A comparative study of Energy Management Systems for non-cooperative and cooperative Multi-Microgrids

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***Abstract*—Nowadays, Multi-Microgrids (MMGs) systems are emerging as one of the alternatives to enhance resiliency and sustainability of electrical energy systems. In spite of the obvious advantages of MMGs, it is necessary to focus on Energy Management System (EMS) in order to achieve optimal power scheduling and improve power system efficiency. Moreover, the power sharing challenges in MMGs and resiliency issues to maintain power supply for critical loads, especially during extreme event outages, still provide scope for further research. In this regard, a comparison between non-cooperative and cooperative MMGs based, respectively, on decentralized and centralized EMS topologies is presented in this paper. EMSs are developed specifically for a day-ahead optimal and cost-effective scheduling of MMGs. Special emphasis is placed on the minimization of the total operating cost and the resilient operation. Thereby, in cooperative MMGs, reward cost strategies are proposed to promote self-consumption and enhance resiliency. Simulations and analyses are carried out under different scenarios, including normal and outage conditions to highlight the benefits of cooperation between Microgrids (MGs). Ultimately, an evaluation metric is employed to quantify the performances of both MMGs regarding resilience and fault tolerance aspects.**

Keywords—multi-microgrids, energy management system, optimization, resiliency, non-cooperative, cooperative, decentralized EMS, centralized EMS

I. INTRODUCTION

The concept of Multi-Microgrids (MMGs) formed through interconnecting a number of juxtaposed Microgrids (MGs) within a certain defined neighborhood (e.g. an energy community) has been gaining increasing interest in recent years. MMGs can provide features for achieving economic efficiency, ensuring stability, reducing the burden on the main grid and mitigating congestion in distribution lines. Moreover, MMGs can improve resiliency in the event of severe natural disasters, massive grid failures and other extreme outage conditions [1]. Nevertheless, coordinated energy trading among MGs, heightened frequency of cyber-attacks and natural phenomena leading to blackouts [2], [3] are the challenges to overcome to achieve reliable, cost-effective, secure and resilient MMGs systems. In particular, the currently major challenges within the frame of reference of the Energy Management System (EMS) for MMGs are economic criteria, customer privacy, and system resiliency [4], [5]. In this perspective, various EMS topologies have been proposed in the existing literature [6]. These EMS topologies can be broadly classified into five categories, namely centralized, decentralized, hybrid, distributed and nested. The EMS is of a prime importance and accountable for handling Renewable Energy Sources (RESs) and load consumption uncertainties, preserving customer privacy, enhancing resilient operation, satisfying the users' demand, reducing computational burden and especially, achieving optimal power scheduling of MMGs.

In the literature, there is a plethora of works related to EMS dedicated to MMGs. The centralized EMS is the most studied topology in electrical power systems for its centralized monitoring, capabilities of managing the energy balance and reaching the global optimum of the entire network. The centralized controller is responsible for collecting the data of each flexible entity such as photovoltaic (PV) panel, load, battery, etc. and also for computing the optimal trajectories of the whole system. This control scheme provides substantial observability and controllability of the entire power distribution networks, but it requires high computational burden, raises privacy concerns and suffers from single point failure. In regard to centralized EMS for MMGs, a Mixed-Integer Linear Programming (MILP) mathematical model is proposed in [7] to optimize the day-ahead power scheduling of pelagic islanded MG Groups with the inclusion of electric vessels for interisland electricity transmission. In [8], a cooperative EMS is developed for minimizing the operating cost of a grid-connected MMGs based on Model Predictive Control (MPC). Also, [9] presents an EMS for cooperative interconnected MGs, considering a price-based demand response to encourage MGs to consume their flexible loads during low-priced intervals with the objective of reducing their operational costs. In [10], a multi-objective optimization model is proposed for a grid-connected MMGs community, equipped with local Energy Storage Systems (ESSs) and RESs. The MGs can exchange power with each other within the community, enabling them to collectively minimize their electricity costs.

The decentralized EMS is the rivaling topology of centralized EMS. In decentralized EMS, each unit (MG) is controlled by its independent controller (decentralized computation). This control scheme is also widely employed for its ability of preserving privacy and reducing computation burden, even though an optimal solution cannot be guaranteed contrarily to the centralized EMS. In [11], a decentralized transactive EMS is proposed using the blockchain technology to ensure reliable cryptocurrency transactions and for enhancing trust among prosumers MGs. In particular, a contribution metric is applied in order to rank MGs for their active participation in the market and for managing energy scheduling. Furthermore, in [12], a power management framework for MMGs is developed based on Alternating

Direction Method of Multipliers (ADMM) to coordinate MGs' day-ahead operational scheduling while considering the intermittent nature of RESs. A decentralized strategy based on Multi-Agent System (MAS) approach is proposed in [13] for optimal power sharing among cooperative MGs and for maximizing the use of local ESSs in smart MGs network. In [14], a decentralized EMS is presented to enable the coordinated operation of networked MGs with the aims of minimizing the operational costs in grid-connected mode and maintaining the voltage stability while satisfying the user's energy demand in islanding mode.

In [15], a distributed incentive mechanism for energy trading in MMGs systems is proposed, which incorporates multiple bids with the aim of achieving flexible and efficient energy allocation. In [16], a hybrid EMS approach that employs a two-level EMS is developed to enhance the performance and minimize operational costs of networked MGs while accounting for uncertainties of RESs and load consumption. In [17], a nested distributed architecture is applied for solving the interactive energy management problem and for preserving customer privacy in networked MGs. However, the resilience issues have not been studied. Particularly, in the present proposed study, the decentralized and centralized topologies are considered for non-cooperative and cooperative MMGs, respectively regarding resilience and fault tolerance aspects in MMGs.

The majority of the aforementioned EMSs dedicated to MMGs have prioritized economic optimization and optimal power scheduling but have ignored resilience issues, except [1]–[3], [5], [6]. Additionally, the benefits and challenges of non-cooperative and cooperative MMGs have not been exhaustively explored so far in the literature. Thus, as a substantive contribution in the field of energy management in MMGs, this paper investigates the discrepancy between non-cooperative and cooperative MMGs performances. Furthermore, the aim of this research is not only to emphasize on EMS topologies for maximizing economic benefit but also to establish reward costs strategies to motivate cooperative MMGs users to share power among their neighbors with fairness in order to promote self-consumption and enhance resilience. Moreover, the wear and tear cost of the battery is taken into account. In essence, the major contributions of this paper can be summarized as follows:

- EMSs for non-cooperative and cooperative MMGs are developed based on decentralized and centralized topologies, respectively. EMS for cooperative MMGs takes into account reward cost strategies proposed to promote self-consumption and enhance resilience.
- A comparative study between non-cooperative and cooperative MMGs is conducted based on an evaluation metric aiming to assess the performances of both MMGs, particularly in terms of resilience and fault tolerance aspects.

The remainder of this paper is structured as follows. Section II illustrates the case study of both non-cooperative and cooperative grid-connected MMGs systems and also details the EMS mathematical modeling. Section III focuses on simulation results related to the condition of extreme outages (simultaneous PV and grid outages). Section IV presents an evaluation metric to assess the performances of both MMGs. Finally, Section V concludes this paper with the major findings.

II. CASE STUDY

A. System description of non-cooperative and cooperative Multi-Microgrids

This study concerns a simplified distribution network with two households connected to the utility grid. The MMGs architecture is deliberately simplified to focus on methodological aspects of EMS, resilient operation and cooperation issues between MGs. Each household is equipped with PV panels and batteries as an ESS. A decentralized and centralized EMS are used for a day-ahead optimal power scheduling of the non-cooperative and cooperative MMGs, respectively. The Microgrid Controller (MGC) computes the power profiles for each flexible entity (e.g. ESS) in order to minimize the electricity cost over a given day and to ensure power balance in the MMGs. The model is assumed to be deterministic, whereby both the potential solar production and the desired power demand of each household are already known in advance. Table I presents the characteristics of the non-cooperative and cooperative MMGs.

TABLE I. GENERAL CHARACTERISTICS OF THE NON-COOPERATIVE AND COOPERATIVE MMGS.

Non-cooperative MMGs	Cooperative MMGs
→ Each MG computes its optimal power profiles allowing load shedding and PV curtailment → Without power exchanges between MGs (constraint) → Without reward cost as exchanging power between MGs is not taken into account in the optimization problem	→ MGs can collaborate with each other in the neighborhood to share power and help critical ones during outages → Possibility of exchanging power between MGs → Reward cost for exchanging power between MGs is included → Introduction of a new decision variable ($P_{MMG,i}$) to ensure cooperative exchanges

The optimization parameters and variables of the system for each unit i (at MG i), namely $P_{sun,i}$, the potential solar production for each group of PV panels and $P^{*}_{l,i}$, the desired power demand for each household are the input parameters. The internal variables are $P_{pv,i}$, the PV production for each group of PV panels and $P_{l,i}$, the power demand for each household. Furthermore, $P_{batt,i}$ is the internal power of the battery. The decision variables are $P_{st,i}$, the power for charging/discharging each battery, $P_{curt,i}$, the curtailed solar power for each group of PV panels which can be used to reduce the PV production, $P_{shed,i}$, the shedded power of each household used to reduce the load demand in case it is higher than the available power and $P_{MMG,i}$, the power exchange with the eco-neighborhood grid only in cooperative MMGs. Finally, $P_{g,i}$ is the recourse variable dealing with grid exchanges for each unit i (at MG i) and P_{g}^{ext}, the total power exchange with the external grid. Therefore, $P_{mg,i}$ is the summation of the power exchanges with the external grid and the eco-neighborhood grid in cooperative MMGs.

In non-cooperative MMGs, each MG has its own local EMS (MGC) to minimize their operational cost and acts as an autonomous entity as shown in Fig. 1. By utilizing decentralized EMS, individual MG can directly trade/exchange energy with the main grid but not among neighbors. Consequently, the user's privacy is well preserved as there is no communication and sharing of information between MGs. However, due to lack of information about the surplus/deficit power of neighbors' MG, an optimal solution for the MMGs cannot be assured. Moreover, the resilience of the MMGs cannot be guaranteed in the event of a grid failure.

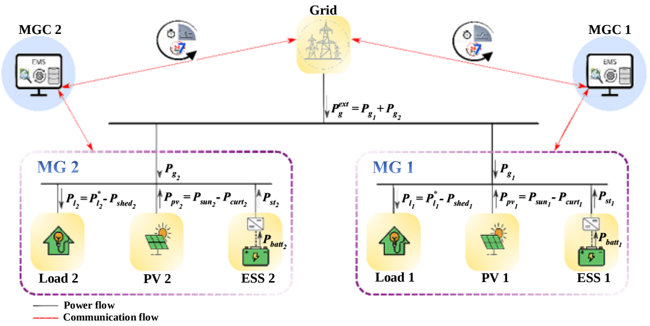

Fig. 1. Non-cooperative grid-connected MMGs.

Fig. 2 illustrates the cooperative MMGs, whereby the Microgrid Central Controller (MGCC) is accountable for managing the energy balance and minimizing the operational cost of the entire network. In cooperative mode, a fair allocation of profits and benefits of the available shared resources is guaranteed. Additionally, MMGs adopting the proposed EMS are ensured to minimize the total operating cost. Consequently, each MG optimally manages its resources for not only reducing its operating costs, but also for supporting the MMGs (especially its neighborhood) and being rewarded for its cooperative behavior which enables resilience enhancement. It is to be noted that the concept of collective self-consumption within an energy community is managed by a "Moral Organizing Entity" (i.e. a legal entity or person) including the contractual and financial/billing aspects [18].

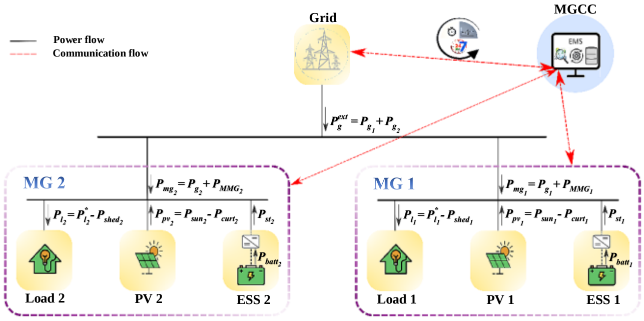

Fig. 2. Cooperative grid-connected MMGs.

B. *Optimization problem of non-cooperative and cooperative Multi-Microgrids*

The multi-objective optimization problem for achieving optimal scheduling of the power references of the Distributed Energy Resources (DERs) and enabling the minimization of the non-cooperative and cooperative MMGs operational costs is mathematically derived using Linear Programming (LP) formulation. The optimization model encompasses both storage and utility grid management constraints such as preventing simultaneous charging/discharging of the battery and purchasing/selling of energy from/to the main grid which are guaranteed cost-wise. Indeed, MGs in cooperative MMGs synchronously (at each time t) purchase/sell energy from/to the neighborhood grid through the constraints (13) and (14).

1) Objective function of non-cooperative and cooperative Multi-Microgrids

The objective function that minimizes the total operating cost of the non-cooperative and cooperative MMGs is given by (1) and (2), respectively. C_E is the electricity cost to be minimized over the time horizon t_{day} (1 day in this study), which is sampled at the time interval Δt (10 minutes) with respect to each unit i (at MG i).

- Non-cooperative MMGs (indexed by i: MG1, MG2)

$$\text{MGi:} \quad \min C_{E,i} = \min \Delta t \sum_t^{t_{day}} \big[c_{g,i}^+(t) P_{g,i}^+(t) + c_{g,i}^- P_{g,i}^-(t) + c_{st,i} P_{st,i}^{dis}(t) + c_{st,i} P_{st,i}^{ch}(t) + c_{sh,i} P_{shed,i}(t) \big] \tag{1}$$

- Cooperative MMGs

$$\min C_E = \min \Delta t \sum_{i=1}^{2} \sum_t^{t_{day}} \big[c_{g,i}^+(t) P_{g,i}^+(t) + c_{g,i}^- P_{g,i}^-(t) + c_{st,i} P_{st,i}^{dis}(t) + c_{st,i} P_{st,i}^{ch}(t) + c_{sh,i} P_{shed,i}(t) + c_{MMG,i}^+(t) P_{MMG,i}^+(t) + c_{MMG,i}^- P_{MMG,i}^-(t) \big] \tag{2}$$

The recourse variable $P_{g,i}(t)$, the decision variables $P_{st,i}(t)$ and $P_{MMG,i}(t)$ are separated into two components to fulfill the linearization of the system, as below:

$$P_{g,i}(t) = P_{g,i}^+(t) + P_{g,i}^-(t) \tag{3}$$

$$P_{st,i}(t) = P_{st,i}^{dis}(t) + P_{st,i}^{ch}(t) \tag{4}$$

$$P_{MMG,i}(t) = P_{MMG,i}^+(t) + P_{MMG,i}^-(t) \tag{5}$$

Where $P_{g,i}^+(t)$ is the power drawn from the utility grid whereas $P_{g,i}^-(t)$ is the power sold to the grid. $P_{st,i}^{dis}(t)$ and $P_{st,i}^{ch}(t)$ are the discharging and charging power of the battery, respectively. $P_{shed,i}(t)$ is the shedded power to reduce the load demand in case it is higher than the available power. $P_{MMG,i}^+(t)$ and $P_{MMG,i}^-(t)$ are the purchasing and selling power from/to the eco-neighborhood grid, respectively associated with a reward cost only in cooperative mode.

In terms of costs, $c_{g,i}^+(t)$ is the electricity purchase tariff according to off- or on-peak energy prices, $c_{g,i}^-$ is the selling price of energy to the utility grid, $c_{st,i}$ is the battery ageing unit cost per energy exchanged (1 kWh) associated with the charging/discharging decision variables, $c_{sh,i}$ is the cost of load shedding. In cooperative MMGs, $c_{MMG,i}^+(t)$ and $c_{MMG,i}^-$ are respectively the purchase and selling price of energy from/to the eco-neighborhood grid.

2) Constraints of non-cooperative and cooperative Multi-Microgrids

In addition to the battery's constraints (6)–(11) detailed in [19], with respect to every unit i (at MG i), the following limitations for the non-cooperative and cooperative MMGs must also be satisfied at each time t for MG1 and MG2 (indexed by i), in order to achieve a feasible solution:

$$0 \le P_{curt,i}(t) \le P_{curt,i}^{max}(t) \tag{6}$$

$$0 \le P_{shed,i}(t) \le P_{shed,i}^{max}(t) \tag{7}$$

Where $P_{curt,i}(t)$ and $P_{shed,i}(t)$ are utilized for PV curtailment and load shedding, respectively. Moreover, the ensuing constraints related to the power exchange with the utility grid must be fulfilled:

$$P_{gmax,i}^- \le P_{g,i}(t) \le P_{gmax,i}^+ \tag{8}$$

Where $P_{gmax,i}^+ \ge 0$ and $P_{gmax,i}^- \le 0$ are defined by the contracted powers subscribed by the user. Furthermore, $P_g^{ext}(t)$, the auxiliary optimization variable is the total power of the MMGs which is directly exchanged with the utility grid and is calculated as given below:

$$P_g^{ext}(t) = \sum_{i=1}^{2}\left[P_{g,i}^{+}(t) + P_{g,i}^{-}(t)\right] \quad (9)$$

The boundaries of $P_g^{ext}(t)$ are as stated below:

$$P_{gmin}^{ext} \leq P_g^{ext}(t) \leq P_{gmax}^{ext} \quad (10)$$

Where $P_{gmax}^{ext} \geq 0$ and $P_{gmin}^{ext} \leq 0$. Thus, $P_g^{ext}(t) \geq 0$ or $P_g^{ext}(t) \leq 0$ implies that the power is directly drawn or sold, respectively from/to the external grid.

Additionally, the power balance relationship at time t for each MG (indexed by i, MG1 and MG2) is given by (11), where $P_{MMG,i}(t)$ is equal to zero for non-cooperative MMGs.

$$P_{MMG,i}(t)+P_{g,i}(t)+P_{st,i}(t)+P_{sun,i}(t)-P_{curt,i}(t)=P_{l,i}^{*}(t)-P_{shed,i}(t) \quad (11)$$

In cooperative MMGs, the decision variables enabling power exchange among MGs are bounded as follows:

$$P_{MMG,i,max}^{-} \leq P_{MMG,i}(t) \leq P_{MMG,i,max}^{+} \quad (12)$$

$$P_{MMG,1}^{-}(t) = -P_{MMG,2}^{+}(t) \quad (13)$$

$$P_{MMG,2}^{-}(t) = -P_{MMG,1}^{+}(t) \quad (14)$$

Where $P_{MMG,i,max}^{+} \geq 0$ and $P_{MMG,i,max}^{-} \leq 0$.

3) Ageing cost of the battery, grid cost, load shedding cost and reward cost

TABLE II. OPTIMIZATION COSTS IN €/KWH.

Cost parameter	**Price (€/kWh)**
$c_{g,i}^{+}(t)$ on-peak	0.9105
$c_{g,i}^{+}(t)$ off-peak	0.68
$c_{g,i}^{-}$	0.20
$c_{st,i}$	0.236
$c_{sh,i}$	1.821
$c_{MMG,i}^{+}(t)$ on-peak (normal condition or PV outages)	0.8605
$c_{MMG,i}^{+}(t)$ off-peak (normal condition or PV outages)	0.63
$c_{MMG,i}^{-}$ (normal condition or PV outages)	0.30
$c_{MMG,i}^{+}(t) = c_{g,i}^{+}(t)$ (only under grid outages)	0.9105
$c_{MMG,i}^{-}$ (only under grid outages)	0.60

The costs considered for the optimization model are given in Table II. The costs $c_{g,i}^{+}(t)$, $c_{g,i}^{-}$ and $c_{st,i}$ are derived from [19]. $c_{g,i}^{+}(t)$ and $c_{g,i}^{-}$ are based on the hypothesis made (with respect to the purchasing/selling price of energy in France during the year 2022) in [19]. Also, according to the off- or on-peak electricity tariff, the 8 off-peak hours per day considered in this study are comprised between 12 am and 8 am. Furthermore, the load shedding cost ($c_{sh,i}$) is arbitrarily taken as the highest cost (two-fold higher than the purchasing price of energy from the utility grid during on-peak hours) for the optimization problem in order to ensure the user's comfort. In cooperative mode, a MG sells and purchases energy to/from its neighborhood with a reward price based on the costs of the main grid ($c_{g,i}^{+}(t)$ and $c_{g,i}^{-}$). The reward costs alter according to the conditions (under normal or outage conditions). Thus, a MG is rewarded 10 c€/kWh for selling and 5 c€/kWh for purchasing energy to/from its neighborhood with respect to the external grid under normal condition so as to promote self-consumption in cooperative MMGs. Moreover, only under grid failure condition (islanded mode), a MG is rewarded 40 c€/kWh for selling energy to its neighborhood. However, in islanded mode, a MG does not benefit from any reward cost when purchasing energy from its neighborhood as it has no other alternative to satisfy its user's energy demand and to avoid power blackout. Thus, the purchasing price of energy from the neighborhood in this condition (grid failure event) is the same as the on-peak price under normal condition. Thereby, the latter price is constant over the time horizon as off-peak price is not considered during grid outages. Additionally, under every other condition (e.g. PV outages), the reward cost is identical to the normal condition except in islanded mode.

III. RESULTS AND DISCUSSION

The results of both non-cooperative and cooperative MMGs presented in this section are exclusively related to the condition of extreme outages whereby the external grid is unavailable due to a grid failure and also a PV default occurs in the MG1 simultaneously for the entire time horizon. Therefore, due to grid failure, both MMGs operate in islanded mode as exchanging power with the external grid is not possible physically. Consequently, PV curtailment and load shedding have pivotal roles under these outage conditions in order to respect the power balance relationship. The LP model is developed in Python using the pyomo modeling language and solved with the GUROBI solver. The power references for the LP based optimal scheduling are computed over a 24-hour prediction horizon by the MGC (non-cooperative MMGs) and MGCC (cooperative MMGs) with a sampling rate of 10 minutes. The simulations are carried out with distinct power profiles with regard to the PV production (in relation to the number of PV panels installed). However, the load consumption power profile is similar for each household. The data for PV production and load consumption is extracted from the "Oahu Archive web site" [20] and "IEEE PES Test Feeder" [21], respectively. MG1 and MG2 are equipped with 4 and 10 PV panels, respectively. Regarding this extreme outage condition, the simulations of both non-cooperative and cooperative MMGs are performed with MG1 deprived of PV production as it undergoes a PV default. The initial State of Energy (SoE) of the batteries of both MGs' is kept at 35%.

A. Scenario 1: Non-cooperative Multi-Microgrids

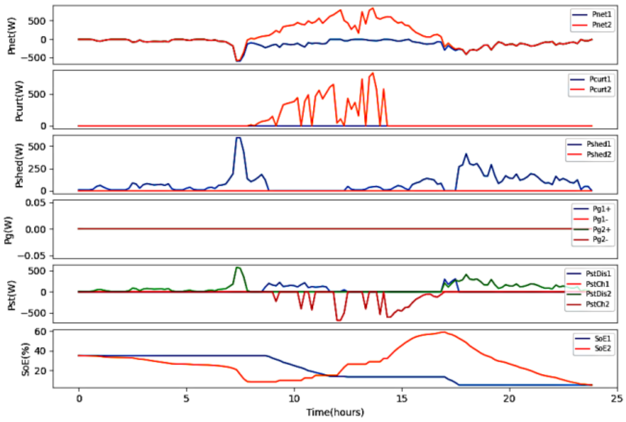

Fig. 3. Power profiles of the non-cooperative MMGs (superposition of the MG1 and MG2 results).

In the non-cooperative MMGs scenario under condition of extreme outages, power cannot be exchanged between MGs. Therefore, each household accommodates for minimizing its own PV curtailment and load shedding without sharing power in the MMGs system leading to an increase of the total operating cost. Fig. 3 shows the superposition of the power profiles of both MGs whereby the net power (P_{net}) is the power difference between the PV production and load consumption. The inexistence of cooperative behavior in the MMGs can be observed as MG2 favored minimizing its own PV curtailment rather than sharing its surplus PV production to its neighborhood which is deeply in need of electricity (power blackout). Indeed, the PV production of MG2 is higher than its load consumption, but it can neither sell the surplus to the external grid nor to its neighborhood in this scenario. Consequently, MG2 is compelled to curtail its solar energy production between 8 am and 2:45 pm in order to respect the power balance relationship leading to a wastage of renewable energy production. Nevertheless, it is to be underlined that PV curtailment is free of cost whereas charging/discharging the battery is costly. Therefore, MG2 charged its battery only at a required level of SoE of about 59% (not charged to its maximum level of SoE) between 9:30 am and 5 pm so as to be able to meet its user's energy demand at the end of the day.

On the other hand, MG1 intermittently undergoes power blackout (load shedding) due to its low PV production and also as it does not have enough energy stored in its battery. Thus, MG1 is unable to fully supply its user's demand even though it discharged its battery to its minimum level of SoE. Hence, due to grid failure and non-cooperative behavior, MG1 requires load shedding that leads to an increase of the total operating cost of the MMGs system and PV curtailment is indispensable for MG2. Therefore, the daily operating cost of the MG1, MG2 and MMGs system for this scenario is 3.7 €, 0.7 € and 4.4 €, respectively. It is to be pointed out that MG1 operating cost is costlier due to low PV production and especially as a consequence of load shedding.

B. *Scenario 2: Cooperative Multi-Microgrids*

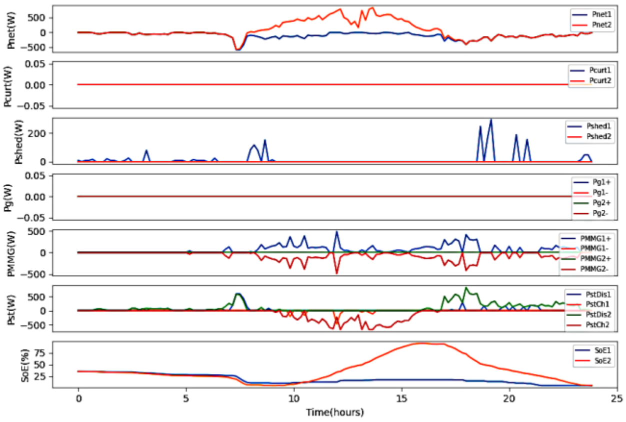

Fig. 4. Power profiles of the cooperative MMGs (superposition of the MG1 and MG2 results).

The simulation is carried out for the cooperative MMGs under the same condition as the previous scenario, but with cooperative behavior enabling power sharing between MGs. Fig. 4 shows the superposition of the power profiles of both MGs. It is observed that the MG2 is able to fully supply its load demand, whereas MG1 is often in a power blackout phase (load shedding) but scarcer than in the previous scenario. Furthermore, despite in grid failure event and although $P_{net} \geq 0$ for MG2, the PV production is not curtailed as it is transferred to MG1 and also stored in both batteries contrarily to the previous scenario. Therefore, MG2 charged its battery to its maximum SoE level between 9:40 am and 4:10 pm with its surplus PV production and also charged intermittently the battery of MG1 between 9:50 am and 1:50 pm so as to be able to fulfill the load demand of the MMGs system. Moreover, at the end of the day, MG2 discharged its battery to its minimum SoE level to supply both MGs load consumption in order to reduce the load shedding of MG1. However, due to an insufficiency of energy available locally in the MMGs system, MG2 is unable to fully supply the load demand of MG1 even though the latter also discharged its battery to its minimum SoE level to fulfill its own load consumption.

The EMS strategy with cooperative behavior ultimately enables to minimize PV curtailment, load shedding and also the total operational cost of the MMGs system. Thus, the total operating cost of the MG1, MG2 and MMGs system is 2.2 €, 0.2 € and 2.4 €, respectively. It is highlighted that the operating cost of the MG1, MG2 and MMGs system is reduced by 38.9%, 74% and 44.8%, respectively compared to the previous non-cooperative MMGs scenario under the same condition. It is to be noted that both MMGs have not exchanged power with the utility grid due to its unavailability.

IV. PERFORMANCES OF THE NON-COOPERATIVE AND COOPERATIVE MULTI-MICROGRIDS

In addition to the condition of extreme outages (PV and grid outages simultaneously), simulations are also performed under normal condition (no outages), PV outage condition (solely PV1 default) and grid outage condition. The initial SoE of the batteries of MG1 and MG2 is maintained at 5% and 57%, respectively only under normal condition. However, under the other conditions, the initial SoE for both MGs' batteries is kept at 35%. The simulations are carried out under all the above-mentioned conditions and every initial SoE is willfully maintained as previously stated to demonstrate the discrepancy between non-cooperative and cooperative MMGs as well as to assess the performances of both MMGs.

Fig. 5 below, is a synopsis of the operating costs of MG1, MG2 and MMGs of eight distinct scenarios. It can be observed that under all conditions, the operating cost of the MG1, MG2 and MMGs is reduced with cooperative behavior compared to non-cooperative MMGs. It is to be pointed out that the reward cost motivates the MMGs users to share power among their neighbors.

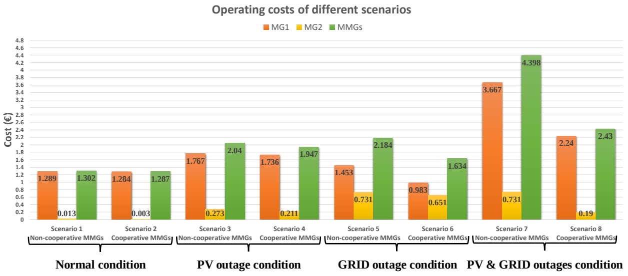

Fig. 5. Operating costs of different scenarios under different conditions.

The performances of the non-cooperative and cooperative MMGs are thoroughly analyzed and assessed through the evaluation metric as shown in Table III. As mentioned above and as it can be observed in Table III, the total operating cost of the cooperative MMGs is less costly contrarily to the non-cooperative MMGs under all conditions. Hence, under normal and PV outage conditions, the total operating cost is reduced by 1.2% and 4.6%, respectively and also fewer energy is drawn from the main grid. Regarding grid outage condition (grid failure event), the total operating cost of cooperative MMGs is reduced by 25.2% and also the external grid is not solicited. Consequently, PV curtailment is required for both non-cooperative and cooperative MMGs equal to 46% and 22.4%, respectively. Nevertheless, PV curtailment is reduced by 51.3% in cooperative mode implying that the usage of renewable energy (PV production) is favored. Furthermore, the total load shedding of the non-cooperative MMGs is 9.6% in contrast to 0% in cooperative mode (reduced by 100%). Moreover, under simultaneous PV and grid outages condition (worst scenario), PV curtailment is equal to 46% and 0% for non-cooperative and cooperative MMGs, respectively (reduced by 100%). The total load shedding of non-cooperative and cooperative MMGs is equal to 37.8% and 6.1%, respectively (reduced by 83.7%). Also, the total operating cost of the cooperative MMGs is reduced by 44.5%.

TABLE III. EVALUATION METRIC OF NON-COOPERATIVE AND COOPERATIVE MMGS UNDER DIFFERENT CONDITIONS.

		Under normal condition		**Under PV outage condition**		**Under GRID outage condition**		**Under PV & GRID outages condition**	
		Non-cooperative MMGs	**Cooperative MMGs**	**Non-cooperative MMGs**	**Cooperative MMGs**	**Non-cooperative MMGs**	**Cooperative MMGs**	**Non-cooperative MMGs**	**Cooperative MMGs**
Cooperative behavior		×	✓	×	✓	×	✓	×	✓
Total operating cost of MMGs	**€**	1.302	1.287	2.04	1.947	2.184	1.634	4.398	2.43
	Reduction of cost (%)	**1.152**		**4.559**		**25.183**		**44.748**	
Total MMGs energy drawn from the grid (kWh)		1.6	1.565	2.167	1.852	0	0	0	0
Total load shedding of MMGs	**kWh**	0	0	0	0	0.491	0	1.931	0.314
	%	0	0	0	0	**9.597**	**0**	**37.788**	**6.146**
	Reduction of P_{shed} (%)	0		0		**100**		**83.74**	
Total PV curtailment of MMGs	**kWh**	0	0	0	0	1.914	1.306	1.914	0
	%	0	0	0	0	**45.98**	**22.412**	**45.98**	**0**
	Reduction of P_{curt} (%)	0		0		**51.26**		**100**	

V. CONCLUSION

In this study, EMSs are proposed to achieve techno-economical goals and also to assess the performances of both non-cooperative and cooperative MMGs under normal and outage conditions. The results demonstrate that the total operating cost of the MMGs soars drastically in the occurrence of load shedding. It is also highlighted that cooperative MMGs perform better economically, motivate users to adopt self-consumption to the utmost through reward cost strategies and enhance resilience contrarily to MMGs without cooperative behavior under all conditions. Particularly, during simultaneous PV and grid outages (worst condition), the load shedding, the PV curtailment and the total operating cost of the cooperative MMGs are reduced by 83.7%, 100% and 44.8%, respectively. Furthermore, besides economic benefits, MMGs with cooperative behavior present numerous advantages such as the reduction of power losses, the relief of the utility grid and the maximization of the use of RESs. Additionally, the paramount benefit of cooperative MMGs is the resilience in outages (especially during grid failure), thus ensuring load demand stability. The next stage of this research entails modeling the design of a decentralized controller by a MAS for an energy community with a more intricate case study while considering the challenges related to resilience.

REFERENCES

[1] S. Backhaus et al., ‘Networked Microgrids Scoping Study’, pp. 1–48, Dec. 2016.

[2] N. Bhusal, M. Abdelmalak, M. Kamruzzaman, and M. Benidris, ‘Power System Resilience: Current Practices, Challenges, and Future Directions’, IEEE Access, vol. 8, pp. 18064–18086, 2020.

[3] CIGRE Technical Brochure 833, ‘Operating strategies and preparedness for system operational resilience, WG C2.25, Apr. 2015.

[4] Z. Wang, K. Yang, and X. Wang, ‘Privacy-Preserving Energy Scheduling in Microgrid Systems’, IEEE Trans. Smart Grid, vol. 4, no. 4, pp. 1810–1820, Dec. 2013.

[5] L. K. Gan, A. Hussain, D. A. Howey, and H.-M. Kim, ‘Limitations in Energy Management Systems: A Case Study for Resilient Interconnected Microgrids’, IEEE Trans. Smart Grid, vol. 10, no. 5, pp. 5675–5685, Sep. 2019.

[6] A. Nawaz, M. Zhou, J. Wu, and C. Long, ‘A comprehensive review on energy management, demand response, and coordination schemes utilization in multi-microgrids network’, Applied Energy, vol. 323, pp. 119596, Oct. 2022.

[7] Q. Sui, F. Wei, C. Wu, X. Lin, and Z. Li, ‘Day-Ahead Energy Management for Pelagic Island Microgrid Groups Considering Non-Integer-Hour Energy Transmission’, IEEE Trans. Smart Grid, vol. 11, no. 6, pp. 5249–5259, Nov. 2020.

[8] A. Ouammi, H. Dagdougui, L. Dessaint, and R. Sacile, ‘Coordinated Model Predictive-Based Power Flows Control in a Cooperative Network of Smart Microgrids’, IEEE Trans. Smart Grid, vol. 6, no. 5, pp. 2233–2244, Sep. 2015.

[9] M. Movahednia, H. Karimi, and S. Jadid, ‘A cooperative game approach for energy management of interconnected microgrids’, Electric Power Systems Research, vol. 213, pp. 108772, Dec. 2022.

[10] M. R. Sandgani and S. Sirouspour, ‘Priority-Based Microgrid Energy Management in a Network Environment’, IEEE Trans. Sustain. Energy, vol. 9, no. 2, pp. 980–990, Apr. 2018.

[11] Y. Amanbek, Y. Tabarak, H. S. V. S. K. Nunna, and S. Doolla, ‘Decentralized transactive energy management system for distribution systems with prosumer microgrids’, in 2018 19th International Carpathian Control Conference (ICCC), Szilvasvarad, pp. 553–558, May 2018.

[12] A. Rajaei, S. Fattaheian-Dehkordi, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, ‘Decentralized transactive energy management of multi-microgrid distribution systems based on ADMM’, International Journal of Electrical Power & Energy Systems, vol. 132, pp. 107126, Nov. 2021.

[13] H. Dagdougui and R. Sacile, ‘Decentralized Control of the Power Flows in a Network of Smart Microgrids Modeled as a Team of Cooperative Agents’, IEEE Trans. Contr. Syst. Technol., vol. 22, no. 2, pp. 510–519, Mar. 2014.

[14] Z. Wang, B. Chen, J. Wang, and J. kim, ‘Decentralized Energy Management System for Networked Microgrids in Grid-Connected and Islanded Modes’, IEEE Trans. Smart Grid, vol. 7, no. 2, pp. 1097–1105, Mar. 2016.

[15] D. An, Q. Yang, D. Li, and Z. Wu, ‘Distributed Online Incentive Scheme for Energy Trading in Multi-Microgrid Systems’, IEEE Trans. Automat. Sci. Eng., pp. 1–14, 2023.

[16] S. E. Ahmadi, N. Rezaei, and H. Khayyam, ‘Energy management system of networked microgrids through optimal reliability-oriented day-ahead self-healing scheduling’, Sustainable Energy, Grids and Networks, vol. 23, pp. 100387, Sep. 2020.

[17] R. Hao et al., ‘Distributed Interactive Energy Management for Networked Microgrids based on Nested Architecture’, in 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, pp. 1–5, Aug. 2020.

[18] A. D. Mustika, R. Rigo-Mariani, V. Debusschere, and A. Pachurka, ‘A two-stage management strategy for the optimal operation and billing in an energy community with collective self-consumption’, Applied Energy, vol. 310, pp. 118484, Mar. 2022.

[19] Y. Gopee, M. Gaetani-Liseo, A. Blavette, G. Camilleri, X. Roboam, and C. Alonso, ‘Energy Management System for a Low Voltage Direct Current Microgrid: Modeling and experimental validation’, in IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, pp. 1–6, Oct. 2022.

[20] National Renewable Energy Laboratory, ‘Solar Radiation Research Laboratory Data: Oahu’, [Online].

[21] IEEE Power & Energy Society Test Feeders Working Group, ‘Resources’, IEEE PES Test Feeders, [Online].