Comprehensive Review on the Decision-Making Frameworks Referring to the Distribution Network Operation Problem in the Presence of Distributed Energy Resources and Microgrids

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Abstract

The distribution network operation problem (DNOP) is an optimization problem in which the objective function is the total operation cost of the distribution company (Disco), to be minimized considering the technical constraints of the network. In the presence of distributed energy resources (DERs) and microgrids (MGs), new decision makers, including MG and DER operators or managing entities, are emerging and are changing the decision-making framework for distribution systems. To describe the cooperation and competition between the Disco, MG and DER operators, different frameworks and models have been proposed in the literature. Moreover, different computational techniques and metaheuristic algorithms have been used to solve the optimal operation problems. Hence, this paper considers DNOP as one of the timely problems under study and of major interest for future research, presenting a comprehensive review on the decision-making frameworks referring to DNOP in the presence of DERs and MGs, as a new contribution to earlier studies. The focus is set on the comparison among different frameworks characterized by increasingly higher level of participation of the DER managers to the distribution system operation, offering a complementary view with respect to available reviews on similar topics based on technical aspects of the DER connection and integration in MGs and distribution networks, which is noteworthy.

Keywords: Distribution network operation problem; Distributed energy resources; Microgrid; Energy and reserve markets.

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Abbreviations

ADN	Active Distribution Network	LMO	Local market operator
DER	Distributed energy resource	LP	Linear programming
DG	Distributed generation	LRM	Local reserve market
Disco	Distribution company	MCDA	Multi-criteria decision aid
DNOP	Distribution network operation problem	MG	Microgrid
DR	Demand response	MILP	Mixed-integer linear programming
DSO	Distribution system operator	MINLP	Mixed-integer non-linear programming
EDS	Electrical distribution system	MO	Market operator
ES	Energy storage	NLP	Non-linear programming
ESCO	Energy service company	PSO	Particle swarm optimization
GA	Genetic algorithm	PV	Photovoltaic
Genco	Generation company	RM	Reserve market
HRES	Hybrid renewable energy system	SQP	Sequential quadratic programming
IL	Interruptible load	TSO	Transmission system operator
ISO	Independent system operator	WEM	Wholesale energy market
KKT	Karush Kuhn Tucker	WT	Wind turbine
LEM	Local energy market		

1. Introduction

The electrical distribution system is subject to an unprecedented modernization, carried out under the smart grid paradigm, with different directions of evolution. The changes occurring in the distribution system require high investments, aiming at improving system operation (such as reducing the power losses and improving the voltage profile) and enhancing reliability through distribution system automation (with reduction of duration of the interruptions and energy not supplied)

The distribution system is composed of a number of networks operated at the Medium Voltage (MV) and Low Voltage (LV) levels, serving a demand that becomes increasingly higher due to the population growth (especially in urban areas) and higher rates of industrialization. The recent introduction and implementation of microgrids (MGs) could change in the next future the role of the distribution system, which could become in the limit case only the structural link among a number of interconnected MGs [1].

One of the major drivers of the changes in progress is the diffusion of distributed energy resources (DERs) that include distributed generations (DGs), energy storages (ESs) and demand response (DR). DERs are used in the distribution system to meet the demand locally [2]. The integration of DER based on renewable energy sources (RES) with local loads has been considered as a hybrid renewable energy system (HRES) [3-5].

The typical problems in distribution system analysis and optimization are generally partitioned into *operation* (with a time scale indicatively ranging from minutes to days) and *planning* (up to a multi-year time horizon). In the presence of DERs, the distribution system studies referring to planning and operation, energy and ancillary service markets, reliability evaluation, control strategies, and so on, have to be reformulated [6], to cope with new constraints such as DER hosting capacity [7, 8]. In distribution network planning, the specific context of evolution of the territorial infrastructures has been recently extended for taking into account the diffusion of DERs. Many literature contributions have addressed the technical aspects of the incorporation of DERs into the distribution system and the evolution of MGs from different perspectives. Some reviews are available in [9-12], addressing the presence of DERs in distribution networks and their environmental benefits compared with conventional power plants [13], as well as identifying suitable investment strategies for long-term development [14]. The main aspects of DER optimal siting and sizing, power quality improvement of the networks, ancillary services, and regulatory issues are investigated in [15].

In [16], DERs in the form of AC microgrids and DC microgrids are studied from different aspects such as operation and energy management, control strategies, and protection systems. Emergency operation, fault detection, safety analysis, and participation in market environment are investigated for DERs connected to MGs in [17]. Demand response programs are modeled in electricity markets in many studies, as reviewed in [18]. Different operation aspects of distribution networks including voltage control, reactive power compensation, control of DERs, adaptive power factor control, reconfiguration of the network, reserve management and so on are investigated and reviewed in [19].

New decision-making frameworks have been proposed by many researchers in recent years to model the behavior of emerging players and the effect of their interaction in the distribution system operation. The players considered are Energy Service Companies (ESCOs), DER and demand aggregators, and other types of economic operators [20]. In the current research stream, DERs can be connected either to the distribution networks or to MGs [21-24]. In the presence of DERs, besides trading energy and reserve with wholesale markets, the Distribution Company

(Disco) has more options to serve the demand, including optimal scheduling of its DERs (which implies that the Disco could be DER owner as well), and trading energy and reserves with MGs and DERs.

The presence of multiple frameworks calls for specific formulations of the distribution network operation problem (DNOP) taking into account DERs and MGs. The main objective of DNOP is to meet the demand of distribution network with minimum operation costs, considering at the same time the technical constraints of the networks. The time scales of the problem are variable from real-time to day-ahead, depending on the time horizon of the requested operation and on the timings of the wholesale markets. Various optimization techniques have been exploited to search for the (pseudo) optimal solutions and to investigate the behavior of interacting players in local energy networks and markets [25], by properly modeling the uncertainties appearing in RES-based DG, demand and electricity prices.

1.1. Contributions of the paper

This paper aims to review the decision-making aspects referring to the DNOP in the presence of DERs and MGs. This paper offers a complementary view of DNOP with respect to other reviews, setting up the focus on comparing different decision-making frameworks that handle increasingly higher levels of participation of DERs, MGs and emerging players in the distribution system operation, also considering the different roles that the Disco can cover. In particular, the hypothesis of new roles for the Disco could require modifying the current market framework and lead to an increased complexity of the DNOP, which needs appropriate models to achieve optimal solutions. Optimal day-ahead plans and real-time actions carried out by the Disco and presented in the wholesale market are considered, presenting a comprehensive review on DNOP in the presence of DERs and MGs from different perspectives. The specific contributions of the paper include all the aspects concerning the categorization of the decision-making frameworks, the formulation of synthetic objective functions for each framework, and the discussion on the characteristics of all the frameworks.

The next sections of this paper are organized as follows. Section 2 describes the proposed frameworks for studying DNOP. Section 3 addresses DNOP in the presence of DERs. Section 4 deals with DNOP in the presence of MGs. Section 5 deals with the solution methods adopted in the literature for the DNOP. Section 6 contains the final discussion and the outline of future works.

2. Decision-making Frameworks for DNOP

This section introduces the four decision-making frameworks proposed for modeling the DNOP, with increasing levels of participation of DERs and MGs. In particular, DERs and MGs are represented by the corresponding managers (ESCOs, aggregators or specific entities). These frameworks also consider the concepts referring to changing the role of the Disco from the traditional one to futuristic developments.

A common point of these frameworks is the presence of a Wholesale Energy Market (WEM) managed by the Market Operator (MO) at the transmission system level. The MO interacts with the Transmission System Operator (TSO) that assesses the transmission system reliability and security. The transmission system supplies the distribution network managed by the Disco, and is indicated in the sequel as supply grid. The Disco interacts with the Distribution System Operator (DSO) that assesses the distribution system reliability and security.

The main aspects of the proposed frameworks are described as follows:

- **Framework 1** (Disco as trading operator): In traditional distribution systems, the Disco aims to guarantee the supply for customers, interacting with the distribution system operator to ensure the proper operation of the infrastructure. The forecast data including the distribution network demand and wholesale electricity prices are considered as the input data for DNOP. According to these data, the Disco purchases the required energy from the wholesale market and delivers it to the consumers with fixed prices (Fig. 1). The difference between costs and revenues for the Disco is expressed as:

$$F_{1,\text{Disco}} = C_{\text{Disco}}^{\text{WEM}} - R_{\text{Disco}}^{\text{sell}} \quad (1)$$

where:

$C_{\text{Disco}}^{\text{WEM}}$	costs of trading energy with the wholesale electricity market
$R_{\text{Disco}}^{\text{sell}}$	Disco revenues from selling energy to the customers

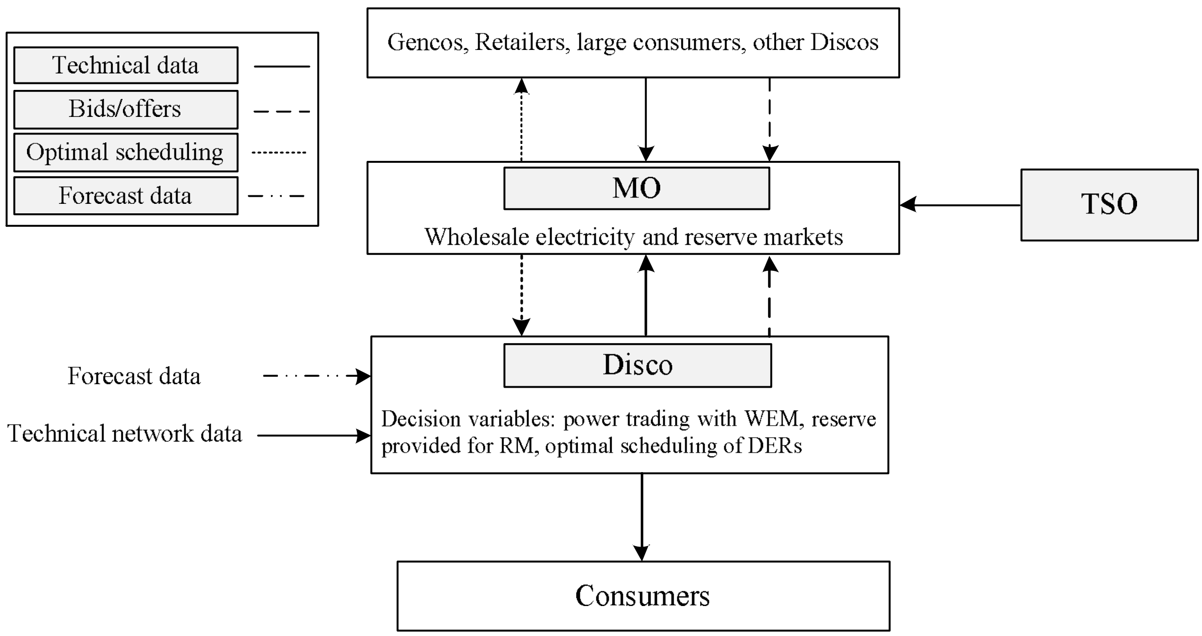


Fig. 1. Framework of trading electricity in traditional distribution networks.

- **Framework 2** (Disco as a player in the wholesale energy and reserve markets, and operating as DER aggregator): In the presence of DERs, the decision-making framework in distribution networks is changed as shown in Fig. 2. In this framework, the DNOP is modeled from the Disco's perspective, in which the objective function of the Disco is maximizing/minimizing its profit/cost considering optimal participation in wholesale energy market (WEM) and in the reserve markets (RM), optimal scheduling of the DERs, and trading energy and reserves with the DER managers that operate on behalf of the DER owners. The DER managers submit their bids/offers to the Disco, according to which the Disco interacts with the Market Operator (MO) that manages the WEM and the RM, and determines the optimal scheduling of DERs to provide energy and reserves. To avoid conflicts of interest, the Disco (being a local decision maker with respect to DER operation) should not be the owner of DERs, even though in some references the Disco is considered a DER owner (see Section 6 for a detailed discussion).

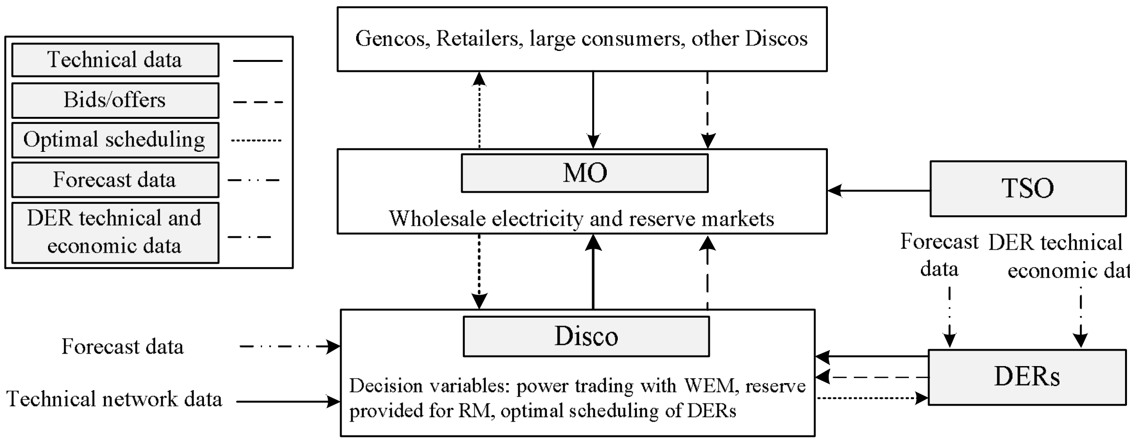


Fig. 2. Decision-making framework in distribution networks with DERs.

- **Framework 3** (Disco as the decision-maker interacting with local markets including DERs and MGs): different players (individual DERs or aggregators of DERs connected to the distribution network, and MGs) are competing on local markets for creating the prices. Each competitor manages a local market. Again, to avoid conflicts the Disco should not be a DER owner (see Section 6 for a detailed discussion). The DER connected to a MG is managed inside the MG. As in the previous framework, the Disco is a player in the wholesale energy and reserve markets. Many studies describe the hierarchical frameworks for operation of Active Distribution Network (ADN) in which the Disco is considered as the leader and MGs are the followers. The DNOP can be modeled as a hierarchical decision-making problem, in which the upper level problem describes the decision-making problem of the Disco, and the lower level problem describes the decision-making problem of each MG, as shown in Fig. 3. In this framework, Disco, MG managers and DER managers trade energy and reserve with each other according to the price signals which couple them to each other. These price signals can be considered as fixed or variable prices. When price signals are variable, they are determined according to the possible cooperation between decision makers.

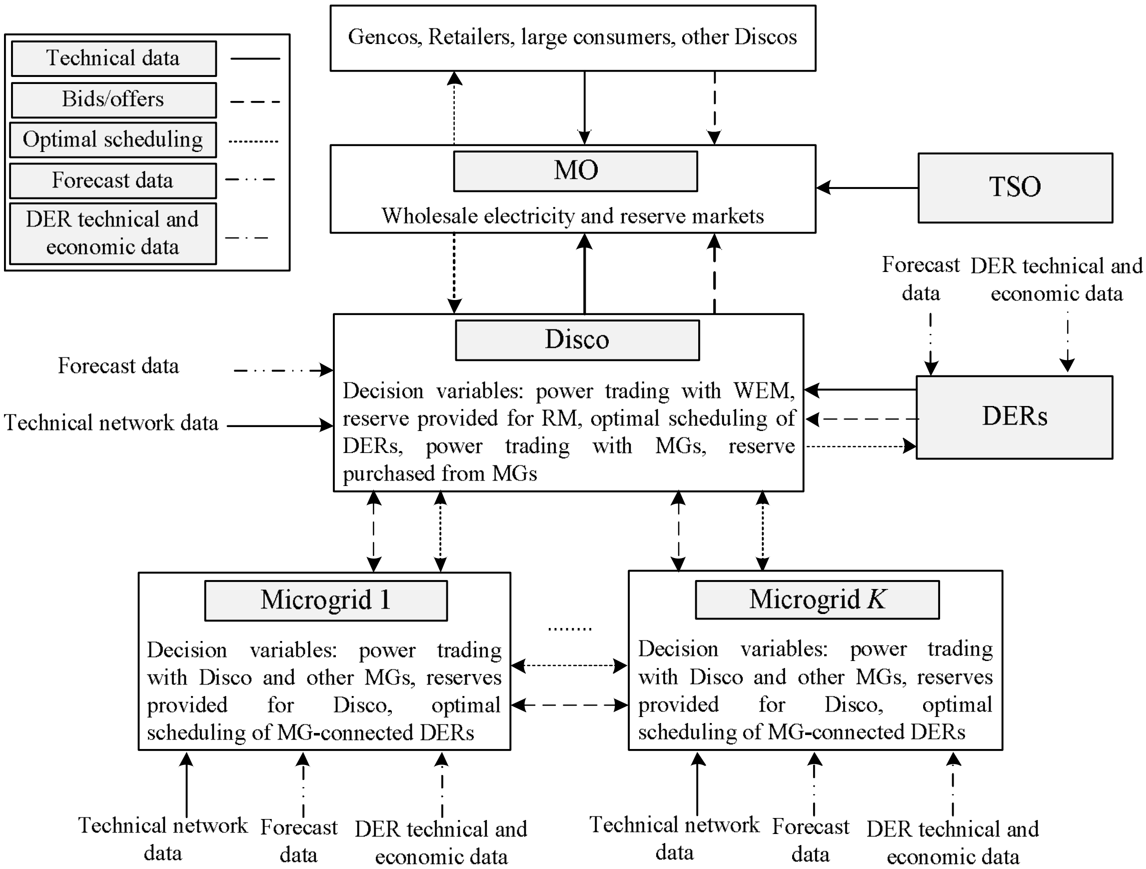


Fig. 3. Decision-making framework in distribution networks with DERs and MGs.

- **Framework 4 (**Disco separated with respect to the operators of the local markets): with respect to the previous framework, a Local Market Operator (LMO) entity separate from the Disco is created to operate local energy markets for energy and reserves independently of the Disco. MG managers and DER managers can exchange energy and reserve with each other in the local energy and reserve markets. The decision makers submit their bids/offers, and the local markets are cleared by the LMO. The Disco acts as a player in the wholesale markets and forms the bids/offers according with the outcomes of the local markets. This framework can be modeled from the perspective of each decision maker (i.e., Disco, and the MG and DER managers). Hence, a bi-level optimization model can be formed in which the operation problem of each decision maker is modeled as the upper level problem, and the local energy market (LEM) and local reserve markets (LRM) are modeled as lower level problems.

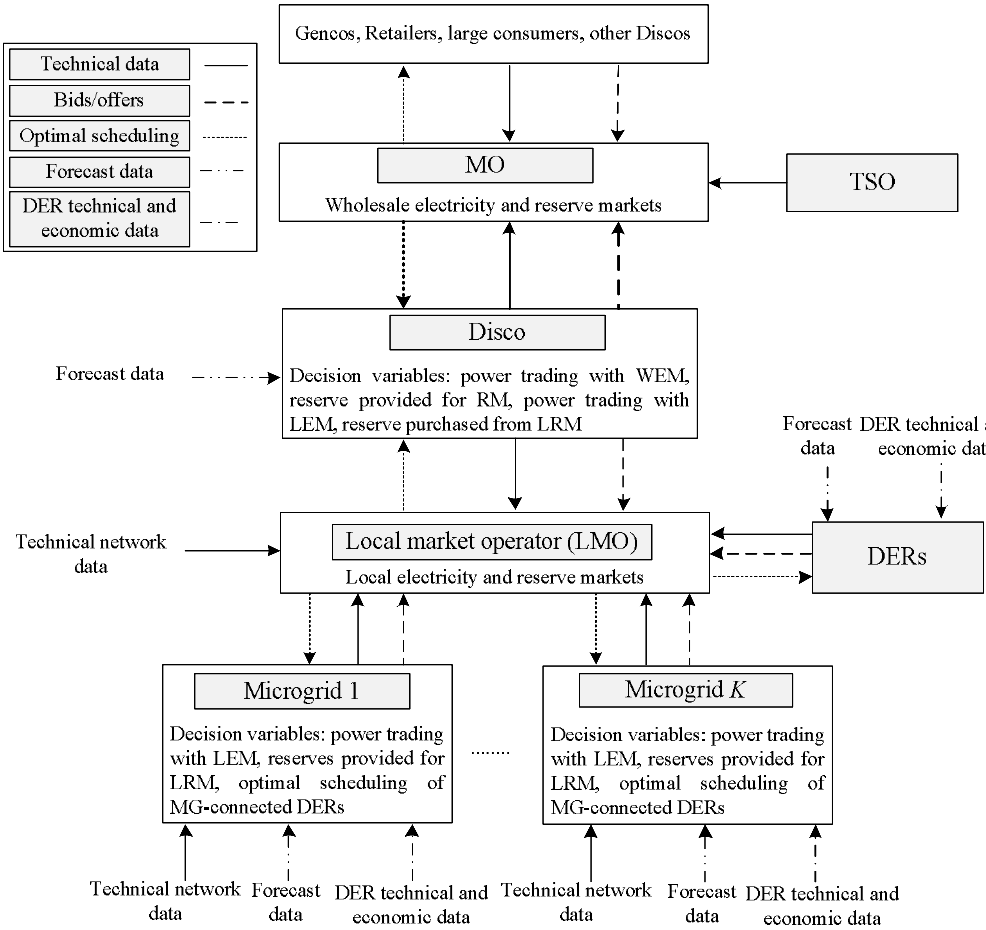


Fig.4. Decision-making framework in distribution networks with DERs and MGs in local markets.

2.1. Considerations on the frameworks

Some descriptions are common for the frameworks 2-4, as follows:

- The output of photovoltaic (PV) arrays and wind turbines (WTs), as well as the demand consumption, are forecast and used as the input data into the problem of Disco, MGs and DERs. Moreover, the forecast errors are modeled in the DNOP.
- The Disco can participate in the wholesale electricity market and in reserve markets either as price maker or price taker. When the Disco is modeled as a price maker [26], its bids/offers are submitted to the markets. On the other hand, when the Disco is modeled as a price taker, it forecasts the wholesale prices to be used in the calculations.

The important issue about Framework 4 is the coordination between different operators. In [27], five coordination schemes developed within the SmartNet project [28] are proposed for the collaboration between TSOs and DSOs in the context of the procurement of ancillary services and local services. In these schemes, different roles and responsibilities are defined for system operators to solve the network problems, including voltage and frequency control and congestion management. Therefore, Framework 4 can be used in each country regarding different roles and responsibilities defined for system operators.

The proposed schemes can be used in the DNOP at different time scales, with day-ahead or intra-day time frames, or closer to the real-time, as mentioned in [27].

On the basis of the above frameworks, a synthetic mathematical formulation that encompasses the literature contributions reviewed is presented in the next two sections. In particular, Section 3 focuses on Framework 2, whereas Section 4 addresses the mathematical formulation for Framework 3 and Framework 4.

3. DNOP in the presence of DERs

Let us consider an energy system in which electricity is supplied by the Electrical Distribution System (EDS) and by additional DERs, according with the structure of Framework 2. The distribution network has N nodes and B branches. The maximum and minimum voltage limits at node n = 1,…, N are $V_n^{\max}$ and $V_n^{\min}$, respectively. The maximum current magnitude at branch b = 1,…, B is $I_b^{\max}$. The operation is studied at successive time steps t = 1, …, T of duration Δt each.

3.1. Objective function for Framework 2

The objective function of DNOP in the presence of DERs can be modeled as follows:

$$F_{2,\text{Disco}} = C_{\text{Disco}}^{\text{WEM}} - R_{\text{Disco}}^{\text{sell}} + C_{\text{DG}} + C_{\text{IL}} + C_{\text{ES}} + C_{\text{DER}}^{\text{reserves}} - R_{\text{Disco}}^{\text{RM}} \qquad (2)$$

where:

$C_{\text{Disco}}^{\text{WEM}}$	costs of trading energy with the wholesale electricity market
C_{DG}	costs of DG generation
C_{IL}	costs of interruptible loads
C_{ES}	costs of energy storage charging/discharging
$C_{\text{DER}}^{\text{reserves}}$	costs of DERs participation in providing reserve
$R_{\text{Disco}}^{\text{RM}}$	Disco revenues from participation in reserve market
$R_{\text{Disco}}^{\text{sell}}$	Disco revenues from selling energy to the customers

The objective function in (2) is formulated from the Disco’s viewpoint. The first term is used to model the trading of the Disco with the wholesale electricity market. DERs provide capability for the Disco to participate in reserve markets, and the revenue of the Disco from the reserve markets is modeled as the second term in the objective function. These terms are different when the Disco is modeled as a price taker or as a price maker in the wholesale electricity market and in reserve markets. When the Disco is modeled as a price taker, the forecast prices of wholesale electricity market and reserve markets are considered in the model. Then, according to these forecast prices, the Disco decides on power trading with the electricity market and reserve provided for the reserve market. On the other hand, when the Disco is modeled as a price maker, its bids/offers submitted to the electricity and reserve markets are considered in the model. For both renewable and fossil-based DGs, the Disco receives bids from the DG managers and uses them in its objective function. The DG generation costs are not disclosed, being private information of the DG owners.

Interruptible loads (ILs) are the most common demand response programs used in the operation problems in the literature. Each load that participates in this program submits its bid to the Disco in the form of the price of interruptible load and the maximum amount of load that can be interrupted.

The last term of (2) is the revenue of the Disco from selling energy to the distribution network consumers.

3.2. Constraints for Framework 2

The constraints are expressed as follows:

- Energy balance constraint for bus *n* at time step *t*:

$$\Delta w_{n,t}^{\mathrm{WEM}} + w_{n,t}^{\mathrm{DG}} + w_{n,t}^{\mathrm{IL}} + \Delta w_{n,t}^{\mathrm{ES}} = w_{n,t}^{\mathrm{Disco,demand}} \tag{3a}$$

for energy trading with the WEM: $\Delta w_{n,t}^{\mathrm{WEM}} = w_{n,t}^{\mathrm{WEM,purchase}} - w_{n,t}^{\mathrm{WEM,sell}}$ (3b)

for energy storage: $w_{n,t}^{\mathrm{ES}} = w_{n,t-1}^{\mathrm{ES}} + \Delta w_{n,t}^{\mathrm{ES}}$ (3c) where:

$\Delta w_{n,t}^{\text{WEM}}$	Energy exchanged with the WEM
$w_{n,t}^{\text{WEM,purchase}}$	Energy purchased from the WEM by the Disco
$w_{n,t}^{\text{WEM,sell}}$	Energy sold to the WEM by the Disco
$w_{n,t}^{\text{DG}}$	Energy generation by DG units
$w_{n,t}^{\text{ES}}$	Energy stored in ES
$w_{n,t}^{\text{Disco,demand}}$	Energy demand of Disco consumers
$w_{n,t}^{\text{IL}}$	Energy of the interruptible loads IL

- Branch currents and bus voltage limits at time step *t*:

$$V_n^{\min} \leq V_{n,t} \leq V_n^{\max}, \text{ for } n = 1,\ldots, N \tag{4a}$$

$$I_{b,t} \leq I_b^{\max}, \text{ for } b = 1,\ldots, B \tag{4b}$$

where $V_{n,t}$ is the magnitude of the voltage at bus *n*, and $I_{b,t}$ is the magnitude of the current flowing in branch *b*.

- Reserve balance constraint at time step *t*, considering the amount of reserves $r_{g,t}^{\text{DER,reserves}}$ provided by DERs from the source $g = 1,\ldots, G$ and the reserves $r_t^{\text{Disco,reserves}}$ provided by the Disco to the reserve market.

$$\sum_{g=1}^{G} r_{g,t}^{\text{DER,reserves}} = r_t^{\text{Disco,reserves}} \tag{5}$$

- Constraints of trading energy and reserves with the supply grid:

$$0 \leq w_{n,t}^{\text{Disco,purchase}}/\Delta t \leq P_{\text{Disco}}^{\max} \tag{6a}$$

$$0 \leq r_t^{\text{Disco,reserves}} + w_{n,t}^{\text{Disco,sell}}/\Delta t \leq P_{\text{Disco}}^{\max} \tag{6b}$$

where $P_{\mathrm{Disco}}^{\max}$ is the maximum power the Disco can inject into or draw from the grid, while $w_{n,t}^{\mathrm{Disco,sell}}$ and $w_{n,t}^{\mathrm{Disco,purchase}}$ are the energy sold to and purchased from the grid, respectively, by the Disco.

- Technical constraints of DG units:

$$P_{\mathrm{DG}}^{\min} \leq w_t^{\mathrm{DG}}/\Delta t \tag{7a}$$

$$r_t^{\mathrm{DG}} + w_t^{\mathrm{DG}}/\Delta t \leq P_{\mathrm{DG}}^{\max} \tag{7b}$$

where w_t^{DG} is the energy produced by the DG, while $P_{\mathrm{DG}}^{\min}$ and $P_{\mathrm{DG}}^{\max}$ are the minimum and maximum power, respectively, of the DG. In addition, the DG model includes the energy coupling constraints between different types of energy (e.g., in a cogeneration system with electricity *e* and heat *h*, with limits on electricity output depending on heat output, and vice versa):

$$w_t^{\mathrm{DG,min},h}(w_t^{\mathrm{DG},e}) \leq w_t^{\mathrm{DG},h} \leq w_t^{\mathrm{DG,max},h}(w_t^{\mathrm{DG},e}) \tag{7c}$$

$$w_t^{\mathrm{DG,min},e}(w_t^{\mathrm{DG},h}) \leq w_t^{\mathrm{DG},e} \leq w_t^{\mathrm{DG,max},e}(w_t^{\mathrm{DG},h}) \tag{7d}$$

- Technical constraints of energy storages at time step *t*:

$$w_{ES}^{\min} \leq w_t^{\mathrm{ES}} \leq w_{ES}^{\max} \tag{8}$$

- Constraints of interruptible loads, considering the amount of energy w_t^{IL} to be interrupted at time step *t*, the constraint imposed on the maximum interrupted power $P_{\mathrm{IL}}^{\max}$, and the amount of reserves r_t^{IL} that can be provided by the interruptible loads:

$$0 \leq w_t^{\mathrm{IL}}/\Delta t \tag{9a}$$

$$0 \leq r_t^{\mathrm{IL}} + w_t^{\mathrm{IL}}/\Delta t \leq P_{\mathrm{IL}}^{\max} \tag{9b}$$

The important constraint of DNOP is the power balance described by (3). When the distribution network is modeled as a single bus, the power balance constraint is modeled for one bus only.

Meanwhile, when test or real distribution networks are used, the power balance constraint must be met for all buses and also other technical constraints of distribution networks should be met as described in (4).

The sum of the reserves provided by the DERs is equal to the reserve provided by the Disco for the reserve market as described by (5). Equations (6)-(9) are used to model the technical constraints of the main grid and DERs.

3.3. Considerations on the objective function and constraints

Table 1 shows the details of objective function and constraints of DNOP in the presence of DERs proposed in the literature for Framework 2. In most studies, the Disco is considered as a price taker in the wholesale energy market and in reserve markets. Although DERs can provide reserves for the Disco, reserves are modeled in a few studies. Standard networks are used in many studies to evaluate the effectiveness of models and optimization techniques.

Variables and constraints in the models from (2)-(9) are different. If the objective function and all constraints have linear expressions, the resulted model uses linear programming (LP), or mixed-integer linear programming (MILP) if integer variables are added.

On the other hand, in the presence of nonlinear expressions in the objective function or constraints (especially in the power balance constraint), the resulted models use non-linear programming (NLP) or mixed-integer non-linear programming (MINLP) techniques for their solution. In [26, 29], different methods are used to linearize the nonlinear expressions in the models.

Table 1
Details of DNOP modelled in the presence of DERs in the literature.

Ref.	Disco		DER managers		Markets		Distribution network model		
	Price taker	Price maker	Disco	Local entities	Electricity	Reserve	Standard network	Real network	Single bus
[30, 31]	✓	-	✓	✓	✓	-	IEEE 33 bus	-	-
[32, 33]	✓	-	✓	-	✓	✓	IEEE 18 bus	-	✓
[34]	✓	-	✓	✓	✓	✓	IEEE 33 bus	-	-
[35]	✓	-	✓	✓	✓	-	IEEE 33 bus	-	-
[36]	✓	-	✓	✓	✓	-	-	144 bus	-
[37]	✓	-	✓	✓	✓	-	-	144 bus	-
[38]	✓	-	✓	✓	✓	✓	84 bus	-	-
[39]	✓	-	-	✓	✓	✓	84 bus	-	-
[40]	✓	-	✓	✓	✓	✓	69 bus	-	-
[41]	-	✓	✓	✓	✓	-	-	-	✓
[42]	-	✓	✓	✓	✓	-	IEEE 6 bus (transmission network)	-	-
[43]	✓	-	-	✓	✓	-	-	120 bus	-
[44]	✓	-	✓	✓	✓	✓	41 bus	-	-
[45]	✓	-	✓	✓	✓	-	18 and 69 bus	-	-
[46]	✓	-	-	✓	✓	-	IEEE 13 bus	41 bus	-
[47]	✓	-	-	✓	✓	-	IEEE 33 bus	-	-
[48]	✓	-	-	✓	✓	-	-	61 bus	-
[49]	✓	-	-	✓	✓	-	IEEE 33 bus	-	-
[50]	✓	-	✓	✓	✓	-	IEEE 33 bus	-	-
[51]	✓	-	✓	-	✓	-	30 bus	-	-
[52]	✓	-	✓	✓	✓	-	-	-	✓
[53]	✓	-	✓	-	✓	-	70 bus	-	-
[54]	-	✓	✓	✓	✓	-	IEEE 14 bus	-	-
[55]	✓	-	✓	✓	✓	-	IEEE 33 bus	-	-
[26]	-	✓	✓	✓	✓	✓	-	-	✓
[56]	✓	-	-	✓	✓	-	IEEE 33 bus	-	-
[29]	-	✓	✓	✓	✓	-	-	-	✓
[57]	✓	-	✓	✓	✓	-	-	-	✓
[58]	✓	-	✓	✓	✓	-	IEEE 33 bus	-	-

3.3. DNOP models and optimization techniques

To solve the proposed models, different optimization techniques and software are used in the literature. The models and optimization techniques used in the literature are shown in Table 2.

In some papers, the models are coded in GAMS software environment and are solved using appropriate solvers. In other ones, the models are coded in MATLAB or other software and metaheuristic algorithms are used to solve the models. As shown in Table 2, LP and MILP models are generally coded in GAMS and are solved using the CPLEX solver. Also, most models are presented as nonlinear ones and are solved by appropriate solvers in GAMS such as DICOPT. Some models are solved using metaheuristic algorithms such as genetic algorithm (GA), particle swarm optimization (PSO) and so on in the MATLAB environment.

Due to uncertain behavior of wind speed, solar radiation, demand consumption and wholesale electricity price, modeling these uncertainties is one of the important issues in DNOP. A stochastic model is introduced to represent these uncertainties. The different uncertain parameters modeled in the literature and the types of models are described in Table 3 (also mentioning some deterministic models in which parameter uncertainty is not considered).

As shown in Table 3, DNOP is described as deterministic model in many cases. Wind speed and demand are the most uncertain parameters modeled in the literature.

Table 2
Resulted model and optimization techniques used in DNOP in the presence of DERs.

Ref.	DNOP model				Optimization techniques	
	LP	NLP	MILP	MINLP	Solvers in GAMS software	Software/algorithms
[30, 31]	-	-	-	✓	DICOPT	-
[32, 33]	-	✓	-	-	-	MATLAB
[34]	-	-	-	✓	DICOPT	-
[35]	-	-	-	✓	-	GA
[36]	✓	✓	-	-	Unknown	-
[37]	-	-	✓	-	Unknown	-
[38]	-	-	✓	-	CPLEX	-
[39]	-	-	✓	-	CPLEX	-
[40]	-	-	-	✓	DICOPT	-
[41]	-	-	-	✓	-	MATLAB
[42]	-	✓	-	-	-	AMPL (IPOPT solver)
[43]	-	-	-	✓	-	MATLAB and EMTP
[44]	-	-	-	✓	DICOPT	-
[45]	-	-	-	✓	MINOS	-
[46]	-	✓	-	-	SNOPT	-
[47]	-	-	-	✓	Unknown	PSO
[48]	-	-	-	✓	CONOPT	-
[49]	-	-	-	✓	DICOPT	-
[50]	-	-	-	✓	-	GA and PSCAD
[51]	-	✓	-	-	-	SQP and MATLAB
[52]	-	-	-	✓	Unknown	GA and PSO
[53]	-	✓	-	-	-	PSO
[54]	-	-	-	✓	CONOPT	-
[55]	-	-	✓	-	CPLEX	-
[26]	-	-	✓	-	CPLEX	-
[56]	-	✓	-	-	-	Unknown
[29]	-	-	✓	-	CPLEX	-
[57]	-	✓	-	-	-	Alternating direction method of multipliers decomposition method
[58]	-	✓	-	-	-	Affine arithmetic-based non-dominated sorting genetic algorithm II

Table 3
The uncertain parameters modeled in DNOP in the presence of DERs.

Ref.	Model		Uncertain parameters			
	Deterministic	Stochastic	Solar radiation	Wind speed	Demand	Electricity price
[30, 31]	✓	-	-	-	-	-
[32, 33]	✓	-	-	-	-	-
[34]	-	✓	-	✓	✓	-
[35]	✓	-	-	-	-	-
[36]	-	✓	-	-	✓	✓
[37]	-	✓	-	-	✓	✓
[38]	✓	✓	-	✓	✓	✓
[39]	✓	-	-	-	-	-
[40]	-	✓	✓	✓	✓	-
[41]	✓	-	-	-	-	-
[42]	✓	-	-	-	-	-
[43]	✓	-	-	-	-	-
[44]	-	✓	-	✓	✓	-
[45]	✓	-	-	-	-	-
[46]	✓	-	-	-	-	-
[47]	✓	-	-	-	-	-
[48]	✓	-	-	-	-	-
[49]	✓	-	-	-	-	-
[50]	✓	-	-	-	-	-
[51]	✓	-	-	-	-	-
[53]	✓	-	-	-	-	-
[54]	-	✓	✓	✓	-	-
[55]	-	✓	-	✓	✓	-
[26]	-	✓	✓	✓	-	-
[56]	-	✓	-	-	✓	-
[29]	-	✓	✓	✓	✓	-
[57]	✓	-	-	-	-	-
[58]	-	✓	✓	✓	✓	-

4. DNOP in the presence of DERs and MGs

The DNOP in the presence of MGs can be modeled in different ways. Mainly it is possible to identify the two frameworks shown in Section 2, corresponding to Framework 3 (Fig. 3) and Framework 4 (Fig. 4). In addition, a further case may be considered as a special situation of Framework 4. The details are described in the following sub-sections.

4.1. Objective functions and constraints for Framework 3

The DNOP can be modeled as a bi-level optimization problem, in which the upper level and lower level problems describe the operation problem of Disco and MGs, respectively.

For the upper level problem (Disco), the objective function is expressed as:

$$F_{3,\text{Disco}} = C_{\text{Disco}}^{\text{WEM}} - R_{\text{Disco}}^{\text{sell}} + C_{\text{DG}} + C_{\text{IL}} + C_{\text{ES}} + C_{\text{DER}}^{\text{reserves}} - R_{\text{Disco}}^{\text{RM}} + C_{\text{MG}}^{\text{reserves}} - R_{\text{Disco}}^{\text{MG}} \tag{10}$$

where:

$C_{\text{MG}}^{\text{reserves}}$ costs of purchasing reserve from the MGs

$R_{\text{Disco}}^{\text{MG}}$ revenues from trading energy with the MGs

The objective function in (10) is described from the Disco's perspective. Trading of energy and reserve with MGs is added with respect to (2) to model the Disco objective function in this framework.

The constraints for the upper level problem are expressed as follows:

- Energy balance constraint for bus *n* of the distribution system, at time step *t*:

$$\Delta w_{n,t}^{\text{WEM}} + \Delta w_{n,t}^{\text{MG}} + w_{n,t}^{\text{DG}} + w_{n,t}^{\text{IL}} + \Delta w_{n,t}^{\text{ES}} = w_{n,t}^{\text{demand,Disco}} \tag{11a}$$

for energy trading with the MGs: $\Delta w_{n,t}^{\text{MG}} = w_{n,t}^{\text{MG,purchase}} - w_{n,t}^{\text{MG,sell}}$ (11b)

in addition, (3b)-(3c) (11c)

where:

$w_{n,t}^{\text{MG,purchase}}/w_{n,t}^{\text{MG,sell}}$ Energy purchased/sold from/to MG by the Disco

- Branch currents and bus voltage limits:

$$\text{the same as (4a)-(4b)} \tag{12}$$

- Reserve balance constraint: considering the amount of reserves provided by DERs $r_{g,t}^{\text{DER,reserves}}$ from the source g = 1,…, G at time step t, the reserves $r_{n,t}^{\text{MG,reserves}}$ provided by the MG connected to node n of the distribution network, and the reserves $r_{t}^{\text{Disco,reserves}}$ provided by the Disco for the reserve market:

$$\sum_{g=1}^{G} r_{g,t}^{\text{DER,reserves}} + \sum_{n=1}^{N} r_{n,t}^{\text{MG,reserves}} = r_{t}^{\text{Disco,reserves}} \tag{13}$$

- Further constraints:

$$\text{from equations (6a)-(9b)} \tag{14}$$

- Constraints on prices:

$$\rho_{\text{energy}}^{\text{offer}} \leq \rho_{\text{energy}}^{\text{max}} \;,\; \rho_{\text{reserve}}^{\text{offer}} \leq \rho_{\text{reserve}}^{\text{max}} \tag{15}$$

where:

$\rho_{\text{energy}}^{\text{offer}}/\rho_{\text{reserve}}^{\text{offer}}$ Energy/reserve prices offered by the Disco to the MGs

$\rho_{\text{energy}}^{\text{max}}/\rho_{\text{reserve}}^{\text{max}}$ Maximum energy/reserve prices offered to MGs by the Disco, which can be determined by a regulatory authority.

For the lower level problem (for each MG), the objective function is expressed as:

$$F_{3,\text{MG}} = C_{\text{Disco}}^{\text{MG}} + C_{\text{DG}}^{\text{MG}} + C_{\text{IL}}^{\text{MG}} + C_{\text{ES}}^{\text{MG}} + C_{\text{DER,MG}}^{\text{reserves}} - R_{\text{MG}}^{\text{reserves}} - R_{\text{MG}}^{\text{sell}} \tag{16}$$

where:

$C_{\text{DG}}^{\text{MG}}$ Generation costs of MG-connected DG

$C_{\text{IL}}^{\text{MG}}$ Costs of MG-connected interruptible loads

$C_{\text{ES}}^{\text{MG}}$ costs of charging/discharging for MG-connected energy storage

$R_{\mathrm{MG}}^{\mathrm{reserves}}$ revenues of procuring reserves for the Disco

$C_{\mathrm{Disco}}^{\mathrm{MG}}$ costs from trading energy with the Disco

$C_{\mathrm{DER,MG}}^{\mathrm{reserves}}$ costs of MG-connected DERs participation in providing reserves

$R_{\mathrm{MG}}^{\mathrm{sell}}$ revenues of MG from selling energy to the customers

The constraints are expressed as follows:

- Energy balance constraint for the MG connected to node *n* of the distribution network at time step *t*:

$$w_{n,t}^{\mathrm{MG,DG}} + w_{n,t}^{\mathrm{MG,IL}} + w_{n,t}^{\mathrm{MG,ES}} = \Delta w_{n,t}^{\mathrm{MG}} + w_{n,t}^{\mathrm{MG,Demand}} \tag{17}$$

where:

$w_{n,t}^{\mathrm{MG,Demand}}$ Energy demand required for MG consumers

- Branch currents and bus voltage limits:

the same as (4a)-(4b) (18)

- Reserve balance constraint: considering the amount of reserves $r_{g,t}^{\mathrm{DER_{MG}},\mathrm{reserves}}$ provided by DERs belonging to the MG from the source *g* = 1,…, *G* at time step *t* and the reserves $r_t^{\mathrm{MG,reserves}}$ provided by the MG for the Disco:

$$\sum_{g=1}^{G} r_{g,t}^{\mathrm{DER_{MG}},\mathrm{reserves}} = r_t^{\mathrm{MG,reserves}} \tag{19}$$

- Constraints of trading energy and reserves with the Disco:

$$0 \le w_{n,t}^{\mathrm{MG,purchase}} \tag{20a}$$

$$r_{n,t}^{\mathrm{MG,reserves}} + w_{n,t}^{\mathrm{MG,sell}}/\Delta t \le P_{\mathrm{MG},n}^{\max} \tag{20b}$$

- Further constraints:

from equations (7a)-(9) (21)

Equations (11)-(14) are based on (3)-(9), adding energy and reserve trading with MGs to the power and reserve balance constraints. The energy and reserve price signals that couple Disco and MGs to each other should be limited as in (15). The operation problems of MGs are modeled as the other constraints of Disco's problem described as (16)-(21). The objective function of each MG is modeled as (16) and its constraints are described as (17)-(21).

4.2. Objective functions and constraints for Framework 4

The DNOP can be modeled as bi-level optimization with upper and lower level problems. The upper level problem describes the operation problem of each decision maker including Disco, MGs, and DERs. The lower level problem describes the social welfare problem solved by the LMO to obtain the local energy and reserve prices and to meet the technical constraints of the distribution network. This model is similar to the models used in transmission networks to represent the behaviors of generation companies (Gencos) and independent system operator (ISO) [59].

If the Disco is considered as the upper level decision maker, the operation problem of Disco is modeled as (22)-(25). In this framework, the bids/offers of the Disco are considered in its objective function and the resulting model is described as follows:

$$F_{4,\mathrm{Disco}} = C_{\mathrm{Disco}}^{\mathrm{WEM}} - R_{\mathrm{Disco}}^{\mathrm{sell}} + C_{\mathrm{DG}} + C_{\mathrm{IL}} + C_{\mathrm{ES}} + C_{\mathrm{DER}}^{\mathrm{reserves}} - R_{\mathrm{Disco}}^{\mathrm{RM}} + C_{\mathrm{Disco}}^{\mathrm{LRM}} - R_{\mathrm{Disco}}^{\mathrm{LEM}} \tag{22}$$

where:

$C_{\mathrm{Disco}}^{\mathrm{LRM}}$ costs of purchasing reserve from the LRM

$C_{\mathrm{Disco}}^{\mathrm{LEM}}$ costs of purchasing energy from the LEM

$R_{\mathrm{Disco}}^{\mathrm{LEM}}$ revenues from trading energy with the LEM

The constraints for the upper level problem are expressed as follows:

- Energy balance constraint at time step *t*:

$$\Delta w_t^{\text{Grid}} + \Delta w_t^{\text{Disco}} + w_t^{\text{DG}} + w_t^{\text{IL}} + \Delta w_t^{\text{ES}} = w_t^{\text{Disco,demand}} \quad (23a)$$

for energy trading with the MGs: $\Delta w_t^{\text{Disco}} = w_t^{\text{LEM,purchase}} - w_t^{\text{LEM,sell}}$ (23b)

as well as (2b)-(2c) (23c)

where:

$w_t^{\text{LEM,purchase}}$ Energy purchased from the local energy market by the Disco

$w_t^{\text{LEM,sell}}$ Energy sold to the local energy market by the Disco

- Reserve balance constraint: considering the amount of reserves provided by DERs $r_t^{\text{g,reserves}}$ from the source $g = 1,\ldots, G$ at time step t and the reserves provided from the LRM $r_t^{\text{LRM,reserves}}$ and reserves $r_t^{\text{Disco,reserves}}$ provided by the Disco to the reserve market.

$$\sum_{g=1}^{G} r_t^{\text{g,reserves}} + r_t^{\text{LRM,reserves}} = r_t^{\text{Disco,reserves}} \quad (24)$$

- Further constraints:

from equations (6a)-(9b) (25)

The lower level operation problem modeled for the LMO is represented in (26)-(32), considering the bids/offers of the decision makers and the technical constraints of the distribution network. The objective function of the LMO, that is, the social welfare of decision makers including Disco, MGs, and local DERs, is described as (26) and the technical constraints of network and decision makers are modeled as (27)-(32).

$$F_{4,\text{LMO}} = C_{\text{Disco}}^{\text{LEM}} + C_{\text{Disco}}^{\text{LRM}} + C_{\text{MG}}^{\text{LEM}} - R_{\text{MG}}^{\text{LRM}} - R_{\text{DER}_{\text{local}}}^{\text{LEM}} - R_{\text{DER}_{\text{local}}}^{\text{LRM}} \quad (26)$$

where:

$C_{\text{Disco}}^{\text{LEM}}$	costs of Disco for trading energy in the LEM
$C_{\text{Disco}}^{\text{LRM}}$	costs of Disco from purchasing reserve from the LRM
$C_{\text{MG}}^{\text{LEM}}$	costs of MG from trading energy in the LEM
$R_{\text{MG}}^{\text{LRM}}$	revenues of MG from providing reserve to the LRM
$R_{\text{DER}_{\text{local}}}^{\text{LEM}}$	revenues of local DERs from purchasing energy in the LEM
$R_{\text{DER}_{\text{local}}}^{\text{LRM}}$	revenues of local DERs from providing reserve to the LRM

The constraints are expressed as follows:

- Energy balance constraint for bus *n* at time step *t*:

$$w_{n,t}^{DER} + w_{n,t}^{MG} + w_{n,t}^{Disco} = 0 \tag{27}$$

- Branch currents and bus voltage limits:

$$\text{the same as (4a)-(4b)} \tag{28}$$

- Reserve balance constraint: considering the amount of reserves $r_t^{\text{g,reserves}}$ provided by DERs from the source g = 1,…, G at time step t and the reserves $r_t^{\text{MG,reserves}}$ provided by the MG for the Disco.

$$\sum_{g=1}^{G} r_t^{\text{g,reserves}} + r_t^{\text{MG,reserves}} = r_t^{\text{Disco,reserves}} \tag{29}$$

- Constraints of trading energy and reserves with the Disco:

$$0 \leq w_{n,t}^{\text{Disco,sell}} \tag{30a}$$

$$r_t^{\text{Disco,reserves}} + w_t^{\text{Disco,purchase}} / \Delta t \leq P_{\text{Disco}}^{\max} \tag{30b}$$

- Constraints of trading energy and reserves with the MGs:

$$0 \leq w_{n,t}^{\text{MG,purchase}} \tag{31a}$$

$$r_{n,t}^{\text{MG,reserves}} + w_{n,t}^{\text{MG,sell}} / \Delta t \leq P_{\text{MG},n}^{\max} \tag{31b}$$

- Constraints of trading energy and reserves with the DERs:

$$r_{n,t}^{\text{DER,reserves}} + w_{n,t}^{\text{DER}}/\Delta t \le P_{\text{DER},n}^{\max} \tag{32}$$

4.3. Special case for Framework 4

In this case, the distribution network is considered as formed by coupled MGs. The Disco has no network and is only the interface between the LEM and the wholesale markets. To model the operation problem of distribution network in this case, two-stage approaches are used.

At the first stage, the DNOP is modeled from the perspective of each MG, using as objective function the operation costs. Let us assume to have $k = 1,\ldots, K$ coupled MGs. The operation cost for the k^{th} MG in the total time interval T partitioned in time steps $t = 1,\ldots, T$ is expressed as:

$$F_{4,\text{MG}_k} = \sum_{t=1}^{T} \sum_{y=1}^{Y} \lambda_{k,t}^{(\text{y})} w_{k,t}^{(\text{y})} \tag{33}$$

where Y is the number of different types of energy is a multi-energy framework, while $\lambda_{k,t}^{(\text{y})}$ and $w_{k,t}^{(\text{y})}$ are the price and amount of energy of the y^{th} energy type purchased by the k^{th} MG at time step t. At the other stage, an appropriate solution methodology is proposed to model the cooperation between MGs and to determine the optimal energy trading between MGs, as well as between MGs and the distribution grid. The solutions are different by taking into account the possible centralized or decentralized control of the MGs [60].

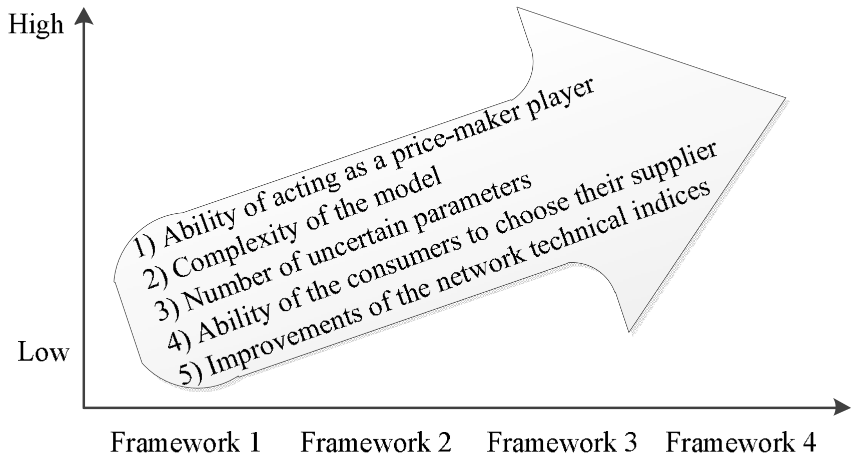
4.4. Comparisons among the Frameworks

The frameworks proposed for DNOP of the Disco are compared with each other from different aspects. Fig. 5(a) indicates that the number of players that interact with the Disco increases from Framework 1 to Framework 4, also giving the consumers more room to choose their supplier. This leads to increasing the complexity of the Disco operation problem and the number of uncertain parameters from Framework 1 to Framework 4. On the other hand, the technical indices of the distribution network including power losses, voltage profile, and reliability [61] improve in the presence of DERs and MGs [62].

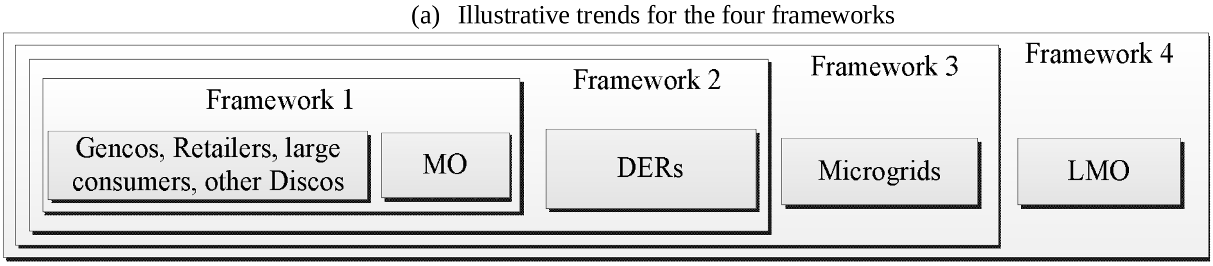
Fig. 5(b) shows the progressive inclusion of decision makers that interact with the Disco in the four frameworks. Fig. 5(c) illustrates the scheme with which the bi-level optimization approach is applied to Framework 3 and Framework 4, with an upper level problem referring to the Disco, and a lower level problem defined for the MGs and the LMO, respectively.

Since the Disco has no capability to change its demand in Framework 1, it has the minimum ability to affect the wholesale market outcomes, which is the main disadvantage of this framework. In the presence of DERs and MGs in other frameworks, the Disco can trade energy and reserves with these resources. Its objective function shown in Fig. 5(d) represents the increasing capability of the Disco to act as a price-maker player in the markets.

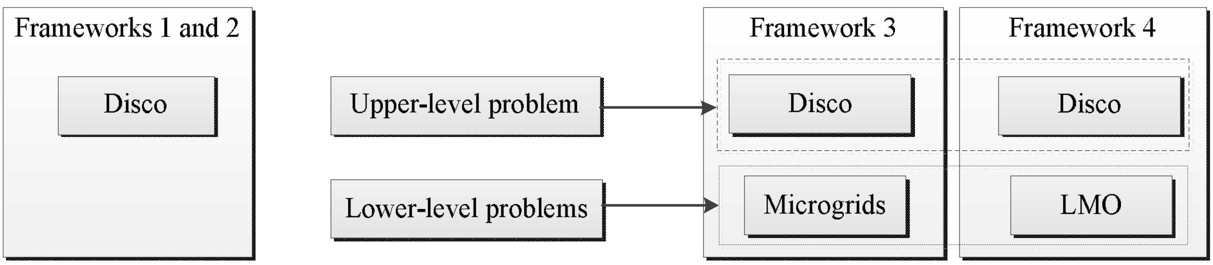
In Framework 1 and Framework 2, the consumers are supplied only by the Disco. In Framework 3 part of the load can be supplied through the MGs. In Framework 4 the consumers have higher ability to choose their suppliers through the local energy market, which is a key advantage of this framework.



(a) Illustrative trends for the four frameworks



(b) The decision makers that interact with the Disco in each framework



(c) The structure of the bi-level model in Frameworks 3 and 4

functions	WEM	consumers	DER	reserves	other terms
$F_{1,\text{Disco}}$	$=C_{\text{Disco}}^{\text{WEM}}$	$-R_{\text{Disco}}^{\text{sell}}$			
$F_{2,\text{Disco}}$	$=C_{\text{Disco}}^{\text{WEM}}$	$-R_{\text{Disco}}^{\text{sell}}+C_{\text{IL}}$	$+C_{\text{DG}}+C_{\text{ES}}$	$+C_{\text{DER}}^{\text{reserves}}-R_{\text{Disco}}^{\text{RM}}$	
$F_{3,\text{Disco}}$	$=C_{\text{Disco}}^{\text{WEM}}$	$-R_{\text{Disco}}^{\text{sell}}+C_{\text{IL}}$	$+C_{\text{DG}}+C_{\text{ES}}$	$+C_{\text{DER}}^{\text{reserves}}-R_{\text{Disco}}^{\text{RM}}$	$+C_{\text{MG}}^{\text{reserves}}-R_{\text{Disco}}^{\text{MG}}$
$F_{4,\text{Disco}}$	$=C_{\text{Disco}}^{\text{WEM}}$	$-R_{\text{Disco}}^{\text{sell}}+C_{\text{IL}}$	$+C_{\text{DG}}+C_{\text{ES}}$	$+C_{\text{DER}}^{\text{reserves}}-R_{\text{Disco}}^{\text{RM}}$	$+C_{\text{Disco}}^{\text{LRM}}-R_{\text{Disco}}^{\text{LEM}}$

(d) Relevant functions for the Disco interactions in the four decision-making frameworks. In the frameworks 3 and 4 other lower-level functions are defined for the MGs and the LMO, respectively. The notation and meaning of the terms are indicated in the specific sections of the paper.

Fig. 5: Comparisons among the frameworks from different aspects

The DNOP of the Disco in the proposed frameworks may be suitable for different time scales regarding the capability of the Disco to participate in different wholesale energy and reserve markets, as shown in Fig. 6. The day-ahead, adjustment, and balancing markets are cleared with different timings, namely, in the previous day, every few hours, and the closer time before the real operation, respectively. In Framework 1, since the Disco has the minimum capability to make strategic decisions in the wholesale markets or provide ancillary services, it prefers to purchase the required energy from the day-ahead energy market. In Framework 2 and Framework 3, in the presence of DERs and MGs, the Disco has capability to participate in the both day-ahead energy and reserve markets as a price-maker player. Moreover, regarding the DERs as the fast-response resources, the Disco can participate in the balancing markets to provide the ancillary services to the wholesale markets. In Framework 4, since the local markets can be cleared in all time scales equivalent to the wholesale markets from the day ahead to the real-time, it is appropriate for the Disco to participate in all wholesale and local energy and reserve markets with their different time scales.

Fig. 6: Different time scales of operation problem regarding the clearing time of the markets

5. Solution methods for bi-level models

The proposed bi-level models in Framework 3 and Framework 4 can be solved using different approaches, as described in [63]. The situations mentioned in the previous section are used in the literature to model the DNOP in the presence of MGs. The literature contributions are collected by highlighting different aspects in Table 4 (decision makers, types of market and distribution network models), Table 5 (model details and solution methods) and Table 6 (deterministic/stochastic models, and uncertain parameters considered). The Disco is considered as price-taker in wholesale energy and reserve markets in all studies, as shown in Table 4.

In many studies, the cooperation between decision makers in distribution networks is considered for energy provision, whereas reserves are modeled in few ones. To evaluate the effectiveness of the proposed models given in Table 4 and their solution methodologies, most studies use either real networks or single bus networks.

The DNOP in the presence of MGs is modeled as Framework 3 in most studies as shown in Table 5. In fact, the hierarchical decision making framework consisting of Disco and MGs as the upper- and lower-level decision makers is considered to model the operation problem of ADNs. On the other hand, modeling the ADNs as coupled MGs is investigated in many studies as the special case of Framework 4. Moreover, the models reviewed in Table 5 show that the local markets in distribution networks are modeled in few studies as Framework 4. Therefore, appropriate models to describe Framework 4 including wholesale and reserve markets have been presented in Section 4.2 and Section 4.3. Also, the coordination schemes proposed in the SmartNet project can be considered in this framework.

Most solution methodologies used in the literature adopt an iterative process to achieve optimal solutions. Also, distributed optimization algorithms are applied on most models to achieve the optimal solutions. From the viewpoint of modeling uncertainties, Table 6 shows that many models are simply deterministic, and do not consider uncertain parameters. However, in the presence of DER the uncertainties play a key role. Thereby, the development of specific models that take into account the uncertainties is particularly valuable.

Table 4
Details of DNOP modeled in the literature in the presence of MGs.

Ref.	Decision makers			Disco in WEM/RM		Wholesale markets		Distribution network model		
	Disco	MGs	DERs	Price taker	Price maker	Electricity	Reserve	Standard	Real	Single bus
[60]	-	✓	-	✓		✓	-	-	-	✓
[64]	✓	✓	-	✓	-	✓	-	-	15 kV urban	-
[65]	✓	✓	-	✓	-	✓	-	-	15 kV urban, 30 kV rural	-
[66]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	128 bus in China	-
[67]	-	✓	-	✓	-	✓	-	-	-	✓
[68]	-	✓	-	✓	-	✓	-	-	-	✓
[69]	✓	✓	-	✓	-	✓	-	-	Hypothetical network	-
[70]	✓	✓	-	✓	-	✓	-	-	Hypothetical network	-
[71]	✓	✓	-	✓	-	✓	-	-	-	✓
[72]	✓	✓	-	✓	-	✓	-	-	-	✓
[73]	✓	✓	-	✓	-	✓	-	-	-	✓
[74]	✓	✓	-	✓	-	✓	✓	-	-	✓
[75]	-	✓	✓	✓	-	-	✓	-	✓	-
[76]	-	✓	✓	✓	-	✓	-	-	Power world simulator	-
[77]	✓	✓	-	✓	-	✓	-	-	-	✓
[78]	✓	✓	-	✓	-	✓	-	-	20 kV rural in Greece	-
[79]	✓	✓	-	✓	-	✓	-	-	Hypothetical network	-
[80]	-	✓	-	✓	-	✓	-	IEEE 33, 69, and 119 buses	-	-
[81]	✓	✓	-	✓	-	✓	-	IEEE 33 and 123 buses	-	-
[82]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	✓	-
[83]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	✓	-
[84]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	Portuguese distribution network	-
[85]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	128 bus in China	-
[86]	-	✓	-	✓	-	✓	-	-	Hypothetical network	-
[87]	✓	✓	-	✓	-	✓	-	IEEE 33 bus	128 bus in China	-
[88]	-	✓	-	✓	-	✓	-	-	-	✓
[89]	-	✓	-	✓	-	✓	-	-	-	✓

Table 5
Details of DNOP modeling and solution methods in the presence of MGs.

Ref.	Framework for the proposed model			Price signal		Time period of operation		Solution methodology
	3	4	4 (special)	Fixed	Variable	Real-time	Day-ahead	
[60]	-	-	✓	-	✓	-	✓	Coordinated dynamic programming algorithm
[64]	✓	-	-	✓	-	-	✓	MCDA
[65]	✓	-	-	✓	-	-	✓	SQP
[66]	✓	-	-	✓	-	-	✓	GA
[67]	-	-	✓	-	✓	-	6 hour	Stochastic gradient iteration
[68]	-	-	✓	-	✓	-	✓	Stochastic gradient iteration
[69]	✓	-	-	✓	-	✓	-	Hierarchical optimization algorithm
[70]	✓	-	-	✓	-	✓	-	Hierarchical optimization algorithm
[71]	-	✓	-	-	✓	-	✓	Multi-agent system
[72]	✓	-	-	-	✓	-	✓	KKT conditions and dual theory
[73]	✓	-	-	-	✓	✓	-	KKT conditions and dual theory
[74]	✓	-	-	-	✓	✓	-	KKT conditions and dual theory
[75]	-	✓	-	-	✓	✓	-	MATPOWER
[76]	-	✓	-	-	✓	-	✓	Multi-agent system
[77]	✓	-	-	✓	-	✓	-	KKT conditions
[78]	✓	-	-	✓	-	-	✓	MATLAB
[79]	-	-	✓	✓	-	✓	-	Multi-agent system
[80]	-	-	✓	✓	-	-	✓	Distributed algorithm
[81]	-	-	✓	✓	-	-	✓	Bender decomposition
[82]	✓	-	-	✓	-	-	✓	Analytical target cascading theory
[83]	✓	-	-	-	✓	-	✓	Column-and-constraint generation and GA methods
[84]	✓	-	-	✓	-	-	1 year	Non-dominated sorting genetic algorithm-II
[85]	✓	-	-	✓	-	-	✓	GA
[86]	-	-	✓	✓	-	✓	-	Non-dominated sorting genetic algorithm-II
[87]	✓	-	-	✓	-	-	✓	Non-dominated sorting genetic algorithm-II
[88]	-	-	✓	✓	-	-	✓	PSO
[89]	-	-	✓	✓	-	✓	✓	MOSEK toolbox

Table 6

Uncertain parameters modeled in DNOP in the presence of MGs.

Ref.	Model		Uncertain parameters			
	Deterministic	Stochastic	Solar radiation	Wind speed	Demand	Electricity price
[60]	✓	-	-	-	-	-
[64]	✓	-	-	-	-	-
[65]	✓	-	-	-	-	-
[66]	✓	-	-	-	-	-
[67]	-	✓	-	-	✓	✓
[68]	-	✓	-	-	✓	✓
[69]	✓	-	-	-	-	-
[70]	✓	-	-	-	-	-
[71]	✓	-	-	-	-	-
[72]	-	✓	-	✓	✓	-
[73]	✓	-	-	-	-	-
[74]	✓	-	-	-	-	-
[75]	✓	-	-	-	-	-
[76]	✓	-	-	-	-	-
[77]	✓	-	-	-	-	-
[78]	✓	-	-	-	-	-
[79]	✓	-	-	-	-	-
[80]	-	✓	✓	✓	-	-
[81]	✓	-	-	-	-	-
[82]	-	✓	✓	✓	✓	-
[83]	-	✓	✓	✓	✓	-
[84]	-	✓	✓	✓	✓	✓
[85]	-	✓	✓	✓	-	-
[86]	✓	-	-	-	-	-
[87]	✓	-	-	-	-	-
[88]	-	✓	✓	✓	✓	-
[89]	-	✓	✓	✓	✓	✓

6. Discussion and conclusions

This paper has presented a comprehensive review of recent contributions addressing DNOP in the presence of DERs and MGs. The DNOP problem has been described by using a decision-making framework in which different perspectives have been presented, investigating the relations between decision makers. Then, different aspects have been addressed, including the role of the Disco, MGs and DERs in wholesale energy and reserve markets, and the cooperation or competition between decision makers. An overview has been given on the resulting models, optimization techniques, and uncertain parameters considered in the literature.

For a critical appraisal of these models, it is important to consider the evolution of the concepts referring to the role of the distribution system (and its Disco operator) in the electricity markets. In [90], instead of having a market for distribution systems, the focus is set on the provision of energy and network services by using DGs owned by the distributor itself or by private entities. In this case, the day-ahead market price is given, and the private DGs can provide the distribution network services through bilateral contracts. In a further view [91], the private DERs are not considered, and the Disco uses its own DGs to minimize the costs of electricity provision in the wholesale electricity market. In both the above cases, in which the Disco is considered as a DG owner, no competition has to be in place between the DG owned by the Disco and the DG owned by private entities. Otherwise, the participation of Disco-owned DGs and private-owned DGs in the same market cleared by the Disco would lead to market distortion, as the Disco will have a direct conflict of interest.

For this reason, the frameworks developed in this paper have been described in the situation in which no market distortion does exist.

The results of this review show that some aspects of DNOP in the presence of DERs and MGs have to be further investigated and can be considered in future works, namely:

- Since in most studies the behavior of some market players is not strategic (i.e., these players behave as price-takers), the Disco and the other decision makers such as Gencos, retailers and other Discos can be modeled as price-makers in wholesale energy and reserve markets.
- Although MGs could be employed to enhance the distribution network resilience in response to the extreme weather events, this aspect is not considered in the literature and could be added to the models developed for Framework 3 and Framework 4.
- Different mutual impacts of wholesale and local markets in Framework 4 can be investigated in future works including: 1) modeling the impact on the wholesale and local market prices of the bidding strategies of Discos that play, simultaneously in both markets; 2) modeling the impact of strategic behavior of local market players such as MGs on the wholesale market prices; 3) modeling the effect of competition between the Disco and other strategic players in local markets on both local and wholesale markets.
- Since different schemes are defined for coordination between DSO and TSO in Framework 4 in presence of MGs and DERs, different formulations can be developed to model the cooperation between these operators to manage the transmission and distribution networks.
- The models proposed in the literature can be developed to include other aspects of distribution network operation in the presence of DERs and MGs (e.g., reconfiguration, reliability evaluation, and voltage profile improvement).

- A clearer distinction has to be made between generation-side DER (e.g., distributed generation, and storage associated to the generation side, for example to limit the power fluctuations) and the demand-side DER (e.g., demand side management, demand response, and storage seen as an energy backup for the local demand).
- The effects of the uncertainty of wind speed, solar radiation, demand, and electricity prices on the DNOP solutions can be investigated by using risk-based indices.
- Finally, future developments depend on possible changes in the regulation, which could enable the diffusion of MGs managed by the local entities that operate in the local markets.

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