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A Two-Stage Flexibility-oriented Stochastic Energy Management Strategy for Multi-Microgrids Considering Interaction with Gas-grid

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***Abstract*— — Introduction of renewable energy sources (RESs) and independently operated multi-microgrid (MMG) systems have led to new issues in the management of power systems. In this context, uncertainty associated with RESs as well as intense ramps inflicted on the network called system flexibility constraints have raised new challenges in power systems. The new condition necessitates implementation of novel frameworks that enable local system operators to efficiently manage the available resources to cope with the flexibility ramp constraints. Moreover, the new framework should facilitate energy management in a system with an MMG structure considering uncertainty of RESs. Consequently, this paper aims to provide a novel framework that composes of a two-level stochastic optimization procedure to optimize the energy management in an MMG considering uncertainty of RESs as well as grid flexibility constraints. In the proposed scheme, resource scheduling in microgrids (MGs) is conducted in the first level by their control units; while the second level procedure focuses on the coordination of MGs considering flexibility constraints. Furthermore, interaction with Gas-grid as a potential flexible resource is optimized in the second level procedure. Finally, the provided flexibility-oriented management scheme is implemented to schedule the local resources in a three-microgrid test system considering flexibility constraints.**

***Index Terms*— Flexibility, energy management strategy, resource management, stochastic optimization, renewable energy, power-gas-power system, flexible resources.**

I. NOMENCLATURE

A. Sets

$I^{DG,k}$, $I^{flex,k}$, $I^{ESS,k}$, $I^{RES,k}$, $I^{D,k}$	Sets of all dispatchable generation units, flexible power units, storage units, RESs units and loads in the k^{th} MG.
I^{MG}	Set of all MGs in the MMG system
$I^{ESS,MGC}$	Set of all ESS units operated by MGC
t	Index for time
k	Index for microgrid
s	Index for scenario

B. Constants

GBP_t, GSP_t	Price of buying and selling power to main grid
$P_t^{buy,max}$, $P_t^{buy,min}$	Maximum and minimum amount of power that overall MMG system could buy from main grid.
$P_t^{sell,max}$, $P_t^{sell,min}$	Maximum and minimum amount of power that overall MMG system could sell to main grid.
$C^{LS,k}$	Cost of load shedding in the k^{th} MG.
MUT_i	Minimum up time of unit *i*.
MDT_i	Minimum down time of unit *i*.
$P_{i,t}^{RES,k}$	Power output of RES unit *i* in the k^{th} MG at *t*.
$P_{k,t}^{short}$, $P_{k,t}^{surp}$	Shortage power and surplus power in the k^{th} MG at *t*.
$P_i^{max,k}$, $P_i^{min,k}$	Maximum and minimum capacity of generating unit *i* in the k^{th} MG.
$RU_i^{DG,\max,k}$, $RD_i^{DG,\max,k}$	Maximum ramp-up and ramp-down of dispatchable unit *i* of MG *k*.
$C_i^{DG,k}$	Production cost of dispatchable unit *i* of MG *k*.
$P_t^{buy,max,k}$, $P_t^{buy,min,k}$	Maximum and minimum amount of power that MG *k* could buy from main grid.
$P_t^{sell,max,k}$, $P_t^{sell,min,k}$	Maximum and minimum amount of power that MG *k* could sell to main grid.
$P_i^{dch,max,k}$, $P_i^{dch,min,k}$	Maximum and minimum possible discharging of storage unit i in the k^{th} MG.
$P_i^{ch,max,k}$, $P_i^{ch,min,k}$	Maximum and minimum possible charging of storage unit *i* in the k^{th} MG.
$\eta_i^{ch,k}$, $\eta_i^{dch,k}$	Charging and discharging efficiency of storage unit *i* in the k^{th} MG.
$E_i^{\max,k}$, $E_i^{\min,k}$	Maximum and minimum capacity of storage unit *i* in the k^{th} MG.
$L_{adj}^{\max,k}$, $L_{adj}^{\min,k}$	Maximum and minimum of adjustable load in each hour in the k^{th} MG.
NE_{adj}^k	Required energy of adjustable load in the k^{th} MG.
a, b	Specified start and end times to calculate the consumed energy of adjustable load
α	Confidence factor
β	proportion of risk factor in objective function
$\Delta P_{k,i,t}^{flex,\max}$, $\Delta P_{k,i,t}^{flex,\min}$	Maximum and minimum possible change in power generation of flexible power unit *i* in the k^{th} MG at *t*.
$P_i^{dch,max,MGC}$, $P_i^{dch,min,MGC}$	Maximum and minimum possible discharging of MGC's storage unit *i*.
$P_i^{ch,max,MGC}$, $P_i^{ch,min,MGC}$	Maximum and minimum possible charging of MGC's storage unit *i*.
$\eta_i^{ch,MGC}$, $\eta_i^{dch,MGC}$	Charging and discharging efficiency of MGC's storage unit *i*.
η_i^{P2G}, η_i^{GFPP}	Efficiency rate of power-to-gas transformation unit *i* and Gas-Fired-Power-Plant *i*.
$E_i^{\max,MGC}$, $E_i^{\min,MGC}$	Maximum and minimum capacity of storage unit *i* in the k^{th} MG.
$\Delta_t^{flexiblity-ramp}$	Flexibility limit at *t*.

C. Variables

$P_t^{buy,k}$, $P_t^{sell,k}$	The amount of power that the k^{th} MG purchased from or sold to the main grid.
$P_{i,t}^{DG,k}$	Output power of dispatchable unit *i* in the k^{th} MG at *t*.
$P_{i,t}^{ch,k}$, $P_{i,t}^{dch,k}$	Charging/Discharging amount of power storage unit *i* in the k^{th} MG at *t*.
$P_t^{lp,inj}$, $P_t^{lp,ex}$	Charging/Discharging amount of power stored in Gas grid at *t*.
LS_t^k	Load shedding in the k^{th} MG at *t*.
$L_{i,t}^k$	Load of kind i in the k^{th} MG at *t*.
$x_{i,t}^k$	On/off state of dispatchable unit *i* in the k^{th} MG at *t*.
$SU_{i,t}^k$	Binary variable for start-up of unit *i* in the k^{th} MG at *t*.

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$SD_{i,t}^{k}$	Binary variable for shut-down of unit *i* in the *k*th MG at *t*.
$T_{i,t}^{on}, T_{i,t}^{off}$	Number of successive ON and OFF hours for unit *i*.
$E_{i,t}^{k}$	Stored energy in the storage unit *i* of the k^{th} MG at *t*.
EP_{t}^{lp}	Stored energy in the Gas grid at *t*.
$P_{i,t}^{GFPP}$	Power produced by Gas-Fired-Power-Plant *i* at *t*.
$P_{i,t}^{P2G}$	Power converted to gas by P2G unit *i* at *t*.
$z_{adj,t}^{k}$	On/off state of adjustable load in the k^{th} MG at *t*.
$\Delta P_{k,i,t}^{flex}$	Change in power generation of flexible power unit i in the k^{th} MG at *t*.
$LS_{k,t}^{ul}$	Load shedding in the k^{th} MG at *t* in upper-level optimization.
$P_{k,t}^{ul,buy}$, $P_{k,t}^{ul,sell}$	The amount of power MG *k* purchased/sold to the main grid in upper-level optimization.
$P_{i,t}^{ch,MGC}$, $P_{i,t}^{dch,MGC}$	Charging/Discharging amount of power of MGC's storage unit *i* at *t*.
$E_{i,t}^{MGC}$	Stored energy in the MGC's storage unit *i* at *t*.
ξ , φ	Auxiliary variables for calculating CVaR

II. INTRODUCTION

DISTRIBUTION systems have experienced a dramatic increasing rate of renewable energy sources (RESs) installation in recent years; which is primarily motivated by the fact that these resources are clean and free from contamination [1]. Nevertheless, the growing tendency to RESs such as solar energy and wind power has caused new challenges in operation and planning of power systems. These issues are primarily emerged as a result of the stochastic and intermittent nature of RESs that should be taken into account by system operator in operational management process [2, 3].

In this regard, high dependence of RESs on environmental factors like solar irradiance and wind speed could result in abrupt changes in the net-load of the system, when the power generation by RESs suddenly drop [4]. In this regard, duck curve, which is seen for example in California electricity network, is one of the newly emerged issues in systems with high-penetration of RESs [5-7].

System operators conventionally rely on fast ramping bulk power units which are connected to the transmission networks and operated by transmission system operator (TSO) to provide flexible-ramp needed in the power grid. However, decreasing investment and operational cost of RESs along with bulk power generation resources investment requirement, construction time, operational cost and transmission system congestion would limit the available flexibility-capacity that could be provided by generation units located in the transmission system [8]. Consequently, local resources should be efficiently managed by local operators in a way that the unbalanced power between demand and generation meets the available flexibility capacity [9].

Development of microgrids (MGs) which normally operate by independent control units could make a dramatic transformation in existing power grids. In this context, MGs could potentially play a key role in future smart grids by forming multi-microgrid (MMG) systems that are composed of several coordinated MGs. The cooperation of MGs in an MMG system primarily aims to minimize the operational cost and improve reliability and stability of the grid. In this regard, flexibility constraints of the system should also be taken into account by MMG control units in the networks with high-penetration of RESs. In the other words, MGs could help the main grid to address intense net-load ramping caused mostly by RESs' intermittent nature [7, 10]. As a result, new coordination methodologies should be developed to enable the MGs cooperation; while the energy management schemes in the MMG structures cope with the available flexibility-ramp-capacity of the network.

Application of one MG to mitigate the net-load ramp of the main grid is carried out in [11, 12]. Authors in [13] have investigated the operational flexibility service that could be provided by electrical vehicles in local systems considering their associated uncertainties. Based upon the dependence of future power systems on local systems to provide flexibility services, a planning framework is developed in [9, 14] in order to improve the flexibility of distribution systems. Development of an accurate model for combined-cycle units as flexible resources that could provide ramping capability for the system operation is investigated in [15]. Reference [16] develops a dynamic pricing model for electric vehicle charging stations to decrease their potential effects on increasing the net-load ramp-up. This study shows the importance of optimal scheduling of local resources to alleviate the ramp-up issues in distribution systems. A home energy management system is developed in [17] to optimize the day ahead operational cost while providing local flexibility services. Efficient scheduling of storage units and demand response programs are employed in [18] to provide flexibility service for efficient operation of power systems. The authors in [19] have investigated advantages of considering an optimal bidding strategy for MGs to provide energy and ancillary services for power grids. While, flexibility ramp constraints in the MG are analyzed in previous studies, coordination of MGs as well as interaction of electricity and Gas grid with the aim of providing flexible services to the main grid are not studied in the previous researches.

Authors in [20] considered power distribution network interaction with the gas system by modeling bidirectional energy trading contracts. In this regard, reserved gas contracts are utilized for mitigating wind generation outputs deviation. In [21] gas-fired units were considered as an option to improve the balance between generation and consumption in short-term scheduling in order to increase the penetration of wind power in the power system and decreasing the operation cost of the system. Authors in [22] modeled a virtual power plant consisted of distributed energy resources to optimize the participation of local resources in day-ahead and real-time electricity markets. Note that while these works have taken into account the co-operation of electricity and gas network; the effects of the interaction of electricity and gas network has not investigated from the flexibility ramp perspective.

As mentioned earlier, operation of MGs in an MMG system could result in reliability and resiliency improvement of the grid. Authors in [23] considered different topologies of power exchanges between MGs and minimized the overall energy cost in a distributed system comprised of MMG systems. Reference [24] proposed a framework for MMG system coordination in order to optimize the amount of energy exchanged between the MGs. A two-stage energy management framework is proposed to perform day-ahead unit commitment operation in [25]. Arefifar et al. [26] have proposed a method to reduce the total operational costs of MMG systems using the tabu search method.

The study in [27] presents a two-stage management scheme for MMGs with the aim of minimizing the operational costs of MMG systems. The first optimization stage is aimed to minimize the system operational cost and the second stage is modelled to minimize the cost of deviation between day-ahead and real-time operation. The study in [28] proposes a cost-effective two-stage control strategy in distributed systems considering coordination between MGs. Reference [29] has formulated the economic operation of MMG systems and used particle swarm optimization (PSO) to minimize the cost of power generation.

Hierarchical control framework of MMG systems is one of the popular employed structures, which focuses on minimizing the operational costs and maximizing the operational benefits. This approach could lead to efficient optimal scheduling; while, breaking down the optimization process among different agents would considerably decrease the computational burden in comparison with the methodologies relying on centralized optimization. Authors in [30] have developed a hierarchical energy management framework for MMGs considering the uncertainty of RESs. A hierarchical energy management system (EMS) has been proposed by [31] for optimal resource scheduling of MMG systems. Additionally, [32] proposes a hierarchical optimization of an MMG structure considering an MGs-community (MGC) that facilitates the coordination of MGs. The MGC entity considered in [27, 30-32] provides the possibility for MGs to interact with each other; while, they may have different operational goals.

Based upon the literature explorations and the above discussions, the following points could be pointed out:

- In conventional studies, flexibility-based operational optimization of local systems is merely focused on scheduling flexible resources located in an MG [10, 12, 33, 34]. However, interaction of independently operated systems in an MMG structure could also have dramatic effects on the overall available flexibility capacity. These studies could finally result in decreasing the investment and operational costs associated with flexibility issues in each MG as well as the main grid.
- Utilities would rely on local resources in order to deal with flexibility issues in future power systems with the high penetration of RESs installations. Despite various studies, which have been conducted on the coordination of a system comprised of MGs; to the best of authors' knowledge, energy management of MMG systems considering flexible-ramp limitations has not been yet thoroughly investigated in the previously proposed methodologies.
- RES units, as the potentially primary energy resources in MGs, significantly affect the net-load ramping. In this regard, the uncertainty associated with RESs as well as stochastic dependence between power-output of RESs have to be taken into account in ramp-oriented operational scheduling of MMG systems.
- The proposed framework considers compromising between operational cost and operational risk due to uncertainty associated with RESs. In this regard, this paper investigates the effects of MGs' perspectives toward risk on the final ramping associated with the net-load of the MMG system. Moreover, sensitivity analysis is taken into account to study the effects of the input parameters on the operational scheduling of the system.
- Interconnection of the electricity grid with the Gas-grid could enable the system operators to smooth the net-load of the system. However, interconnection with the Gas-grid has not been taken into account in previous studies to assess its effectiveness in improving the system flexibility from the flexible-ramp perspective.

To address the above-mentioned challenges, coordination of MMG systems, in a way that the available flexible-ramp in the network meets the supply-demand gap, is studied for the first time in this paper. In this regard, a two-level stochastic EMS framework is proposed for optimal MMG management with the aim of minimizing the operational costs of the MMG system and enhancing the flexibility of the overall grid. In the first level, EMS agents in each MG independently conducts resource scheduling optimization for the next 24 hours. Then, the results obtained in the first level will be transmitted to the MGC which is responsible for operational optimization of the MMG system and determining the power exchanges among MGs as well as between the MMG system and the main grid. Furthermore, the transformation of power-to-gas (P2G) and gas-to-power (G2P) with the aim of improving flexibility of the MMG system is optimized by MGC.

In this paper, stochastic optimization is taken into account to address the uncertainties associated with the operation of RESs. Furthermore, variables associated with power production of RESs are transformed into a common domain, the rank/uniform domain, by applying the cumulative distribution function transformation and finally Gaussian Copula is utilized to model their associated dependence. Furthermore, for the first time, a complete formulation is developed to facilitate incorporating ramp capabilities of conventional distributed generations in the second-level optimization considering privacy concerns. In this regard, the requisite data communication between the control agents in the proposed management framework has not changed in comparison to the previous hierarchical management schemes, while the optimization procedures in the model are developed in a high-resolution way that resources' ramp constraints, as well as the main grid flexibility constraints, are fulfilled. In the proposed EMS scheme, MMGs as local control units can capture the intense net-load ramping and enhance the flexibility of the system to ensure that the net-load seen by the main grid has sufficient ramps within the allowed ranges. Finally, this paper employs sensitivity analysis in order to investigate the effects of operational characteristics associated with the MMG system (i.e. P2G capacity, and risk factor) on the operational costs as well as ramping of the MMG's net-load.

Based upon the above discussions, it is noteworthy that the presented scheme aims to study the management of power systems as well as the effects of different flexible resources from ramping perspective, which would be a significant management issue in systems with high penetration of RESs. As a result, while it is strived to completely model the MMG system considering the structure of the community of MGs presented in [27, 32, 35], the primary studies are focused on the effects of different technologies on flexibility-based management of MMG systems. Furthermore, a novel formulation is developed to facilitate the interaction of independent entities in the system in order to address the privacy concerns in the operational scheduling of the MMG system.

The rest of this paper is structured as follows. In section III, the outline of the proposed two-stage flexibility-oriented MMG optimal scheduling model is introduced and the associated formulations are developed. Section IV presents numerical results of applying the proposed framework on a three-MG test system to show the merits and effectiveness of the proposed model. Finally, Section V discusses the specific features of the proposed model and concludes the paper.

III. METHODOLOGY

A. *System Modelling*

It is expected that future power grids compose of several MGs that will be independently controlled and operated. In this regard, MGs could cooperate with the aim of increasing the flexibility, reliability, and stability of the system besides the fact that coordination of MGs could decrease their operational costs. It is noteworthy that the objectives taken into consideration in the operational management of MGs as subsystems of an MMG system could be different, while, their cooperation in the system level should follow a common goal; i.e. operational cost minimization and coping with the power grid operational constraints. Accordingly, in this paper, a hierarchical structure shown in Fig. 1 is proposed in order to conduct EMS procedure in an MMG system. In this structure, MGC entity is employed to facilitate the interaction among the MGs in the community (i.e. MMG system) by determining the power exchanges among the MGs and the power transaction between each MG and the main grid. Furthermore, it is considered that MGC could directly control some flexible resources which are indicated as MGC’s resources as well as optimize the P2G and G2P transformations in the proposed structure.

In the proposed structure, each EMS agent in the respective MG is responsible for optimally scheduling of the MG’s associated resources. EMS agents conduct the operational optimization procedure merely considering the main grid electricity prices; that is why the achieved optimum point may cause the overall MMG system to violate the flexibility constraints of the main grid. In this regard, the MGC management agent called CEMS is introduced to coordinate the operational points of MGs in order to minimize operational costs of the MMG system, while the flexibility constraints of the utility are addressed. It is worth mentioning that the grid operator specifies limits of the MMG’s net-load variability seen by the main grid taking into account the required grid flexibility in each hour. CEMS performs the MGC optimization by managing MGs and MGC’s resources (i.e. ESS) that are operated under its control as well as power-gas-power transformation. Based upon the above discussions, in the lower level optimization, MGs would independently schedule their resources, while CEMS strives to revise their preliminary scheduling in the second stage to maximize the social welfare of the overall system. In this context, the second stage optimization would be conducted based on the received information from each MG.

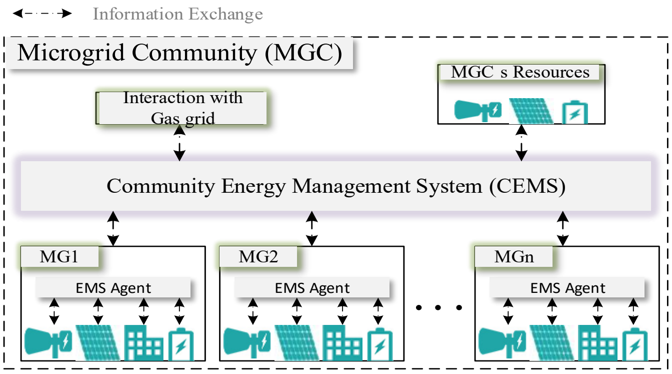

Fig. 1. Two-stage management structure and communication links in the MMG system model.

B. *Proposed Flexibility Management Philosophy*

In the proposed flexibility-oriented optimization, CEMS considers the MMG’s net-load variability besides the operational costs to evaluate the power exchanges with the main-grid and among the MGs, as well as the Gas grid. EMS agents conduct the preliminarily resource scheduling of their respective MGs considering the possibility of buying/selling energy from/to the main grid. The price of buying energy from the main grid is considered as grid-buying-price (GBP); while, the price of selling energy to the grid is considered as grid-selling-price (GSP). In this regard, operational conditions of MGs could be determined based on the amount of power exchange with the main grid. On one hand, the operational limitations and high-operational-costs of local resources could enforce MGs to buy energy from the main grid. In this state, an MG confronts with the power shortage and so power should be purchased from other MGs or the main grid in order to fulfill the supply-demand balance. On the other hand, an MG would intend to sell energy to the grid provided that it has surplus power capacity with the operational cost lower than the GSP. In this state, the MG would merely rely on its local resources to supply local demand and could also sell the surplus power to other MGs or the main grid.

Additionally, it is possible that the operational price of an MG lays between the energy sell/buy prices to/from the grid; which means that the power exchange with the main grid would not be efficient. However, MG could sell power to adjacent MGs facing the lack of power production based upon a bilateral contract with a rational price (i.e. between the GSP and GBP), which is beneficial for both parties. In this context, an MG that purchases energy from other MGs would benefit in comparison with the state that it buys energy at the rate of GBP from the grid. In this regard, the power supplied from the main grid would decrease which results in improving the system flexibility.

Following the preliminary optimization (i.e. first-level optimization) conducted by each EMS agent, the results of the resource scheduling would be sent to CEMS which is responsible for the coordination of power exchanges among MGs as well as power trade with the main grid. In this regard, CEMS optimizes the MMG operation (i.e. second-level optimization) considering batteries located in MGC, operational results of MGs, interaction with the Gas grid, costs of power exchange with the main grid as well as flexibility ramps that could be provided in each hour by the main grid. Finally, the results of optimization would be sent back to the MGs in order to adjust their preliminary resource scheduling. The procedure of the proposed framework is presented in Fig. 2.

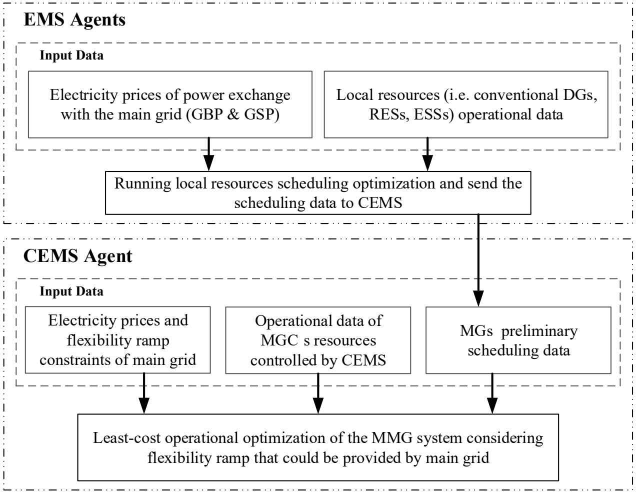

Fig. 2. Proposed MMG management framework

C. Copula-based Scenario Generation

As mentioned, stochastic optimization algorithm is taken into consideration in the operational scheduling of the MMG system to address the uncertainty of RESs, which is initiated based on their dependence on meteorological parameters. However, meteorological characteristics are usually correlated in the geographical area that the MMG system is located. Therefore, it is considered that CEMS is responsible of scenario generation for RES units considering their corresponding correlation. In this regard, Gaussian copula is employed in this paper to model the correlation between the power productions by RES units in different MGs. Copula functions facilitate formulating multi-variable functions to model the correlation among stochastic variables. Finally, the following three-step procedure is utilized to generate scenarios for RES units considering their respective correlation.

1) Measurement of Stochastic Dependence:

Rank correlation (ρ_r) is utilized to measure the strength of dependence between corresponding decision variables. In this regard, the rank correlation of random variables *X* and *Y* with cumulative distribution functions (CDFs) F_X and F_Y is considered as follows:

$$\rho_r(X,Y)=\rho(F_X(X),F_Y(Y)) \qquad (1)$$

Where ρ is the function measuring the linear correlation between $F_X(X)$ and $F_Y(Y)$.

2) Copula-based Correlation Modelling:

Gaussian copula function $C(u_1,u_2,...,u_N)$ is employed to model the multi-variable joint distribution $F(x_1,x_2,...,x_N)$ based on the CDF functions of its variables, as follows:

$$F(x_1,x_2,...,x_N)=C(F_{x_1}(x_1),F_{x_2}(x_2),...,F_{x_N}(x_N)) \qquad (2)$$

3) Scenario-Generation using K-means Clustering:

In this step, *N* scenarios in the $[0,1]^N$ domain are generated using the joint multi-variable function presented in (2). Then, the inverse-CDF function is deployed to transform the variables to their respective primary domains. Finally, the K-means-based clustering procedure is developed to partition the N-generated scenarios into S clusters with probability ρ_s, serving as the final scenarios for running the bi-level operational optimization of the MMG system. It is noteworthy that in this paper the represented three-step procedure is conducted to generate operational scenarios for PV and wind power units. In this regard, the correlation between wind speed and solar irradiance could be taken into account to model the rank correlation and formulating the copula function. Finally, each MG utilizes its associated solar irradiance and wind speed in each scenario to calculate the power output of its respective RES units. It is noteworthy that the copula model could also be developed utilizing the accumulated power output of PV and wind units in the MGs. As a result, the generated scenarios would specify the output power of the RES units in each MG and could easily be allocated to the respective resources in the operational optimization procedure.

D. First-level optimization: Microgrid Optimization

In the lower level, an EMS agent in each MG optimizes MG's resource scheduling for day-ahead operation. In this regard, the resource scheduling optimization conducted by each EMS agent with the aim of the least-cost operation of the MG *k* is modelled as follows:

$$Min\ \left((1-\beta)\cdot E\left[F_{s,k}\right]+\beta\cdot CVaR_\alpha\left(F_{s,k}\right)\right) \qquad (3)$$

$$F_{s,k}=\left.\sum_{t=1}^{24}\left(\begin{array}{l}\sum_{i\in I^{DG,k}} C_i^{DG,k}.P_{i,t,s}^{DG,k}+\sum_{i\in I^{ESS,k}} C_i^{dch,k}.P_{i,t,s}^{dch,k}+\\ C^{LS,k}.LS_{t,s}^{k}+(GBP_t.P_{t,s}^{buy,k}-GSP_t.P_{t,s}^{sell,k})\end{array}\right)\right|_{k\in I^{MG}} \qquad (4)$$

Subject to:

$$CVaR_\alpha\left(F_{s,k}\right)=\xi_s+\frac{1}{1-\alpha}\sum_s\rho_s\cdot\varphi \qquad (5)$$

$$\varphi\geq\left(F_{s,k}-\xi_s\right),\quad\forall s \qquad (6)$$

$$\varphi\geq0,\quad\forall s \qquad (7)$$

$$\begin{array}{l}\sum_{i\in I^{DG,k}}P_{i,t,s}^{DG,k}+\sum_{i\in I^{RES,k}}P_{i,t,s}^{RES,k}+\sum_{i\in I^{ESS,k}}P_{i,t,s}^{dch,k}+LS_{t,s}^{k}\\ +P_{t,s}^{buy,k}=\sum_{i\in I^{D,k}}L_{i,t,s}^{k}+\sum_{i\in I^{ESS,k}}P_{i,t,s}^{ch,k}+P_{t,s}^{sell,k}\end{array} \qquad (8)$$

$$P_t^{buy,min,k}\leq P_{t,s}^{buy,k}\leq P_t^{buy,max,k} \qquad (9)$$

$$P_t^{sell,min,k}\leq P_{t,s}^{sell,k}\leq P_t^{sell,max,k} \qquad (10)$$

$$P_i^{min,k}.x_{i,t,s}^{k}\leq P_{i,t,s}^{DG,k}\leq P_i^{max,k}.x_{i,t,s}^{k}\ ,i\in I^{DG,k} \qquad (11)$$

$$P_{i,t,s}^{DG,k}-P_{i,t-1,s}^{DG,k}\leq RU_i^{DG,\max,k}\ ,\quad i\in I^{DG,k} \qquad (12)$$

$$P_{i,t-1,s}^{DG,k}-P_{i,t,s}^{DG,k}\leq RD_i^{DG,\max,k},\quad i\in I^{DG,k} \qquad (13)$$

$$\left[T_{i,t-1,s}^{on}-MUT_i\right]\cdot\left[x_{i,t-1,s}^{k}-x_{i,t,s}^{k}\right]\geq0 \qquad (14)$$

$$\left[T_{i,t-1,s}^{off}-MDT_i\right]\cdot\left[x_{i,t-1,s}^{k}-x_{i,t,s}^{k}\right]\geq0 \qquad (15)$$

$$x_{i,t,s}^{k}-x_{i,t-1,s}^{k}\leq SU_{i,t,s}^{k} \qquad (16)$$

$$x_{i,t-1,s}^{k}-x_{i,t,s}^{k}\leq SD_{i,t,s}^{k} \qquad (17)$$

$$x_{i,t,s}^{k}-x_{i,t-1,s}^{k}\leq SU_{i,t,s}^{k}-SD_{i,t,s}^{k} \qquad (18)$$

$$P_i^{dch,min,k}\leq P_{i,t,s}^{dch,k}\leq P_i^{dch,max,k}\ ,\quad i\in I^{ESS,k} \qquad (19)$$

$$P_i^{ch,min,k}\leq P_{i,t,s}^{ch,k}\leq P_i^{ch,max,k}\ ,\quad i\in I^{ESS,k} \qquad (20)$$

$$E_{i,t+1,s}^{k}=E_{i,t,s}^{k}+\Delta t.\left(\begin{array}{l}P_{i,t,s}^{ch,k}.\eta_i^{ch,k}\\ -\dfrac{P_{i,t,s}^{dch,k}}{\eta_i^{dch,k}}\end{array}\right),\ i\in I^{ESS,k} \qquad (21)$$

$$E_i^{\min,k}\leq E_{i,t,s}^{k}\leq E_i^{\max,k},\quad i\in I^{ESS,k} \qquad (22)$$

$$L_{adj}^{\min,k} \leq L_{adj,t,s}^{k} \leq L_{adj}^{\max,k} \tag{23}$$

$$\sum_{[a,b]} L_{adj,t,s}^{k} = NE_{adj}^{k} \tag{24}$$

Objective (3) aims to minimize the operational cost and risk from the k^{th} MG point of view. In this regard, (4) represents the cost associated with each of the operational scenarios; which includes the operational cost of dispatchable generation units (DGs), cost of battery discharging, load shedding cost, and the costs associated with the power exchange with the main grid. Moreover, (5) shows the conditional value at risk (CVaR), which is taken into account to model the risk of operational scheduling in the MG. In this regard, α (i.e. Confidence factor) is a parameter indicating the right tail probability of density function and β is a parameter that models the perspective of the MG towards risk. Additionally, constraints (5)-(7) are modeled to provide a linear formulation for the CVaR term. The supply-demand balance equation (8) ensures that the sum of the power injected by local DGs, RESs, discharging of ESSs, the amount of power purchased from the main grid beside the load curtailment should match with the sum of the total loads, power charging of ESSs and the amount of power sold to the main grid. The associated constraints for power exchange with the main grid are expressed in (9) and (10). Constraints (11) - (13), respectively, show power generation, ramp-up, and ramp-down limits for DGs. $x_{i,t}^{k}$ is a binary variable, which is one, if unit i in the k^{th} MG is committed in time t and zero otherwise. Equations (14) - (18) determine the number of hours for which unit has been on or off at time t in the k^{th} MG. Equations (19) - (22) represent constraints associated with the storage operation. The operational limits of storage units in discharging and charging modes are defined by (19) and (20), respectively. Equation (21) determines the value of energy stored in the storage units in each time period and (22) ensures that the stored energy meets the available capacity limits of respective storages. Finally, operational constraints of adjustable loads are shown by (23) - (24). It is noteworthy that EMS agents determine the preliminary scheduling of local resources by conducting the optimization model and the requisite scheduling and operational results of this level will be transmitted to the upper level as input data.

E. Second-level optimization: Microgrid Community Optimization

In the upper level, the amount of power exchange among MGs, and the amount of power transactions of MGs with the main grid, as well as the interaction with the Gas-grid will be optimized by considering the concept of flexibility. In this regard, the amount of power shortage and the surplus power in each scenario are received from each MG, when the preliminary local resource scheduling is conducted by the respective EMS agents. Moreover, the operational data associated with the preliminary scheduling of dispatchable units with the operational costs between GSP and GBP called flexible power units is also received from each MG. It is also considered that there are storage units operated by CEMS that could facilitate flexibility-based scheduling of the MMG system. Finally, the optimization model is implemented by the CEMS agent to efficiently coordinate the MMG system, which is formulated as follows:

$$\min \sum_{t=1}^{24} \sum_{s \in \Omega_s} \rho_s \cdot \left(\begin{array}{l} \sum_{k \in I^{MG}} \left(\begin{array}{l} C_{k,t}^{flex} . \Delta P_{k,t,s}^{flex} + C^{LS,k} . LS_{k,t,s}^{ul} + \\ \left(GBP_t . P_{k,t,s}^{ul,buy} - GSP_t . P_{k,t,s}^{ul,sell} \right) \end{array} \right) \\ + \sum_{i \in I^{ESS,MGC}} C_i^{dch,MGC} . P_{i,t,s}^{dch,MGC} \end{array} \right) \tag{25}$$

Subject to

$$\begin{aligned} & \sum_{k \in I^{MG}} \left(\Delta P_{k,t,s}^{flex} + LS_{k,t,s}^{ul} + P_{k,t,s}^{ul,buy} - P_{k,t,s}^{ul,sell} \right) + \\ & \sum_{i \in I^{G2P}} P_{i,t,s}^{GFPP} + \sum_{i \in I^{ESS,MGC}} P_{i,t,s}^{dch,MGC} = \sum_{i \in I^{P2G}} P_{i,t,s}^{P2G} + \\ & \sum_{i \in I^{ESS,MGC}} P_{i,t,s}^{ch,MGC} + \sum_{k \in I^{MG}} (P_{k,t,s}^{short} - P_{k,t,s}^{surp}) \end{aligned} \tag{26}$$

$$P_t^{buy,min} \leq \sum_{k \in I^{MG}} P_{k,t,s}^{ul,buy} \leq P_t^{buy,max} \tag{27}$$

$$P_t^{sell,min} \leq \sum_{k \in I^{MG}} P_{k,t,s}^{ul,sell} \leq P_t^{sell,max} \tag{28}$$

$$0 \leq LS_{k,t,s}^{ul} \leq P_{k,t,s}^{short} \tag{29}$$

$$\begin{aligned} & \Delta P_{k,t-1,s}^{flex} + \Delta P_{k,t,s}^{flex,Ramp\_down} \leq \\ & \Delta P_{k,t,s}^{flex} \leq \Delta P_{k,t,s}^{flex,Ramp\_up} + \Delta P_{k,t-1,s}^{flex} \end{aligned} \tag{30}$$

$$\Delta P_{k,t,s}^{flex,\min} \leq \Delta P_{k,t,s}^{flex} \leq \Delta P_{k,t,s}^{flex,\max} \tag{31}$$

$$P_i^{dch,min,MGC} \leq P_{i,t,s}^{dch,MGC} \leq P_i^{dch,max,MGC}, i \in I^{ESS,MGC} \tag{32}$$

$$P_i^{ch,min,MGC} \leq P_{i,t,s}^{ch,MGC} \leq P_i^{ch,max,MGC}, i \in I^{ESS,MGC} \tag{33}$$

$$E_{i,t+1,s}^{MGC} = E_{i,t,s}^{MGC} + \Delta t . \left(\begin{array}{l} P_{i,t,s}^{ch,MGC} . \eta_i^{ch,MGC} \\ - \dfrac{P_{i,t,s}^{dch,MGC}}{\eta_i^{dch,MGC}} \end{array} \right), i \in I^{ESS,MGC} \tag{34}$$

$$E_i^{\min,MGC} \leq E_{i,t,s}^{MGC} \leq E_i^{\max,MGC}, \ i \in I^{ESS,MGC} \tag{35}$$

$$EP_{t+1,s}^{lp} = EP_{t,s}^{lp} + \Delta t . \left(P_{t,s}^{lp,inj} - P_{t,s}^{lp,ex} \right) \tag{36}$$

$$EP^{lp,\min} \leq EP_{t,s}^{lp} \leq EP^{lp,\max} \tag{37}$$

$$P_{t,s}^{lp,inj} = \sum_{i \in I^{P2G}} \eta_i^{P2G} . P_{i,t,s}^{P2G} \tag{38}$$

$$P_{t,s}^{lp,ex} = \sum_{i \in I^{GFPP}} P_{i,t,s}^{GFPP} / \eta_i^{GFPP} \tag{39}$$

$$P^{inj,\min} \leq P_{t,s}^{lp,inj} \leq P^{inj,\max} \tag{40}$$

$$P^{ex,\min} \leq P_{t,s}^{lp,ex} \leq P^{ex,\max} \tag{41}$$

$$\sum_{t} \sum_{i \in I^{GFPP}} P_{i,t,s}^{GFPP} / \eta_i^{GFPP} \leq \sum_{t} \sum_{i \in I^{P2G}} \eta_i^{P2G} . P_{i,t,s}^{P2G} \tag{42}$$

$$\begin{aligned} & \sum_{s \in \Omega_s} \rho_s \cdot \left(\sum_{k \in I^{MG}} \left(\begin{array}{l} \left[P_{k,t,s}^{ul,buy} - P_{k,t,s}^{ul,sell} \right] - \\ \left[P_{k,t-1,s}^{ul,buy} - P_{k,t-1,s}^{ul,sell} \right] \end{array} \right) \right) \\ & \leq \Delta_t^{flexiblity-ramp} \end{aligned} \tag{43}$$

$$\begin{aligned} & -\Delta_t^{flexiblity-ramp} \leq \\ & \sum_{s \in \Omega_s} \rho_s \cdot \left(\sum_{k \in I^{MG}} \left(\begin{array}{l} \left[P_{k,t,s}^{ul,buy} - P_{k,t,s}^{ul,sell} \right] - \\ \left[P_{k,t-1,s}^{ul,buy} - P_{k,t-1,s}^{ul,sell} \right] \end{array} \right) \right) \end{aligned} \tag{44}$$

The objective function in (25) strives to minimize overall operational costs of the CEMS, which include costs of increasing or decreasing scheduled operational point of flexible power units, costs of load shedding, power exchange with the main grid as well as the operational costs associated with MGC's storage units operated by CEMS. Equation (26) shows that sum of the changes in power generation by flexible power units, load shedding, power exchange with the main grid of all MGs, discharging of

MGC's storage units and G2P units equals to the sum of power stored in P2G and power charging of MGC's storages as well as the difference between the surplus power and power shortage announced by MGs. The associated constraints for power exchange of the overall MMG system with the main grid and MGs' possible load shedding are considered in (27) - (29). The possible variations in the operational point of flexible power units are shown in (30) and (31). It is noteworthy that constraint (30) ensures that the ramp-limits of flexible power units in each time interval are conceived; while the change in the operational point of the flexible power units affects the scheduling of the following intervals and their associated operational costs. The constraints associated with the operation of MGC's batteries are represented in (32) - (35). Operational model of interaction with the Gas grid is demonstrated in (36) – (42). In this regard, the amount of gas stored in the Gas grid and its respective capacity constraints are represented in (36) and (37). The amount of electrical power converted to gas in each time interval is limited by (40); while, (41) imposes limitations on the power produced by burning gas. Eventually, (43) and (44) are responsible for the flexibility constraints, which means that the expected net-load variability of the MMG system seen by the utility should be less than a manageable ramp. As discussed in [36, 37], the ramping limits could be selected by the grid operator based on the grid flexibility and net-load forecasts. In this regard, implementation of the proposed management model could mitigate the net-load ramping of the MMG system.

F. Information exchange between EMSs and CEMS

Regarding the developed optimization model, flexible power units are introduced in order to exploit their operational point in the second-level optimization to benefit the system by decreasing the overall operational costs while providing flexibility services. In this regard, the operational data (i.e. preliminary scheduled operational point, maximum and minimum power production as well as ramping constraints) associated with each flexible power unit, along with the total power shortage and surplus power determined by each EMS in the first-level optimization, need to be sent to the CEMS to model the second-level optimization for coordinating MGs. While this procedure benefits the MMG system, transmitting detailed operational data of each flexible power unit in MGs to CEMS could engender privacy concerns in the system. In this context, as shown in (45)-(48), a new formulation is proposed, in which the information exchange between EMS agents of MGs and CEMS is limited to the accumulated operational constraints of the flexible power units to address the privacy concerns as well as keeping the amount of data communication between EMSs and CEMS comparable to previously proposed methods for energy management of MGC. Based upon the proposed formulation, each EMS agent sends the possible accumulated deviation from the preliminary scheduled operational point of flexible power units to CEMS without exchanging their respective scheduled operational points. In this regard, the operational point of flexible power units in each MG could be re-scheduled in the second-level optimization considering their operational constraints. This would benefit the system by minimizing the operational cost as well as increasing flexibility of the system.

$$\Delta P_{k,t,s}^{flex,Ramp\_up} = \sum_{i \in I^{flex,k}} \left(RU_i^{flex,\max,k} - \left(P_{i,t,s}^{flex,k} - P_{i,t-1,s}^{flex,k} \right) \right) \tag{45}$$

$$\Delta P_{k,t,s}^{flex,Ramp\_down} = \sum_{i \in I^{flex,k}} \left(-RD_i^{flex,\max,k} - \left(P_{i,t,s}^{flex,k} - P_{i,t-1,s}^{flex,k} \right) \right) \tag{46}$$

$$\Delta P_{k,t,s}^{flex,\max} = \sum_{i \in I^{flex,k}} \left(P_i^{flex,\max,k} - P_{i,t,s}^{flex,k} \right) \tag{47}$$

$$\Delta P_{k,t,s}^{flex,\min} = \sum_{i \in I^{flex,k}} \left(P_i^{flex,\min,k} - P_{i,t,s}^{flex,k} \right) \tag{48}$$

In the presented formulation, constant $P_{i,t,s}^{flex,k}$ denotes optimal power scheduling of the flexible power unit i computed by EMS agent in the MG k. Furthermore, $RU_i^{flex,\max,k}$, $RD_i^{flex,\max,k}$, $P_i^{flex,\max,k}$, and $P_i^{flex,\min,k}$ represent the constraints associated with ramp-up, ramp-down, maximum capacity, and minimum capacity of flexible power unit i.

IV. IMPLEMENTATION

In this section, the proposed flexibility-based MMG hierarchical management framework is implemented on an MGC consisting of three-MG to efficiently coordinate the operation of MGs considering the flexibility ramp that the main grid could provide in each hour. Each MG comprises of four dispatchable generation units, one ESS, adjustable and fixed loads, and RESs. Moreover, it is assumed that MG2 and MG3 have wind plants; while, MG1 has PV units. The final scenarios for conducting operational scheduling of the MMG system are generated taking into account the correlation between the output power of PV units and wind power units. In this regard, the expected value of renewable generation in three MGs is represented in Fig. 3. Finally, a simplified model of the MMG system is shown in Fig. 4.

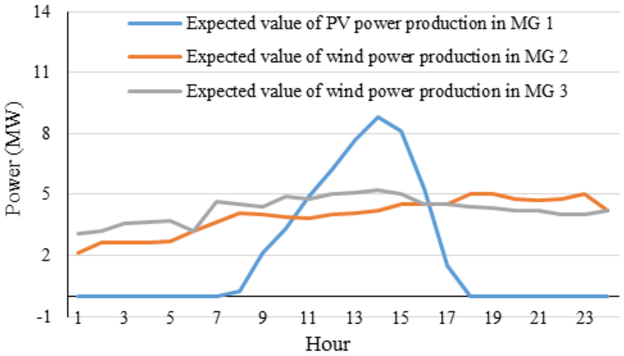

Fig. 3. Expected value of final scenarios associated with RESs power production in each MG.

Regarding the proposed procedure, EMS agent in each MG conducts the preliminary resource scheduling optimization to determine the surplus power and power shortage. In this step, MGs tend to minimize their costs, while the ramp imposed on the main network is not considered. Next, the power shortage and surplus power of MGs in each hour would be sent to CEMS in order to coordinate the operation of MGs. As shown in Fig. 5, the overall net-load of the power requested by MGs has the maximum ramp of 12 MW/h at hour 16.

CEMS will facilitate the cooperation of MGs which indicates that in case an MG has surplus power and at the same time another MG confronts with the power shortage; they can exchange power at an affordable price compared to

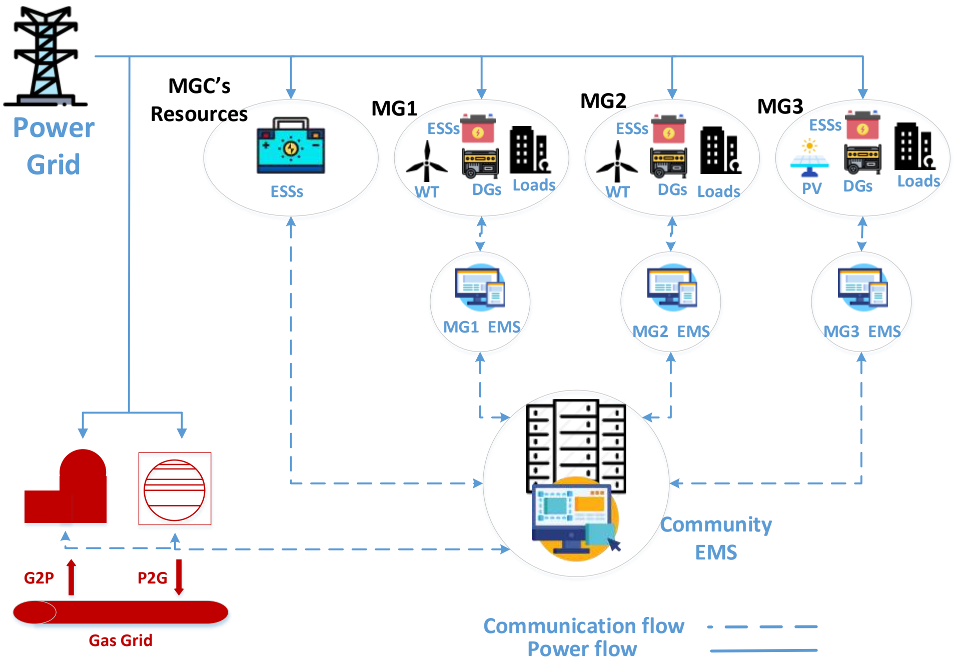

Fig. 4. System model.

the market price in order to reduce their operating costs. Moreover, the CEMS is responsible for coordinating the MGs in a way that the net-load variability seen by the main grid meets the available flexibility ramp that could be provided by the main grid. In order to investigate the applicability of the proposed MMG, two different cases are studied in this section. Noted that the expected results are demonstrated and analyzed in this section.

Case1: In this case, the permissible ramp for the main network is considered to be 10MW/h determined by the grid operator, and CEMS is considered to be responsible to coordinate the operation of MGs to cope with this constraint. In this regard, four different states are defined in order to determine the advantages of the proposed framework. States 1 & 2 are considered as the operational optimization of the MMG system without considering interaction with the Gas grid; while interaction with the Gas grid is considered in states 3 and 4 to provide flexibility services. Moreover, the constraints associated with the flexibility ramp are not taken into account in states 1 & 3, while they are considered in the optimization conducted by CEMS in states 2 & 4. The overall ramp seen by the grid in each of the defined states is presented in Table I, which shows that CEMS has changed the operation of the MGC in states 2 & 4 to keep the load variability seen by the grid in limits defined by flexibility constraints. Figures 6 - 7 represent the results of optimizations conducted in states 3 & 4. Based upon the presented results, the preliminary scheduling of flexible power units has been modified by CEMS to efficiently deal with supply/shortage power announced by MGs as well as coping with the flexibility constraints. In this regard, comparing the results presented in Figs. 6 and 7 indicates that the scheduled power production of flexible power units is decreased in hour 16 in state 3; while the power production by flexible power units is not changed in hour 16 in state 4 to enforce the MMG system to sell energy to the grid and so meet the flexible-ramp constraints. Moreover, power generation by flexible power units is decreased in hour 19 in case of considering flexibility constraints; which results in decreasing the trade with the grid in this time period. As a result, the required ramp-down in hour 19 is decreased in comparison with the case of dismissing the flexibility ramp constraints (i.e. states 3). In this respect, the results indicate the importance of considering the flexible power units in the flexibility-oriented MMG management model. Regarding the operational scheduling results in states 1-4, interaction with the Gas grid has increased the volatility of the MMG net-load in several time periods, which is mainly resulted from the CEMS economical preferences to buy power at low prices and sell it at high prices.

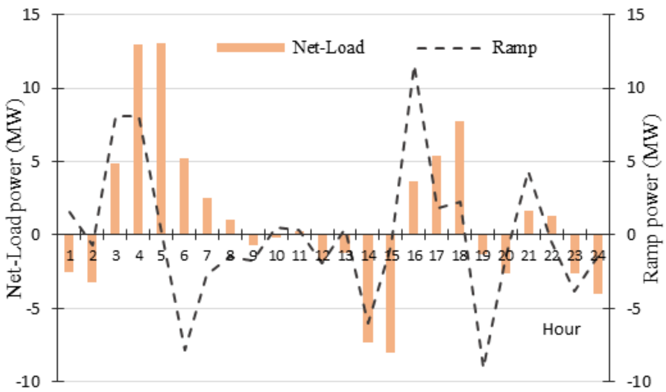

Fig. 5. Overall requested power by MGs determined by their respective EMS agents.

Table I. Overall ramp seen by the main grid in States 1-4.

Hour	STATE			
	1	2	3	4
1	1.30	1.32	-2.03	-1.97
2	-1.24	-1.25	1.07	2.21
3	6.07	6.28	10.59	10.00
4	11.24	10.00	13.47	10.00
5	1.43	2.44	-4.42	-1.57
6	-10.11	-10.00	-8.00	-8.00
7	-2.17	-2.29	-0.51	-0.51
8	-1.73	-1.73	-5.89	-5.18
9	-1.34	-1.34	-1.98	-2.69
10	-1.27	-1.27	-0.90	-0.90
11	2.64	2.64	3.98	3.98
12	-5.24	-5.24	-10.72	-10.00

Hour	STATE			
	1	2	3	4
13	3.46	3.46	6.95	6.22
14	-8.26	-8.26	-9.68	-9.68
15	-0.33	0.54	-0.50	2.03
16	14.42	10.00	17.37	10.00
17	0.31	4.25	1.80	6.64
18	0.94	1.83	-0.70	-2.90
19	-7.88	-9.16	-13.23	-10.00
20	-1.80	-1.80	-2.58	-1.84
21	6.02	6.02	14.42	10.00
22	-2.12	-2.12	-6.01	-3.37
23	-1.39	-1.39	2.91	2.91
24	-2.92	-2.92	-5.38	-5.38

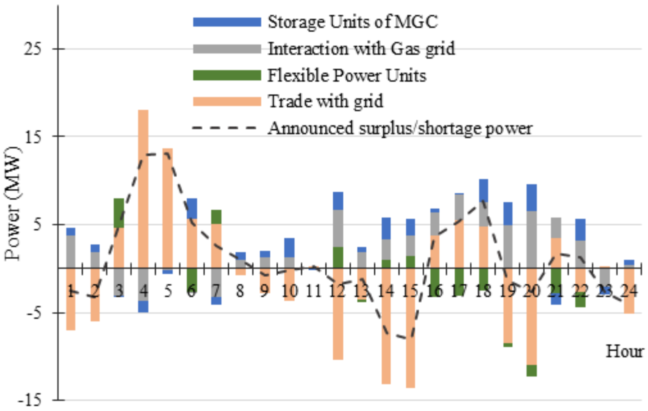

Fig. 6. Results of operational optimization conducted by CEMS without considering flexibility constraints (State 3).

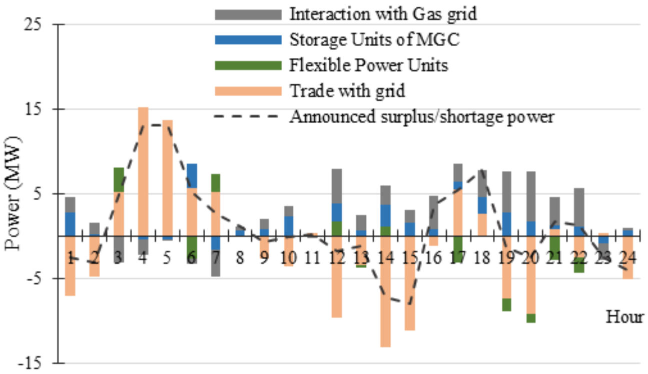

Fig. 7. Results of operational optimization conducted by CEMS considering flexibility constraints (State 4).

Case2: In this case, it is considered that the grid operator desires that the overall net-load seen by the grid from MGC and a group of customers copes with the flexibility constraints of the system (i.e. 10 MW/h). In this regard, the grid operator would determine the announced flexibility constraints to CEMS based upon the operational condition of the system and the forecasted net-load of the customers. Therefore, CEMS could provide the flexibility service to the utility by addressing the announced flexibility constraints in the MMG operational management. In the other words, it is aimed to study the proficiency of the proposed framework in order to enable the MMG system to support the system coping with the flexibility constraints.

Figure 8 describes the net-load of the MGC and customers as well as their respective overall net-load. It is clear that the variability of the overall net-load has exacerbated in several hours, which shows the importance of scheduling local resources in an efficient way to decrease the net-load variability seen by the grid. In this regard, the preliminary overall net-load and its associated ramp are shown in Fig. 9, which indicates that the grid flexibility constraint is dismissed by the flexibility ramp of the overall net-load in 6 hours of a day. However, after implementing the proposed framework, as shown in Fig. 9, the CEMS has managed the local resources to decrease the overall net-load ramp and fulfill the flexibility constraints. As a way to meet the flexibility constraints in each time period (i.e. time periods 1, 2, 15, 16, 18, 19, 20, 21), CEMS has increased/decreased the power exchange with the grid in one hour; while decreasing/increasing the traded power with the grid in the next hour. The analyzed results show that implementing the presented scheme would enable the efficient operation of the MMG system while providing flexibility service to the grid operator. Table II compares the hourly amount of objective function in the optimization conducted by CEMS in two states of considering flexibility constraints and neglecting them. It is clear that the CEMS prefers to purchase power from the grid at low prices and sell power to the grid at high prices. However, considering flexibility constraints limits the power exchange with the main grid and so the CEMS has to purchase power at higher prices from the grid or the local resources. Additionally, in order to analyze the effects of the interaction with the Gas grid on the operational cost of the system, the increase in costs of the MMG due to providing flexibility service to the grid considering different amount of P2G capacities is indicated in Fig. 10. Regarding the obtained results, increasing the capacity of the P2G system would benefit the system by decreasing the operational costs of providing the flexibility service to the grid. Noted that the increase in operational costs of the MMG system due to provision of flexibility ramp service would finally be compensated by the system operator.

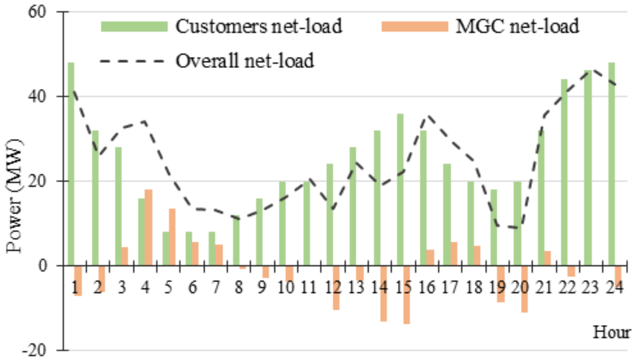

Fig. 8. Net-load of the system.

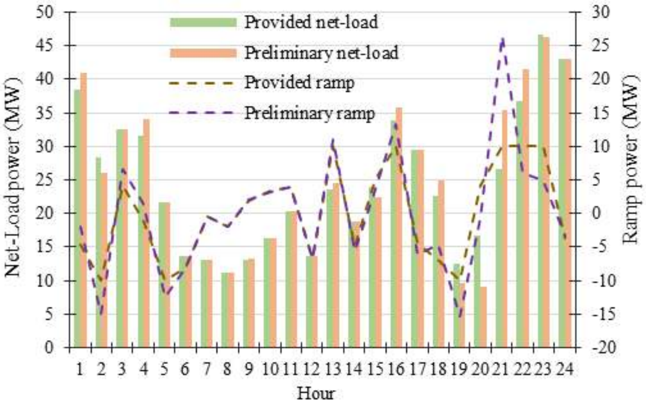

Fig. 9. Overall net-load and ramp seen by the main grid before and after implementation of the proposed methodology.

Table II. Hourly objective function of CEMS.

Hour	With Flexibility Constraints	Without Flexibility Constraints	Hour	With Flexibility Constraints	Without Flexibility Constraints
1	-365.70	-264.34	13	-250.66	-168.13
2	-111.83	-222.95	14	-716.40	-716.40
3	285.35	317.36	15	-709.64	-717.63
4	468.60	541.33	16	152.71	80.44
5	408.60	408.60	17	175.97	175.97
6	139.36	139.36	18	167.85	158.93
7	262.50	262.50	19	-397.36	-515.98
8	3.37	3.37	20	-307.97	-738.07
9	-94.10	-83.61	21	-205.04	61.64
10	-102.19	-102.19	22	-293.57	-201.19
11	66.48	66.48	23	54.24	39.46
12	-359.44	-359.44	24	-187.67	-187.67

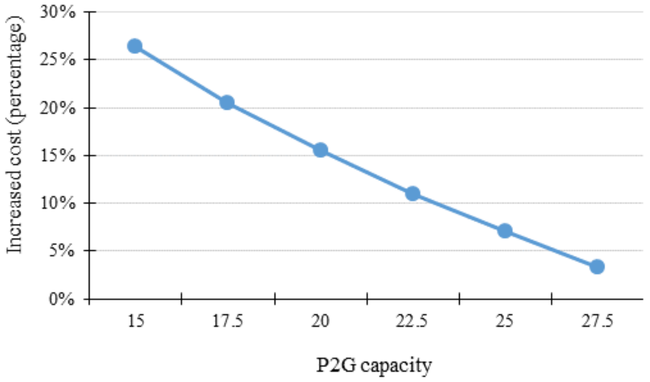

Fig. 10: Increase in costs of CEMS considering different amounts of P2G capacities.

Sensitivity Analysis: The proposed model is aimed to provide flexibility services to the main grid by exploiting the operational scheduling of the local flexible resources. In this regard, sensitivity analysis is taken into consideration to study the effects of the operational characteristics of the MMG (P2G capacity, ramp constraints, and risk) on the objective function of the optimization conducted by the CEMS. In this respect, the proportional increase in the cost of the CEMS in the case of considering different amounts of net-load ramping constraints is indicated in Table III. The obtained results show that while the cost of CEMS generally increases as the ramp constraints decrease; the amount of increase in the cost of the CEMS is significantly lower in case of considering interaction with the Gas grid. This analysis indicates the importance of developing P2G systems to improve the flexibility of the power system from the operational cost of the system point of view. In addition, the increase in costs of the CEMS due to ramping constraints while considering different capacities of the P2G system is shown in Fig. 11. The results illustrate that increasing the capacity of the P2G system in the MMG system would result in decreasing the operational cost of the system.

Table III. Increase in costs of CEMS considering different ramp constraints

Ramp Constraint	Increase in CEMS Objective Value (Percentage)	
	MMG System with P2G Technology	MMG System without P2G Technology
4	17%	100%
5	13%	55%
6	9%	30%
7	7%	18%
8	5%	11%
9	3%	8%
10	2%	5%

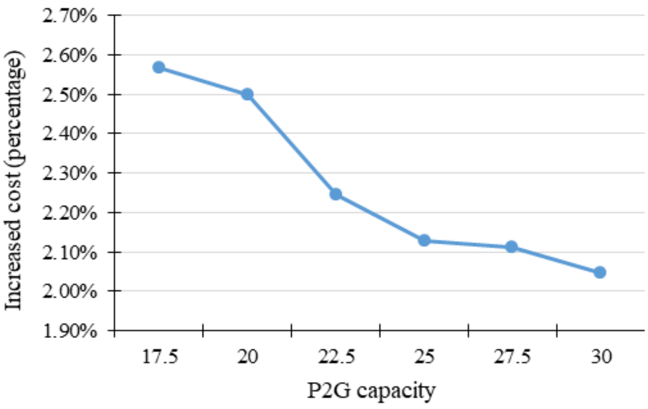

Fig. 11. Increase in costs of CEMS considering different amounts of P2G capacities.

The previous studies are conducted considering risk-neutral MGs (i.e. $\beta = 0$) to analyze the application of the proposed two-stage MMG management model to efficiently improve the flexibility of the system. In this section, the effects of the MGs' perspectives toward risk are studied by considering different values of β, while α equals 0.9. In this regard, the value of the objective function associated with the optimization conducted by MG1 is shown in Table IV; which demonstrates the increase in operational costs of the MGs in case of considering higher values β. In other words, the study shows that risk-averse MGs would accept higher operational costs in order to decrease their associated risks.

Table IV. Objective value of MG1 considering different values of β.

Risk Factor (β)	Objective Value ($)
0	11127
0.2	11138
0.4	11148
0.6	11159
0.8	11170
1	11180

Moreover, considering different levels of risks in the operational management of each MG would affect the resource scheduling in the second-level optimization. In this regard, the hourly ramps associated with the net-load of the MMG system considering P2G technology as well as the maximum ramp up/down to be 10 MW/h are shown in Fig. 12. Additionally, costs of operational optimization conducted by CEMS for MMG systems with P2G technology and without P2G technology are represented in Table V. Regarding the obtained results, the costs associated with the optimization conducted by CEMS increase as the MGs become more risk-averse. Furthermore, similar to the obtained results in previous studies, the costs of the CEMS would be higher in MMG systems without P2G technology, which indicates the advantages of developing P2G technologies in MMG systems to improve the flexibility of the system in an efficient way.

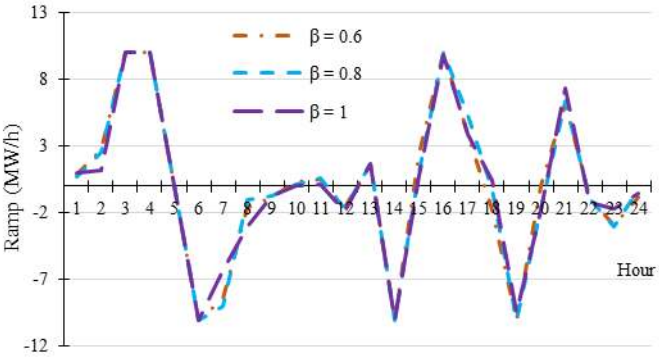

Fig.12. Overall ramp seen by the main grid in case of considering different values of β .

Table V. Costs associated with the optimization conducted by CEMS in case of considering different values of β .

Risk Factor (β)	CEMS Objective Value ($)	
	MMG System with P2G Technology	MMG System without P2G Technology
0.6	916	1275
0.8	918	1277
1	1259	1621

V. CONCLUSION

This paper proposes an efficient and applicable approach to coordinate the procedure of local resources scheduling in an MMG system with the aim of minimizing the operational costs of the MMG; while ensuring that local resources associated ramp limits and the grid flexibility constraints are fulfilled. In this regard, flexible load demands, storage units as well as interaction with the Gas-grid are modeled as the future potential flexible resources in this paper. The proposed methodology relies on a two-stage optimization in which EMS agents are responsible to conduct the operational optimization in their respective MGs and send the requested data to the CEMS which coordinates the operational scheduling of MGs to meet the flexibility constraints announced by the grid operator.

The proposed approach is implemented on an MGC consisted of three MGs and its operational scheduling results are studied in different cases to investigate the effectiveness of the proposed two-stage approach, P2G technology, and risk modeling in the operational management of the MMG system. The results show the importance of considering flexibility constraints and the flexibility ramp service that the MMG system could provide for the grid operator. The high-resolution modelling of the proposed framework and its hierarchical structure that leads to the computation burden reduction provide the possibility of its scalability and application in modern power systems.

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