variables are returned to the DER AG's offering strategy problem so that this entity can evaluate its daily profit.

2.2 | Solving the proposed bilevel problem

As shown in section 2.1.2, the LL's model is continuous, linear, and thus convex. Consequently, the introduced bilevel scheme could be rewritten as a one-level scheme by replacing the LL with its corresponding Karush–Kuhn–Tucker (KKT) conditions [26,27]. In this regard, by forming the LL's Lagrangian function and utilising the related KKT conditions, the bilevel problem's one-level model is formulated as stated in Equation (24):

$$\mathrm{ObjFun}_{\Omega}^{\mathrm{one-level}} = \mathrm{Max\ Equation}(1) \quad (24)$$

In the above expression, Ω is a set of decision variables in the ultimate one-level model, which includes:

$$\Omega = \left\{ \begin{array}{l} q_{\mathrm{WEM,DA}}^{\mathrm{AG}}(h), q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h), \lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h), \\ P_{\mathrm{DG}}(j,h), R_{\mathrm{DG,up}}(j,h,s), R_{\mathrm{DG,dn}}(j,h,s) \\ P_{\mathrm{BSU,dch}}(b,h,s), P_{\mathrm{BSU,ch}}(b,h,s), SOC_{\mathrm{BSU}}(b,h,s), \\ U_{\mathrm{BSU,dch}}(b,h,s), U_{\mathrm{BSU,dch}}(b,h,s) \\ q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h), P_{\mathrm{com}}(c,h), P_{\mathrm{d}}(d,h) \\ \lambda_{\mathrm{LEM,DA}}(h), \underline{\mu}(h), \bar{\mu}(h), \underline{\alpha}(c,h), \bar{\alpha}(c,h), \\ \underline{\beta}(d,h), \bar{\beta}(d,h) \end{array} \right\}$$

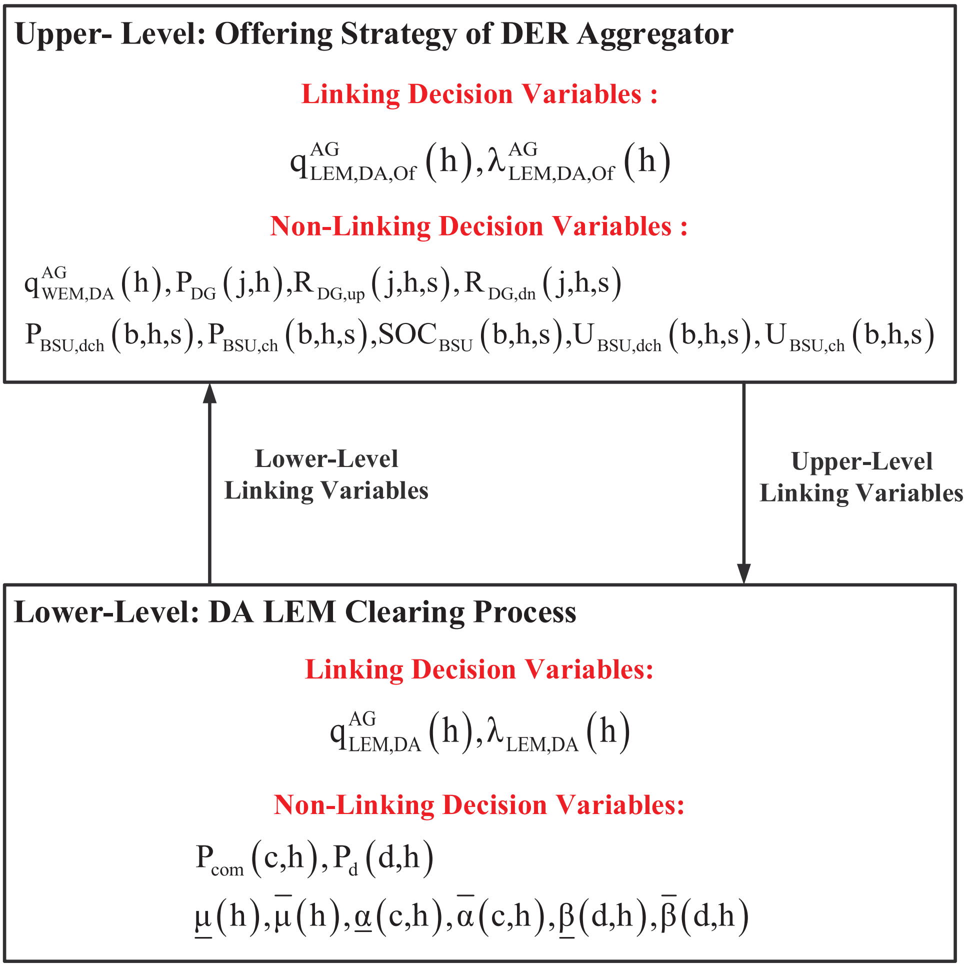

FIGURE 2 Decision variables in the proposed bilevel problem

On the other hand, Equation (24) is subject to a set of constraints, as follows:

$$\text{Equations}(2) - (18), \text{Equation}(20) \tag{25}$$

$$-\lambda^{AG}_{LEM,DA,Of}(h) + \lambda_{LEM,DA}(h) - \bar{\mu}(h) + \underline{\mu}(h) = 0, \quad \forall h \tag{26}$$

$$-\lambda_{com}(c,h) + \lambda_{LEM,DA}(h) - \bar{\alpha}(c,h) + \underline{\alpha}(c,h) = 0, \quad \forall c, h \tag{27}$$

$$\lambda_{d}(d,h) - \lambda_{LEM,DA}(h) - \bar{\beta}(d,h) + \underline{\beta}(d,h) = 0, \quad \forall d, h \tag{28}$$

$$0 \le \left(q^{AG}_{LEM,DA,Of}(h) - q^{AG}_{LEM,DA}(h)\right) \perp \bar{\mu}(h) \ge 0, \quad \forall h \tag{29}$$

$$0 \le q^{AG}_{LEM,DA}(h) \perp \underline{\mu}(h) \ge 0, \quad \forall h \tag{30}$$

$$0 \le (P^{max}_{com}(c,h) - P_{com}(c,h)) \perp \bar{\alpha}(c,h) \ge 0, \quad \forall c, h \tag{31}$$

$$0 \le \left(P_{com}(c,h) - P^{min}_{com}(c,h)\right) \perp \underline{\alpha}(c,h) \ge 0, \quad \forall c, h \tag{32}$$

$$0 \le \left(P^{max}_{d}(d,h) - P_{d}(d,h)\right) \perp \bar{\beta}(d,h) \ge 0, \quad \forall d, h \tag{33}$$

$$0 \le \left(P_{d}(d,h) - P^{min}_{d}(d,h)\right) \perp \underline{\beta}(d,h) \ge 0, \quad \forall d, h \tag{34}$$

$$\lambda_{LEM,DA}(h) \quad \text{Unrestricted}, \tag{35}$$

Nevertheless, the provided one-level problem in Equations (24) to (35) is nonlinear owing to the presence of two sources of nonlinearities, namely the product of $q^{AG}_{LEM,DA}(h) \cdot \lambda_{LEM,DA}(h)$ in Equation (24) as well as the complementary slackness constraints in Equations (29) and (34).

To linearise complementary slackness, the Big-M method [28] is exploited in this work. Also, to linearise $q^{AG}_{LEM,DA}(h) \cdot \lambda_{LEM,DA}(h)$, the strong duality theorem (SDT) [29] and the LL's KKT conditions are utilised. Based on the SDT concept, the

LL's dual problem is written by Equation (36).

$$\sum_{h=1}^{H}\left\{\sum_{d=1}^{D}P_{\mathrm{d}}(d,h)\cdot\lambda_{\mathrm{d}}(d,h)-\sum_{c=1}^{C}P_{\mathrm{com}}(c,h)\cdot\lambda_{\mathrm{com}}(c,h)\right.$$
$$\left.-q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)\right\}$$
$$=\sum_{h=1}^{H}\left\{\sum_{d=1}^{D}\left(P_{\mathrm{d}}^{\max}(d,h)\cdot\bar{\beta}(d,h)-P_{\mathrm{d}}^{\min}(d,h)\cdot\underline{\beta}(d,h)\right)\right.$$
$$+\sum_{c=1}^{C}\left(P_{\mathrm{com}}^{\max}(c,h)\cdot\bar{\alpha}(c,h)-P_{\mathrm{com}}^{\min}(c,h)\cdot\underline{\alpha}(c,h)\right)$$
$$\left.+q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)\cdot\bar{\mu}(h)\right\} \quad (36)$$

From Equation (26):

$$\lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)=\lambda_{\mathrm{LEM,DA}}(h)-\bar{\mu}(h)+\underline{\mu}(h)$$
$$q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)=q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(t)$$
$$\cdot\left(\lambda_{\mathrm{LEM,DA}}(h)-\bar{\mu}(h)+\underline{\mu}(h)\right) \quad (37)$$

From Equations (29) and (30):

$$q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\bar{\mu}(h)=q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)\cdot\bar{\mu}(h) \quad (38)$$

$$q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\underline{\mu}(h)=0 \quad (39)$$

According to Equations (37) and (39):

$$q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\lambda_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)$$
$$=q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\lambda_{\mathrm{LEM,DA}}(h)-q_{\mathrm{LEM,DA,Of}}^{\mathrm{AG}}(h)\cdot\bar{\mu}(h) \quad (40)$$

Finally, by replacing Equation (40) in (36), the considered non-linear term turns into a linear term, as displayed in Equation (41).

$$\sum_{h=1}^{H}q_{\mathrm{LEM,DA}}^{\mathrm{AG}}(h)\cdot\lambda_{\mathrm{LEM,DA}}(h)=$$
$$\sum_{h=1}^{H}\left\{\sum_{d=1}^{D}P_{\mathrm{d}}(d,h)\cdot\lambda_{\mathrm{d}}(d,h)-\sum_{c=1}^{C}P_{\mathrm{com}}(c,h)\cdot\lambda_{\mathrm{com}}(c,h)\right.$$
$$-\sum_{c=1}^{C}\left(P_{\mathrm{com}}^{\max}(c,h)\cdot\bar{\alpha}(c,h)-P_{\mathrm{com}}^{\min}(c,h)\cdot\underline{\alpha}(c,h)\right)$$
$$\left.-\sum_{d=1}^{D}\left(P_{\mathrm{d}}^{\max}(d,h)\cdot\bar{\beta}(d,h)-P_{\mathrm{d}}^{\min}(d,h)\cdot\underline{\beta}(d,h)\right)\right\} \quad (41)$$

3 | CASE STUDY

In this section, the effectiveness of the suggested framework for the simultaneous participation of the DER AG as a price-maker and price-taker player in the LEM and WEM is scrutinised through a typical case study. Accordingly, first, the technical specification of the DER AG and the considered electricity markets are introduced. Next, the results of the simulation and their discussions are presented more accurately.

3.1 | Input data

Characteristics of DERs, including DGs, WTs, PVs, and BSUs, integrated inside the AG are summarised in Table 1 [30,31]. In addition, the solar irradiance and wind speed during the day and in each of the scenarios are displayed in Figures 3 and 4, respectively. Notably, the forecasted values in the DA stage are distinguished with bold lines in these figures. On the other hand, as mentioned earlier, in the two-stage programming scheme, the DER AG is able to participate within the RT WEM to adjust the excess/shortage of its provided offers in the DA first stage. In this regard, energy prices in the RT WEM are demonstrated in Figure 5. In this figure, the energy price in the DA WEM is distinguished with bold lines as well. Concerning the DA LEM, it is presumed that six varied producers participate in this market as the DER AG's non-strategic competitors. Besides, bids from four different consumers are submitted to the LEM operator. It is noteworthy that in this study, offers and bids of these participants are considered on an hourly basis.

3.2 | Simulation results and discussions

In this section, obtained results from the simultaneous participation of the studied DER AG in introduced markets are provided, and the optimal performance of this entity in the presence of both markets is compared with the situation in which this player is only able to take part in one of the existing markets. The considered one-level model in Equations (24) and (41) is a mixed-integer linear programming (MILP) problem that has been solved by the CPLEX solver in GAMS software.

Regarding the outputs, offers of the DER AG to both DA LEM and WEM, as well as the WEM forecasted prices and the LEM clearing prices, are displayed in Figure 6.

Based on Figure 6, the DER AG has provided more power to the DA LEM in the early hours of the day. In contrast, in the middle of the day, when WEM prices are high, the AG has sold more power to this market so that at hours 10 to 12, the AG's total generation capacity is allocated to the WEM. After these hours, since the LEM prices have increased, this player has preferred to allocate most of its production to the local market. Finally, in the last hours of the day, by increasing the energy price in the DA WEM, the entire production capacity of aggregated units has been sold to this market. It is also important to point out that in the studied problem, the offer price of the DER AG

TABLE 1 Technical specifications of the considered DER AG

DGs						
# Unit	P_{DG}^{max}	λ_{DG}	RU_{DG}/RD_{DG}	$R_{DG,up}^{max}/R_{DG,dn}^{max}$	$\lambda_{DG,up}$	$\lambda_{DG,dn}$
1	1.3	37.0	0.5	0.2	37.0	17.5
2	1.5	35.5	0.7	0.2	35.5	16.7
3	2.5	32.3	1.1	0.4	32.3	11.6
4	2.7	27.5	1.4	0.6	27.5	7.9
5	3.1	29.4	1.5	0.9	29.4	8.4
WTs						
# Unit	P_{WT}^{R}	V_{WT}^{ci}	V_{WT}^{R}	V_{WT}^{co}		
1	2×2	4.0	13.0	25.0		
2	4×1.25	3.0	11.0	25.0		
3	5×1	3.6	12.5	20.0		
PVs						
# Unit	P_{PV}^{R}	T^{Ref}	G^{Ref}	Ψ		
1	2×3.0	25.0	1.0	−0.005		
2	4×2.0	25.0	1.0	−0.005		
BSUs						
# Unit	SOC_{BSU}^{max}	SOC_{BSU}^{min}	$P_{BSU,dch}^{max}/P_{BSU,ch}^{max}$	$\eta_{BSU,dch}/\eta_{BSU,ch}$		
1	10.0	1.0	2.0	0.95		

Abbreviations: AG, aggregator; BSUs, battery storage units; DER, distributed energy resource; DGs, dispatchable generators; PVs, photovoltaics; WTs, wind turbines.

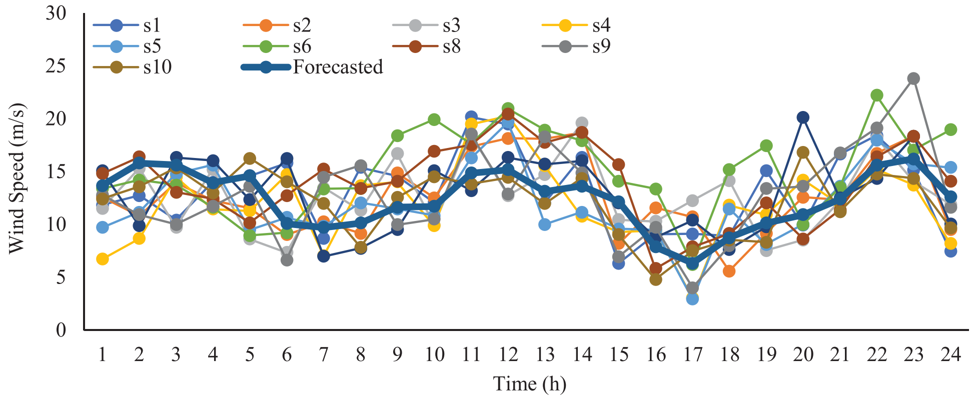

FIGURE 3 Wind speed in DA and RT stages. DA, day-ahead; RT, real-time.

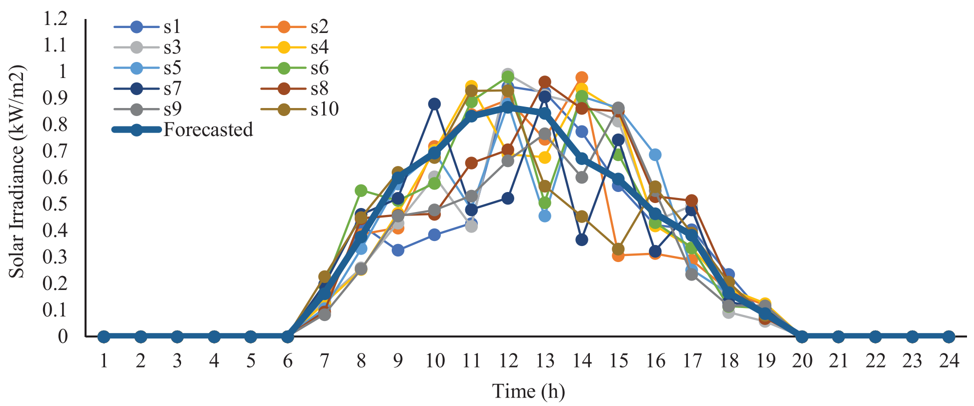

FIGURE 4 Solar radiation in DA and RT stages. DA, day-ahead; RT, real-time.

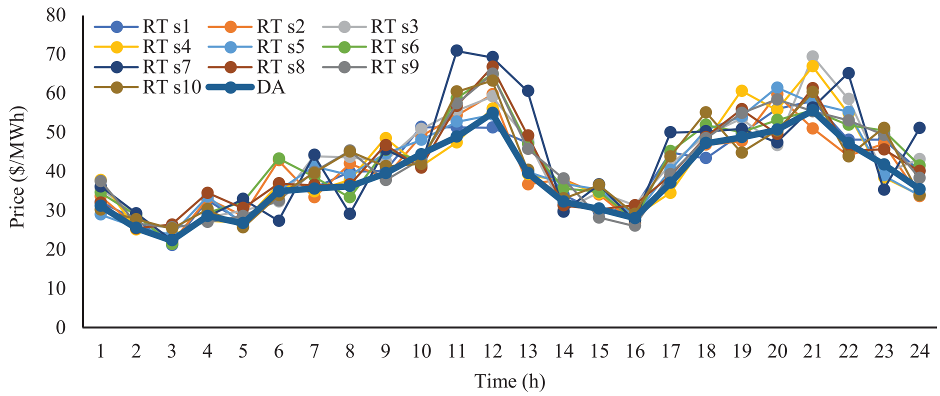

FIGURE 5 DA and RT WEM energy prices. DA, day-ahead; RT, real-time; WEM, wholesale electricity market.

FIGURE 6 Offers of the AG to the DA markets and their energy prices. AG, aggregator; DA, day-ahead.

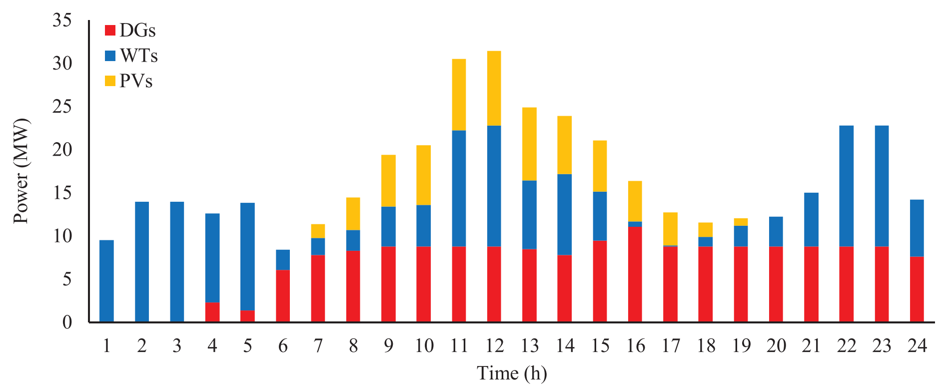

FIGURE 7 Operating points of DERs integrated within the AG. AG, aggregator; DERs, distributed energy resources.

in the LEM is equal to the LEM clearing price, as depicted in Figure 6.

On the other hand, the share of each DER in the AG's offers to the DA markets is determined in Figure 7. It should be noted that in this figure, the total generation of DGs, WTs, and PVs is depicted. Accordingly, the output power of non-dispatchable resources, i.e. WTs and PVs, has been calculated based on the forecasted wind speed and solar radiation. Furthermore, the output power of DGs has been determined according to their marginal prices as well as energy prices in the DA markets. As depicted in this figure, in the early hours of the day, DGs have not been exploited since their marginal prices are higher than the price of energy in both markets.

The DSO, as the LEM operator, settles the market with the aim of social welfare maximisation after receiving offers and bids from all producers and consumers. Figure 8 depicts

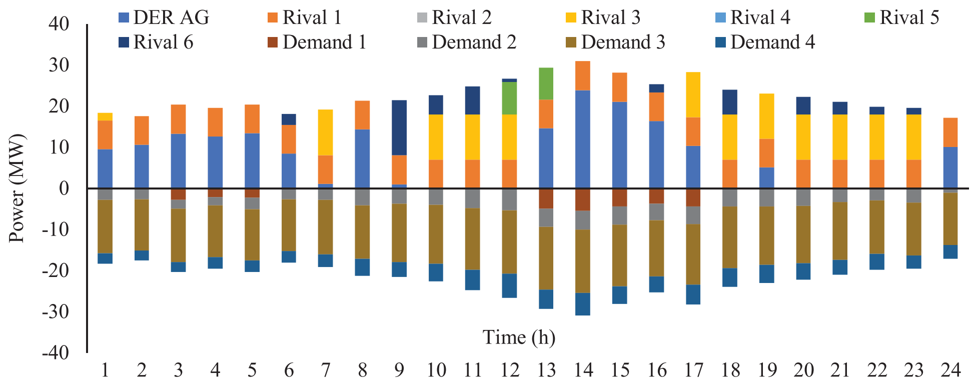

FIGURE 8 LEM clearing points. LEM, local electricity market.

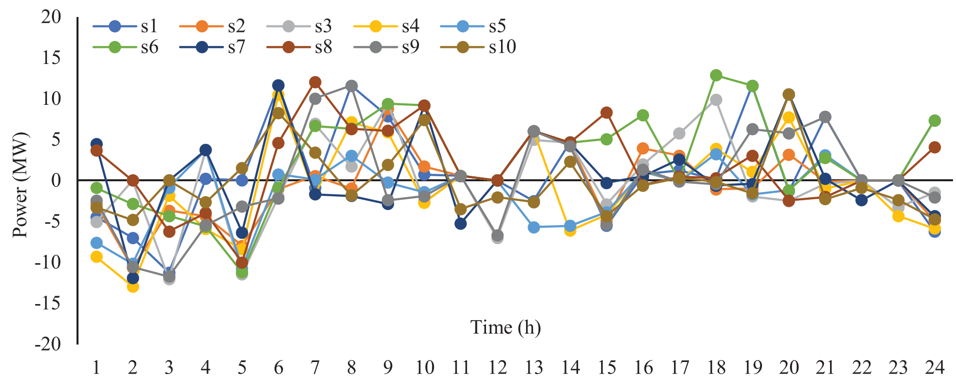

FIGURE 9 Variations of WTs' generation power in the RT stage. RT, real-time; WTs, wind turbines.

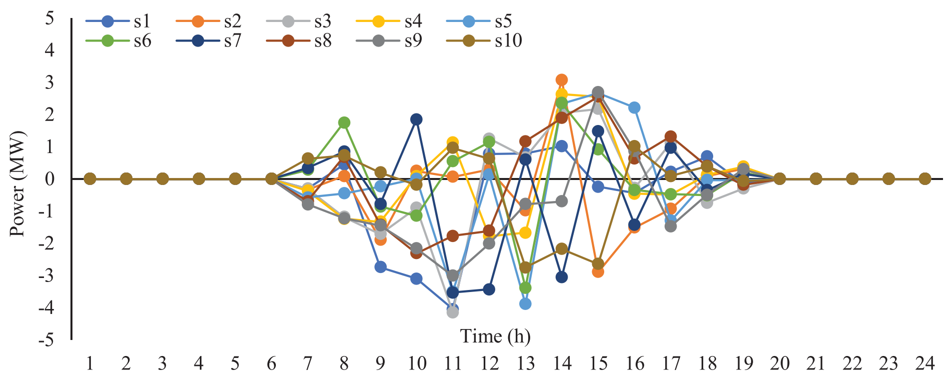

FIGURE 10 Variations of PVs' generation power in the RT stage. PVs, photovoltaics; RT, real-time.

accepted offers and bids of the market players in the DA LEM, in which offers of sellers and bids of buyers have been specified by positive and negative bars, respectively.

It must be noted that the LEM clearing prices in Figure 6 have been determined based on the marginal producers/consumers that are illustrated in Figure 8. Moreover, as evident in Figure 8, the accepted offers of all sellers, including the DER AG and its non-strategic competitors, have supplied the accepted bids of all buyers in the LEM.

As described in the above sections, at the second stage of the two-stage offering strategy and after the realisation of stochastic variables, the DER AG makes optimal decisions regarding its participation in the RT WEM. These decisions directly depend on the generated scenarios that clarify the changes in the real values of random parameters from their forecasted values. For further understanding, the variations of WTs and PVs' generation power over the day and for each of the scenarios are presented in Figures 9 and 10, respectively. It is worth emphasising

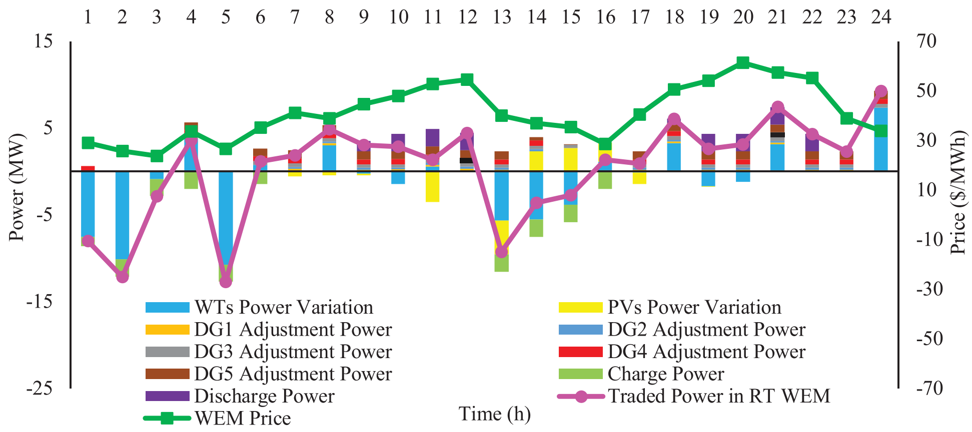

FIGURE 11 Optimal performance of the AG in scenario 5. AG, aggregator.

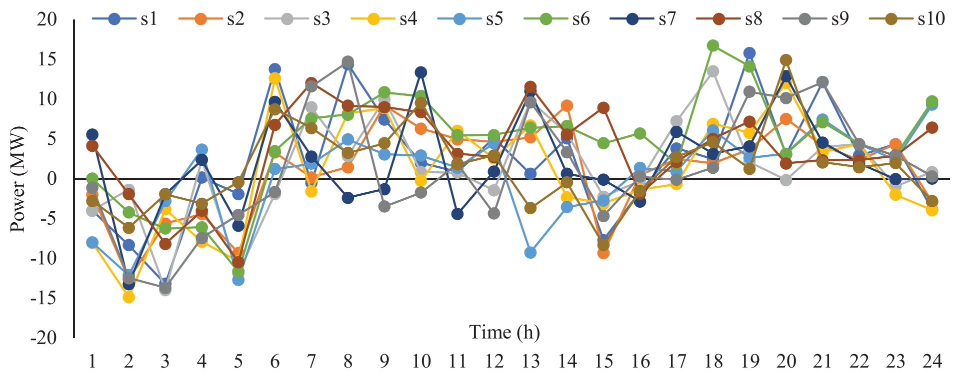

FIGURE 12 Optimal involvement of the AG in RT WEM and all scenarios. AG, aggregator; RT, real-time; WEM, wholesale electricity market.

that, in these two figures, an increase in the generation power of WTs and PVs has been demonstrated by positive values, while a decrease in the generation power of these units has been demonstrated by negative values.

At this stage of programming, the DER AG can compensate for/supply its shortage/excess by involvement in the RT WEM or by adjusting the upward/downward power of DGs and discharge/charge power of BSUs. To investigate the influence of uncertain factors on the optimal performance of the AG, this entity's participation in the RT WEM, upward/downward adjustment power of DGs, discharge/charge power of BSUs, as well as changes of WTs and PVs' generation power are provided for a sample scenario, i.e. scenario 5, in Figure 11. It is noteworthy that in this figure, the RT WEM energy prices for scenario 5 have been depicted as well. In Figure 11, an increase in the generation power of all resources and discharge power of BSUs have been specified by positive bars; hence, a decrease in the generation power of all units and charge power of BSUs have been determined by negative bars. In addition, positive values in the traded power of the AG with the RT WEM indicate the selling energy to the market and negative values indicate the purchasing energy from the market.

In Figure 11, it can be seen that the involvement of the DER AG in the RT WEM is completely consistent with changes in the market's energy prices. In other words, at hours when the price of energy is minimum, the AG has provided its shortage from the RT WEM. In contrast, at hours when the price of energy is maximum, this player has supplied its excess to the market. In the end, Figure 12 shows the studied AG's optimal participation in the RT WEM and the entire scenarios.

Referring to Figure 12, in the early hours of the day, the DER AG is mainly the buyer in the RT WEM, while in the middle and last hours of the day, it is mainly the seller in the target market. This matter has originated from the pattern of energy price. In addition to the traded power of DER AG in the RT WEM, this player's distribution of income at the second stage and for each of the scenarios is reported in more detail in Table 2. Notably, for calculating the presented income, the probability of scenarios is taken into account as well. Clearly, the negative income in the table represents the AG's cost in the RT WEM.

On the other hand, to evaluate the daily profit of the DER AG and shed light on the role of each scenario and each market in the expected profit, the income and cost distribution of this agent in the DA and RT markets are expressed in Table 3.

TABLE 2 AG's distribution of income in the RT WEM

Revenue of the DER AG ($)										
# Hour	**RTS1**	**RTS2**	**RTS3**	**RTS4**	**RTS5**	**RTS6**	**RTS7**	**RTS8**	**RTS9**	**RTS10**
1	−9.7	−5.8	−15.9	−31.8	−30	−0.2	22.9	12.5	−3.1	−7.1
2	−17.4	−28.1	−4.5	−39.1	−40.3	−16.1	−44.7	−4.8	−23.8	−14.3
3	−21	−10.6	−33.9	−9.5	−8.8	−17.7	−5.2	−20.6	−25	−4.2
4	0.3	−12.7	7.3	−22.6	15.7	−23.6	7.6	−13.3	−14.3	−7.9
5	−4	−23	−39.8	−29.1	−43.7	−49.4	−22.4	−30.5	−9.3	−1
6	37	12	−6.9	48	5.3	19.5	30.3	23.5	−4	24.4
7	−1.5	0.4	43.4	−5.9	9.8	38.3	14	41.5	32.7	20.8
8	42.8	5.1	13.7	32.2	24.6	34.9	−8.1	31.7	47.1	12
9	22.4	30.4	47	44.7	17.4	64.3	−7	39.7	−9.5	15.1
10	7.5	26.4	4.6	−1.3	17.8	58.2	63.4	32.4	−5.5	33
11	3.1	23.1	4.4	29.6	9.2	41.6	−36.4	16.7	7.6	8.9
12	19.5	23.6	−9.7	14.7	31.1	46.3	6.9	17	−20.4	15.2
13	2.1	16.3	51.8	27.3	−47.8	39.2	76.2	53.8	31.1	−12.5
14	12.8	29.8	18.9	−9.1	−17.2	30.7	1.9	16.3	8.9	−1.4
15	−17.2	−27.4	−8.8	−11.3	−12.6	20.1	−0.7	25.6	−9.4	−25.3
16	−3.8	1	−1	−4.1	4.9	20.4	−9.1	−5.7	0.4	−3.8
17	12.7	7.7	33.3	−2.5	4.5	10.7	33.7	7.7	−0.5	9.8
18	8	7.6	73.4	34	39.7	113.2	18	23.2	4.7	20.8
19	58.6	15	12.1	36.1	18	92.3	23.7	38	42.4	4.5
20	12.6	38.3	−1	69.6	24.5	21.7	70	8.9	41.9	62.1
21	52.5	18.2	30.3	23	55	51.7	29.2	13.4	47.5	10.2
22	10.3	8.7	27.9	24.5	30.6	29.2	14.2	9.9	16.2	5.1
23	15.5	17.4	−4.3	−8.2	11.6	18.8	−0.4	12.4	10	8.2
24	−11.8	−8.6	3.9	−14	40.5	52.5	−0.3	24.2	0.7	−8
Total	231.5	164.6	246.4	195.3	159.9	696.8	277.8	373.4	166.4	164.8

Abbreviations: AG, aggregator; DER, distributed energy resource; RT, real-time; WEM, wholesale electricity market.

Accordingly, the second and third columns of the table show the AG's revenue from taking part in the DA WEM and LEM, respectively. In the last row of these two columns, the daily income has been calculated. Additionally, in the fourth column of the table, the operating cost of DGs at the DA stage has been stated on an hourly basis. Considering the probability of each scenario, the revenue from involvement in the RT WEM and the operating costs of DGs at the RT stage are listed in columns 5 and 6, respectively. Ultimately, the AG's hourly and daily profit, which is obtained from the difference between all incomes, including columns 2, 3, and 5, and all costs, including columns 4 and 6, are computed in the last column of Table 3. As shown, the DER AG has earned nearly about $13,660 benefit from simultaneous participation in both LEM and WEM.

To conclude, the optimal performance of the DER AG in the presence of both LEM and WEM is compared with the situation in which this player is only able to take part in one of the existing markets. Table 4 summarises the results of the mentioned cases. To calculate the third column of the table, it is assumed that the DER AG participates in the DA and RT WEM, whereas to calculate the fifth column of the table, it is assumed that this entity only takes part in the DA LEM. In the last case, since it is not possible for the DER AG to participate in the RT market, it cannot utilise the adjustment power of DGs as well as the storage capacity of BSUs. Furthermore, in this case, the scheduling of renewable units is merely based on the forecasted wind speed and solar irradiance.

As obvious in Table 4, by providing the possibility of simultaneous participation in both markets, the AG is capable to sell more energy and consequently make more profit. This profit in the second and third cases has decreased by 8.3% and 25.7% in comparison with the first base case, respectively. The obtained results not only confirm the importance of a two-stage stochastic programming framework but also the impact of flexible energy resources in the two-stage decision-making process of the DER AG.

TABLE 3 DER AG's revenue, cost, and profit

# Hour	DA WEM Income ($)	DA LEM Income ($)	DA Operating Cost ($)	RT WEM Income ($)	RT Operating Cost ($)	Expected Profit ($)
1	0	347.3	0	−68.2	51.7	227.4
2	86.5	375.2	0	−233.1	8.5	220.1
3	15.6	432.3	0	−156.3	0	291.5
4	0	399.4	65.9	−63.5	34.4	235.6
5	12.2	440.9	39.8	−252.1	23.5	137.7
6	0	304.3	182.8	189.3	53.1	257.6
7	365.7	41.5	240.1	193.5	66.4	294.3
8	6.6	519.1	258.6	236.1	61.6	441.5
9	728	40.7	277.1	264.6	70.4	685.8
10	910.8	0	277.1	236.4	70.4	799.8
11	1492.6	0	277.1	107.7	70.4	1252.9
12	1726.2	0	277.1	144.3	70.4	1523
13	407.3	630.7	266	237.5	69.7	939.7
14	0	994.2	237.8	91.8	42.2	806
15	0	827.1	290.5	−67	11.8	457.8
16	0	674	347.5	−1	0	325.5
17	90.7	439.8	277.1	117.3	68.9	301.9
18	546.3	0	277.1	342.5	70.4	541.3
19	340	250.9	277.1	340.7	70.4	584.1
20	620.1	0	277.1	348.6	70.4	621.2
21	834.4	0	277.1	331	70.4	817.8
22	1075.2	0	277.1	176.7	70.4	904.4
23	951.7	0	277.1	80.9	68.7	686.7
24	146.8	378.8	233.8	79.1	64.6	306.3
Total	10356.6	7096.2	5211.1	2676.8	1258.5	13660.1

Abbreviations: AG, aggregator; DER, distributed energy resource; LEM, local electricity market; RT, real-time; WEM, wholesale electricity market.

TABLE 4 Comparison between the mentioned cases

	Both LEM and WEM	Only WEM		Only LEM	
		Value	Variation	Value	Variation
Traded energy (MWh/day)	694.1	439.3	−36.7 (%)	370.5	−46.6 (%)
Daily income ($/day)	20129.7	18483.9	−8.2 (%)	13930.5	−30.8 (%)
Daily cost ($/day)	6469.6	5962.4	−7.8 (%)	3784.3	−41.5 (%)
Expected profit ($/day)	13660.1	12521.5	−8.3 (%)	10146.2	−25.7 (%)

Abbreviations: LEM, local electricity market; WEM, wholesale electricity market.

4 | CONCLUSION

The authors have presented an optimisation model to investigate the offering strategy of a DER AG as a price-maker player in the LEM and as a price-taker player in the WEM. This novel framework not only suggested a new approach for simultaneous participation of DER AGs in both WEM and LEM but also allowed the AG to involve in the LEM as a price-maker actor which has not been addressed in previous studies. In the proposed framework, a bilevel programming approach was performed to examine the participation of the AG as a strategic entity in the LEM. In this context, at the UL of the problem, the DER AG's offering strategy in both mentioned markets was modelled through a two-stage stochastic scheme, while at the LL, the DA LEM was cleared with the objective of social welfare maximisation and in the presence of the AG's non-strategic competitors. To scrutinise the suggested framework for the simultaneous participation of the considered AG in different electricity markets, a typical case study was implemented, and the optimal performance of the DER AG in the presence of both markets was compared with the situation in which this actor is merely able to take part in one of the existing markets. The simulation results represented that providing the possibility of offering in both markets can considerably increase the expected profit of the AG. That is because by utilising the proposed framework, the studied AG has the privilege of participating in both electricity markets and can select any market in each time step that is economically more attractive and profitable. It is expected that in the coming years, with the development of ICT infrastructures, high deployment of DERs, as well as the enactment of appropriate regulations and policies, LEMs will play a more dominant role in the distribution systems. In such networks, the aggregation of small- and medium-scale resources in the AG platform will be vital, and these AGs will be able to participate more effectively in both LEM and WEM. For future work, the LEM could be cleared by the market operator in both DA and RT stages and in the presence of the distribution system's technical constraints to assess the electricity trading at the local level based on distribution locational marginal prices.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

NOMENCLATURE

$b \in B$	set of BSUs
$c \in C$	set of competitors in DA LEM
$d \in D$	set of demands in DA LEM
$j \in J$	set of DGs
$s \in S$	set of scenarios
$h \in H$	set of hours
$p \in P$	set of PVs
$w \in W$	set of WTs
Ω	set of decision variables
Ω^{LL}	set of LL decision variables
Ω^{UL}	set of UL decision variables
$SOC_{BSU}^{ini}, SOC_{BSU}^{fin}$	initial/final energy stored in BSUs (MWh)
$SOC_{BSU}^{max}, SOC_{BSU}^{min}$	maximum/minimum energy stored in BSUs (MWh)
$P_{BSU,ch}^{max}, P_{BSU,ch}^{min}$	maximum/minimum charge power of BSUs (MW)
$P_{BSU,dch}^{max}, P_{BSU,dch}^{min}$	maximum/minimum discharge power of BSUs (MW)
P_{d}^{max}, P_{d}^{min}	maximum/minimum bid of demands in DA LEM (MW)
$P_{DG}^{max}, P_{DG}^{min}$	maximum/minimum generation power of DGs (MW)
$P_{com}^{max}, P_{com}^{min}$	maximum/minimum offer of competitors in DA LEM (MW)
P_{PV}, P_{PV}^{F}	generate/forecast power of PVs (MW)
P_{WT}, P_{WT}^{F}	generate/forecast power of WTs (MW)
$R_{DG,dn}^{max}, R_{DG,dn}^{min}$	maximum/minimum downward adjustment power of DGs (MW)
$R_{DG,up}^{max}, R_{DG,up}^{min}$	maximum/minimum upward adjustment power of DGs (MW)
RD_{DG}, RU_{DG}	ramp down/up rate of DGs (MW/h)
,	scenario probability (constant)
λ_{d}	bid price of demands in DA LEM ($/MWh)
λ_{DG}	marginal price of DGs ($/MWh)
$\lambda_{DG,dn}, \lambda_{DG,up}$	downward/upward adjustment power price of DGs ($/MWh)
λ_{com}	offer price of competitors in DA LEM ($/MWh)
$\lambda_{WEM,DA}, \lambda_{WEM,RT}$	DA/RT WEM price ($/MWh)
$\eta_{BSU,ch}, \eta_{BSU,dch}$	charge/discharge efficiency of BSUs (%)
SOC_{BSU}	energy stored in BSUs (MWh)
$P_{BSU,ch}$	charge power of BSUs (MW)
$P_{BSU,dch}$	discharge power of BSUs (MW)
P_{d}	bid of demands in DA LEM (MW)
P_{DG}	generation power of DGs (MW)
P_{com}	offer of competitors in DA LEM (MW)
$q_{LEM,DA}^{AG}$	accepted offer of AG in DA LEM (MW)
$q_{LEM,DA,Of}^{AG}$	submitted offer of AG in DA LEM (MW)
$q_{WEM,DA}^{AG}$	offer of AG in DA WEM (MW)
$q_{WEM,RT}^{AG}$	offer of AG in RT WEM (MW)
$R_{DG,dn}$	downward adjustment power of DGs (MW)
$R_{DG,up}$	upward adjustment power of DGs (MW)
$\lambda_{LEM,DA}$	DA LEM clearing price ($/MWh)
$\lambda_{LEM,DA,Of}^{AG}$	submitted offer price of AG in DA LEM ($/MWh)
α, β, μ	dual variables
$U_{BSU,ch}$	charge situation of BSUs (0 or 1)
$U_{BSU,dch}$	discharge situation of BSUs (0 or 1)
χ	linearization of non-linear terms (0 or 1)
BSU	battery storage unit
DA	day-ahead
DER AG	distributed energy resource aggregator
DG	dispatchable generator
DSO	distribution system operator
LEM	local electricity market
LL	lower level
PV	photovoltaic
RT	real-time
UL	upper level

WEM	wholesale electricity market
WT	wind turbine

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