INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IV, April 2025

Energy Management of Islanded Micro-Grid with Uncertainties Using Nash Bargaining Solution

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DOI : https://doi.org/10.51583/IJLTEMAS.2025.140400036

Received: 19 April 2025; Accepted: 23 April 2025; Published: 06 May 2025

Abstract: With the increasing integration of solar PV and wind energy in island micro-grids (MGs), the intermittent nature of non-dispatchable sources and the unpredictability of load demands are unavoidable. As a result, maintaining high reliability and system stability becomes a significant challenge. Additionally, demand-side management technologies and energy storage are commonly implemented in island MGs to mitigate the negative effects of RESs. However, these solutions also introduce uncertainties. Moreover, RESs in MGs are highly susceptible to external environmental factors such as solar radiation, temperature fluctuations, and wind speed variations, making it difficult to ensure system stability, particularly in islanded mode. To address these uncertainties, this paper considers six participant sites and proposes a Cooperative Game Theory (CGT) based on Nash Bargaining Solution (NBC) for collaboration among the participants of MG under the condition of uncertainties introduced by each participant. First energy transaction among the MG participants is modeled. Secondly, CGT using NBS is applied to model the uncertainties in dispatchable and non-dispatchable energy resources of the participants. Moreover, using NBS, a cooperative operation model among MG participants is established, which is transformed into profit maximization in cooperation, ensuring fair profit distribution and improves economic outcomes. The simulation results show that cooperation among all participants leads to an increase in their benefit values. Additionally, the findings suggest that the proposed model demonstrates strong economic performance.

Keywords: Uncertainties, Nash Bargaining Solution, Micro-grid participants, Energy management system, Cooperative game theory, etc.

I. Introduction

MGs have emerged in response to the growing adoption of dispatchable, non-dispatchable, and energy storage technologies. They offer several advantages over traditional power systems, including reduced carbon emissions, increased operational flexibility, cost savings, and improved efficiency. A typical MG is made up of distributed energy generation sources, RESs, energy storage units, and various types of loads [1], [2]. MG functions include either while making connection to the upstream network or in standalone (islanded) mode.

Globally, studies have shown that the implementation of islanded MGs for power generation remains relatively limited [3], with a heavy reliance on diesel generators. This study introduces a model of a representative MG made up of six participants. Each site is equipped with a solar PV array, a diesel generator, storage energy system (as illustrated in Fig. 1), and the capacity to share excess energy with other participants based on demand at different times of the day. The MG model is characterized by three core components: solar PV integration, battery storage, and an energy scheduling system. However, the design and operation of MGs come with significant challenges, particularly in developing effective scheduling strategies. Addressing these challenges under uncertainty is essential for efficient MG operation. In CGT, a major focus is placed on the fair distribution of profits among MG participants. CGT provides a powerful framework for analyzing collaborative decision-making among multiple stakeholders [4], [5]. In power systems, game theory (GT) is typically divided into cooperative and non-cooperative models [4], and both have been widely studied for optimizing collaboration in multi-micro-grid and multi-stakeholder environments.

There many related reviews in this EMS of MG. Fuzzy optimization techniques [6] and Model Predictive Control (MPC)-based optimization approaches [7] have been proposed for scheduling of MGs incorporating renewable energy sources to reduce emissions and operational costs. However, both approaches rely on deterministic forecast data, which is not well-suited for islanded MG operations, as small-scale demand is difficult to predict, and RES generation is highly variable [8]. In [9], a chance-constrained stochastic optimization method was proposed to minimize the operational costs of MGs. However, this technique involves high computational complexity and large problem sizes, which makes it difficult to guarantee solution accuracy [10]. Reference [11] provides an overview of various strategies for modeling uncertainty, defining objective functions, and identifying possible constraints. Although simulations and experimental results using an Energy Management System (EMS) are presented, the treatment of uncertainty is not sufficiently addressed. In [12], recent developments in uncertainty modeling are reviewed, focusing on novel methods for capturing uncertainties in MGs caused by renewable energy variability and load fluctuations. Reference [13] discusses approaches for managing uncertainties, the use of simulation tools, parameter modeling, and unit commitment in power systems. In [14], different uncertainty management techniques are classified, and the strengths and limitations of these methods are evaluated and compared.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IV, April 2025

In the cooperative operation of MGs, ensuring a fair distribution of benefits among participants is a critical concern. Both domestic and international researchers have thoroughly investigated how different game theory approaches can be applied to optimize MG systems collaboratively. In [15], a robust scheduling method based on non-cooperative game theory is proposed to achieve equitable profit distribution among microgrids. Reference [16] addresses the energy management challenges among multiple MGs and introduces a non-cooperative game model that utilizes shared energy storage and flexible control strategies to enhance the economic efficiency of each system. Nonetheless, since non-cooperative game theory prioritizes individual gains, it may result in suboptimal outcomes for the entire system and fall short in achieving overall fairness.

Unlike non-cooperative games, cooperative game theory focuses on collective interests, allowing for stable solutions and achieving Pareto optimal outcomes [17]. For example, Reference [18] introduces a cross-regional cooperation model between a large power grid and smaller microgrids, leading to increased profits for all parties involved. Reference [19] presents a cooperative model for multiple microgrids based on the Nash Bargaining Solution (NBS), which ensures fair profit distribution and enhances the system's economic performance. In Reference [20], game theory utilizing NBS is applied to minimize costs and distribute expenses fairly among MG participants. These studies demonstrate that cooperative game theory supports mutual economic benefits. However, they do not adequately consider the uncertainties associated with energy transfer, particularly those arising from renewable energy variability and fluctuating load demands. Effectively addressing these uncertainties can significantly boost the profitability of each participant and improve overall system performance [21]. Therefore, further research is essential to better understand and manage the uncertainties related to renewable energy generation and energy trading among MG participants.

This paper proposes an uncertainty-aware EMS based on the NBS to promote distribution of profits with fairness. The system encourages equitable cooperation, allowing participants to benefit reasonably from collaboration while also enabling energy sharing. This reduces dependence on expensive grid electricity. Furthermore, the paper introduces a CGT-based framework utilizing the NBS, specifically designed for islanded MGs where uncertainties stem from fluctuating renewable energy output and varying load demands. These uncertain parameters can be estimated for each time interval using historical data. This paper has the following key contributions:

A comprehensive energy management framework for isolated islanded MGs is developed, considering energy transfer between participants, renewable energy scheduling, battery storage charging and discharging, and diesel generator utilization.

A CGT approach based on NBS is proposed, allowing participants with varying peak energy demands to efficiently transfer excess energy between sites, thereby reducing overall operational costs.

It also ensures profits that are fairly distribution among the MG players.

The structure of this paper is as follows: Section 2 presents the optimization problem formulation. Section 3 explores uncertainty modeling for MG participants and forecast generation scheduling is presented in Section 4. Section 5 details the simulations and results and discussion, and Section 6 concludes with key insights into managing uncertainty in MGs.

Figure 1: A Typical Islanded MG Considered in Optimization Formulation

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Optimization Problem Formulation

This section discusses the challenge of uncertainty in scheduling within modern power systems. One notable example that has attracted significant interest in recent years is the MG, which comprises various elements such as distributed generation units (including both energy production and storage systems) and different types of loads (both controllable and uncontrollable). The complexity of scheduling operations in such systems is mainly due to the extensive integration of renewable energy sources like solar PV, which exhibit unpredictable behavior. The primary goal is to optimize the participants' profit, calculated as the revenue generated minus the annual operational costs.

$$\max fx. = \pi_s\left(P_{rs} - P^L{}_{rgs}\right) \quad (1)$$

where P_{rs} is the profit in lower bound of the players/participants in the site and $P^L{}_{rgs}$ is the lower profit (i.e status quo profit) of the participants in the site.

$$P_{rs} = I_s - AC_s \quad (2)$$

where I_s the MGs income, AC_s is the annualized cost of MG.

Maximizing individual profits P_{rs} as shown in equation (2) can results to an unequal distribution of earnings among participants, which may ultimately weaken the microgrid concept by making participation less appealing to some members. This method treats each participant independently (independent approach), allowing them to pursue their own maximum profit and negotiate based on self-interest. However, to enhance the overall performance of the microgrid while ensuring fair compensation for all participants, equation (1) is employed. This equation promotes equitable profit distribution without compromising collective efficiency. Game theory supports this idea by offering a framework for fair profit sharing. Under this model, individual profts P_{rs} may be minimized to some extent to maximize the objective in equation (1), thereby achieving both fairness in rewards and optimal system-wide performance.

The total income of the participant is calculated as follows [4], [22]

$$I_s = TSC_s \quad (3)$$

where TSC_s is the transfer selling price

$$TSC_s = \sum W_p\, T_t\, E_{ss'}\, y_{tpss'} \quad (4)$$

where $E_{ss'}$ is the transfer price of electricity between sites s and s′ and $y_{tpss}{}'$ represents electricity transfer at certain day and time.

The total annual MG cost (AC_s) includes annualized Captial Cost (ACCs), cost of operation and maintenance cost (OMC), annualized cost of replacement (ARC), transfer cost of buying energy (TBC) and annualized cost of fuel (AFC).

$$AC_s = ACC_s + OMC_s + ARC_s + TBS_s + AFC_s \quad (5)$$

where ACC_s is calculated as follows

$ACC_s = Ccap \cdot CRF(i, y)$, where Ccap is the cost of capital (US $) and CRF (i, y) is the capital recovery factor (i represents 12% interest rate and y is the annualized project lifetime). The calculation aspect of CRF is as follows [22]

$$CRF = \frac{(1+i)^y}{(1+i)^y - 1} \quad (6)$$

The second and third terms of (5) indicates annualized cost of operation and maintenance (OMC) and annualized cost of replacement calculated in (7) and (8) respectively

$$OMC = Ccap\, \frac{(1-\lambda)}{y} \quad (7)$$

where, λ is the component reliability.

$$ARC = (Crep) SFF(i, y_{rep}) \quad (8)$$

where Crep is the cost of replacement of battery (in US $), yrep is the battery lifetime, SFF is the sinking fund factor, which is calculated as follows [12]

$$SFF = \frac{1}{(1+i)^{Yrep} - 1} \quad (9)$$

The fourth term of (5) is the MG transfer buying cost. This is given in [20] as follows.

$$TBS_s = \sum w_p T_t E_{s's} y_{tps's} \quad (10)$$

where,

$E_{s's}$ represents electricity price transfer between sites s' and s and $y_{tps's}$ is the quantity of electricity transferred.

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The fifth term of (5) represent annualized cost of fuel (AFC), in which is associated with both the generated and rated power. In this scenario, the diesel generator is expected to operate at its rated power. Therefore, the annual cost of the diesel generator is equivalent to the annual fuel cost and is represented in [20] as follows

$$AFC_{ds} = C_f \sum_{i=1}^{8760} F(t) \qquad (11)$$

in which C_f is the cost of fuel.

$F_{(t)}$ represents the diesel generator's hourly fuel consumption, which can be expressed in [22] given as

$$F_{(t)} = 0.246 P_{DG}(t) + 0.08415 P_R \qquad (12)$$

where P_{DG} represents the actual power output of the diesel generator in kilowatts (kW), and P_R denotes the generator's rated power.

3.1 Constraints

.a) Constraints of Energy demand:

The consumption of primary energy resources is determined based on the efficiency of local electricity generation.
The total primary energy consumption includes both the energy used locally at a site and the energy imported from or exported to other sites.

At each time step, the energy demand is met by the combined output of the solar PV, diesel generator, battery storage, and the energy imported from other sites.

$$\sum_{s'} y_{tps's} - \sum_{s'} y_{tpss'} + P_{B_s}(t) + P_{pv_s}(t) + P_{DG_s} = L_{tps} \qquad (13)$$

where $y_{tps's}$ represents the energy imported from other sites, $y_{tpss'}$ represents energy imported to other sites, $P_{DG_s}(t)$ represents energy supplied from diesel generator, $P_{B_s}(t)$ represents energy stored in the battery and $P_{pv_s}(t)$ represents solar power, all at time t.

b) Constraints of Power Balanced: The power balance represents the quantity of power that must be supplied or absorbed within the system to maintain equilibrium in islanded mode. In this study, solar PV, diesel generator and a battery storage are utilized. The equation for this power balance defines the relationship between the generated power and the required power at any given moment.

$$P_{Ld_s}(t) = P_{pv_s}(t) + P_{B_s}(t) + P_{DG_s}(t) \qquad (14)$$

where $P_{Ld_s}(t)$ is the load power, $P_{pv_s}(t)$ represents the power of solar PV, $P_{B_s}(t)$ represents power of the battery and $P_{DG_s}(t)$ represents the power of diesel generator all at time t for the site s.

c) Battery Power Output: The use of upper and lower limits is equivalent to charge/discharge of battery storage units

$$P_B \min(t) \le P_B(t) \le P_B \max(t) \qquad (15)$$

where, $P_B \min(t)$ and $P_B \max(t)$ indicate the minimum power discharged and maximum power charged by the battery units respectively.

d) Constraints of price level Transfer

In general, there are k discrete levels of transfer pricing. Accordingly, for the electricity price $E_{ss'}$, between two sites, the decision variable $X_{ss'k}$ and the parameter $E_{ss'k}$, correspond to each price level and can be aggregated across these discrete pricing levels.

$$E_{ss'} = \sum_k E_{ss'k} X_{ss'k} \qquad \forall s, s' \qquad (16)$$

By using one transfer price at a certain time

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$$\sum_k X_{ss'k} \leq 1 \qquad \forall s, s' \qquad (17)$$

For every pair of sites and in both directions of energy transfer, the transfer prices remain identical. $X_{ss'k} = X_{s'sk} \qquad \forall s, s'$ (18)

Electricity from a given site must first satisfy its own demand before it can be sold to another site. Additionally, a site cannot simultaneously purchase electricity from others and sell it to participants.

Modelling Uncertainties for Micro-Grid Participants

In modeling MG, uncertainties in scheduling and operation are primarily influenced by the level of RE integration, especially from solar sources. Within power distribution networks—and particularly in MGs—solar PV systems are the most widely adopted type of RES. Since PV output relies on solar irradiation, the variability and unpredictability of sunlight introduce significant uncertainties into power generation [14]. Another major source of uncertainty is the fluctuation in daily electricity demand. Consequently, when developing models aimed at profit maximization, it's necessary to account for numerous uncertain variables. In such scenarios, probabilistic analysis becomes a vital method for managing these uncertainties in power system scheduling and operation. This section outlines a framework based on Cooperative Game Theory (CGT) to address problems involving these uncertain parameters.

a) Solar PV

The generation of power from solar PV systems depends on solar radiation and ambient air temperature. In modeling these uncertainties, both irradiation and air temperature are commonly expressed by a normal distribution [23].. The probability distribution of the forecasted solar irradiation, characterized by its mean (μ) and standard deviation (σ), is provided in [12], [23]:

$$F(G_{ING}, T_r) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(\frac{-((G_{ING}, T_r) - (\mu))^2}{2 \times \sigma^2}\right) \qquad (20)$$

The solar PV output power generated is calculated as

$$P_{PV} = P_{STC} \times \frac{G_{ING}}{G_{STC}} \times (1 + K(T_c - T_r) \qquad (21)$$

where, P_{PV} is the output PV power generated, G_{ING} represents irradiation in hour (hr), G_{STC} denotes standard irradiation, T_c and T_r are the temperature for air and cell respectively. P_{STC} and K are respectively power of solar PV rated power an temperature coefficient at maximum [23], [24].

b) Load Modelling

Due to the wide variety of electrical appliances—such as air conditioners, heaters, and refrigerators—accurately modeling electrical load becomes a complex task. Load behavior is influenced by several factors, including time of day and prevailing weather conditions [25]. Load models are generally classified into two categories: static and dynamic [13]. Static models reflect the magnitude and frequency of the electrical load at a specific time, while dynamic models capture how load changes over time, considering its time-dependent characteristics. This study employs a dynamic load model, which better represents the real-time behavior of electrical demand, as shown in Table 1. Load modeling is essential for several applications, including long-term system stability, equipment aging analysis, and inter-area oscillation assessments [22], [25]. According to Table 1 (adapted from [22]), residential buildings show the highest peak and annual electricity demand, whereas fire stations have the lowest demand in both categories

Table 1: Annual demand profile of each participant [22].

	School	Hotel	Restaurant	Fire station	Residential building	Hospital	Total
Annualized energy demand (kW)	49859	66028.5	90082	37631.5	68036	75004.5	456641.5
Energy peak demand (kw)	10.7	11.6	17.7	6.8	18.6	7.2	0

Case study

The Table 2 and Table 3 proposed that the MG has six participant's sites having the characteristics of solar PV units and battery storage sources respectively in each site.

Table 2: Characteristics of Solar PV in each site

Technology	T_c	P_{STC}	G_{STC}	K
PV	25°C	20kW	$1000\ w/m^2$	0.001

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Table 3: Characteristics of battery storage units in each site

Battery storage unit	Min/max charge/discharge power (kW)	Minimum charge/discharge time (hr)	Capacity (kWh)
	-10/+10	2	20

Considering the uncertainty in modelling solar PV and load demand, the value of these parameters is forecast as shown in Figure 2 and Table 4

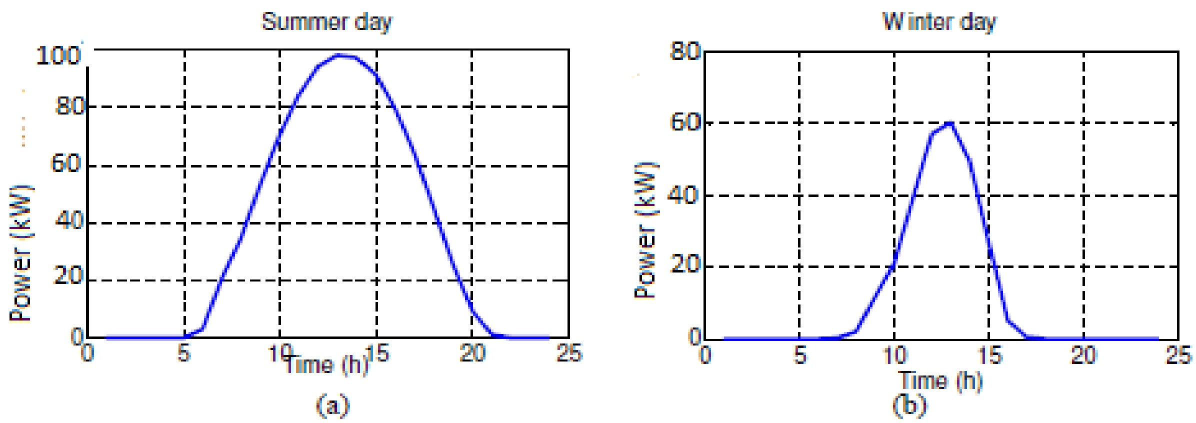

Figure 2: Solar Power for each Participant's site (a) Summer (b) winter

Scheduling of Generation Uncertainty with Respect to The Load

In islanded mode, the energy demand needs to be entirely supplied by power generated locally. Any mismatch between generation and consumption can lead to system instability and degraded power quality. Table 5 illustrates the energy scheduling under this mode. Since the main grid is unavailable, the microgrid (MG) relies entirely on local energy sources to meet demand. In this setup, the diesel generator serves as the only dispatchable source, providing backup to the non-dispatchable solar PV system. Based on the load profiles in Table 4 and the generation schedules in Table 5 (column 1 for each participant), it's evident that diesel generator operation varies with changes in demand. Batteries stored excess solar energy during periods when sun radiation is high and discharge low solar inputs, helping stabilize power availability from the solar PV system.

This combination of dispatchable and non-dispatchable sources with battery as a storage source is used to manage fluctuations in power demand. For instance, between 1 a.m. and 6 a.m., when solar generation is inactive, the power generation using diesel and batteries are used to meet the load. During this period, some participants experience low demand while others have high needs. As a result, certain diesel generators are turned off, and their power shortfalls are covered by surplus energy from other participants. For example, during early morning hours, the hospital, residential building and restaurant keep running of their diesel generators to meet their own needs and supply power to others whose generators are off. Between 7 a.m. and 5 p.m. solar generation is sufficient in meeting the entire load demand. During this period, all generations from diesel generators remain off, batteries are being charged, and energy exchange among the MG participants is possible. If there's a sudden drop in solar PV output, the system activates both diesel generators and batteries to maintain a balance between energy supply and demand.

For instance, from 6 p.m. to 9 p.m., most MG participants experience a surge in electricity demand. To compensate for this, diesel generators and batteries are utilized to bridge the power shortfall. Later, between 10 p.m. and midnight, some participants show lower energy usage while others maintain high demand, as shown in the load profile. In this scenario, each participant's battery storage discharges equal amounts of power to satisfy their load requirements. Facilities like an hotel, a restaurant, and a residential building continue to consume significant electricity, prompting the diesel generator to be activated to supply an hotel, school and a residential building. Meanwhile, generators for other participants are turned off to conserve fuel and prolong equipment lifespan. The battery performance during the mode of charging and discharging is shown Figure 3.

As indicated in the last column of Table 5, energy transfers between sites are tracked hourly. During early morning hours (1 a.m. to 6 a.m.), energy transfer is minimal due to generally low consumption, with the exception of high energy demand of about 8.9 kWh from the restaurant. In the afternoon, most participants generate enough solar power to meet their needs, resulting in little to no energy transfer during certain hours—such as from 1 p.m. to 4 p.m., when no energy exchange takes place within the MG. From 6 p.m. to 9 p.m., energy transfer significantly increases due to high demand at some locations where local generation falls short. To optimize energy usage, power is redistributed from participants with surplus to those in need. Between 10 p.m. and midnight, aside from the restaurant, electricity demand remains low, leading to reduced energy exchange among MG participants. Figures 4 and 5 show the total excess electricity after local consumption and total electricity transferred to other participants respectively.

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ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IV, April 2025

Table 4: Energy consumption during the winter (Day 1) and summer (Day 2) seasons. [22]

Day	Period (hr)	School (kW)	Hotel (kW)	Restaurant (kW)	Fire Station (kW)	Residential Building (kW)	Hospital (kW)
Daytime1	P_1	2.11	2.31	8.91	2.11	3.71	2.19
Daytime1	P_2	2.11	9.29	3.51	3.29	5.61	4.49
Daytime1	P_3	10.7	11.61	8.91	6.79	7.51	7.31
Daytime1	P_4	10.69	11.61	17.71	6.79	7.51	7.30
Daytime1	P_5	10.7	11.61	8.89	6.81	7.51	7.3
Daytime1	P_6	4.30	9.31	17.69	4.11	18.60	5.41
Daytime1	P_7	2.11	2.29	8.90	2.11	3.71	3.01
Daytime2	P_1	2.11	2.29	8.91	2.10	3.71	3.01
Daytime2	P_2	2.10	9.31	3.49	3.31	5.60	4.50
Daytime2	P_3	10.71	11.61	8.89	6.81	7.49	7.31
Daytime2	P_4	10.7	11.6	17.7	6.8	7.5	7.3
Daytime2	P_5	10.7	11.6	8.9	6.8	7.5	7.3
Daytime2	P_6	4.3	9.3	17.7	4.1	18.6	5.4
Daytime2	P_7	2.1	2.3	8.9	2.1	3.7	3.0

Given that: Pers. gen= Participant's personal generation, Sf/Sl =Shortfall/Surplus, Dem = demand, Negative sign written under Sf/Sl column represents shortfall.

Table 5: Scheduling of Generation Uncertainties with Respect to the Load

Time (Hrs)	School (kW)		Hotel (kW)		Restaurant (kW)		Fire Station (kW)		Residential Building (kW)		Hospital (kW)		Total excess Energy (kW)	Total energy transf. (kW)
	Pers Gen	Sf /Sl	Pers Gen	Sf /Sl	Pers Gen	Sf /Sl	Pers Gen	Sf /Sl	Pers Gen	Sf /Sl	Pers Gen	Sf /Sl		
1	2.09	0	2.09	-0.21	5.41	-3.51	2.09	-0.1	5.51	1.81	5.1	2.09	3.81	3.81
2	2.09	0	2.09	-0.21	5.41	-3.51	2.09	-0.1	5.51	1.81	5.1	2.09	3.81	3.81
3	2.09	0	2.09	-0.21	5.41	-3.51	2.09	-0.1	5.51	1.81	5.1	2.09	3.81	3.81

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4	2.09	0	2.09	-0.21	5.41	-3.51	2.09	-0.1	5.51	1.81	5.1	2.09	3.81	3.81
5	2.09	0	2.29	0	5.59	-3.31	2.31	0.2	5.6	1.91	5.31	2.31	4.42	3.32
6	2.69	0.59	2.51	0.21	5.79	-3.09	2.41	0.3	5.79	2.1	5.89	2.91	5.51	3.11
7	5.31	3.19	5.31	-3.9	5.61	2.09	5.31	2	5.51	-0.1	5.39	0.92	8.2	4.1
8	7.71	5.61	7.21	-2.1	7.81	4.29	6.49	3.2	7.31	1.71	6.31	1.8	16.61	2.1
9	10.21	-0.51	9.01	-2.59	9.51	0.61	7.91	1.1	10.51	3.1	7.81	0.5	5.19	3.09
10	11.71	1.01	10.59	-0.71	11.39	2.51	8.4	1.6	11.51	4.09	8.52	1.21	10.3	0.71
11	12.81	2.1	12.11	0.49	12.61	3.69	9.51	2.7	12.61	5.09	9.63	2.32	16.4	0
12	13.01	2.31	12.81	1.21	13.11	-4.61	10.09	3.2	13.09	5.5	10	2.71	14.9	4.61
13	15.01	4.29	14.81	3.21	15.01	6.11	10.09	3.2	15.08	7.5	10	2.72	26.79	0
14	14.81	4.09	14.81	3.21	15.01	6.11	9.81	3	14.61	7.1	9.71	2.41	25.89	0
15	14.31	3.59	13.89	2.29	14.51	5.61	9.29	2.5	14.2	6.7	9.11	1.81	22.49	0
16	12.91	2.21	12.39	0.81	13.11	4.2	8.5	1.7	12.8	5.3	8.7	1.4	15.61	0
17	10.71	0	10.21	-1.41	10.81	1.91	7.09	0.32	10.61	3.11	7.21	-0.11	5.32	1.5
18	11.72	7.41	11.69	2.42	11.82	-5.89	9.91	5.81	11.52	17.09	10	4.59	20.22	13.1
19	11.11	6.81	11.21	1.89	11.21	-6.5	9.61	5.51	10.61	-8.1	9.82	4.41	18.61	14.5
20	10.89	6.59	10.79	1.5	10.9	-6.8	9.52	5.41	10.39	-8.2	9.5	4.1	17.6	15
21	10.5	6.71	10.61	1.3	10.69	-7	9..2	5.09	10.1	-8.52	9.33	3.9	16.5	15.5
22	2.09	0	2.09	-0.21	5.41	-3.51	2	-0.1	5.51	1.8	5.1	2.9	3.81	3.81
23	2.09	0	2.09	-0.21	5.41	-3.51	2	-0.1	5.51	1.8	5.1	2.09	3.81	3.81
24	2.09	2.1	2.3	2.12	8.9	5.41	2.11	2.09	3.7	5.51	3.1	2.09	3.81	3.81

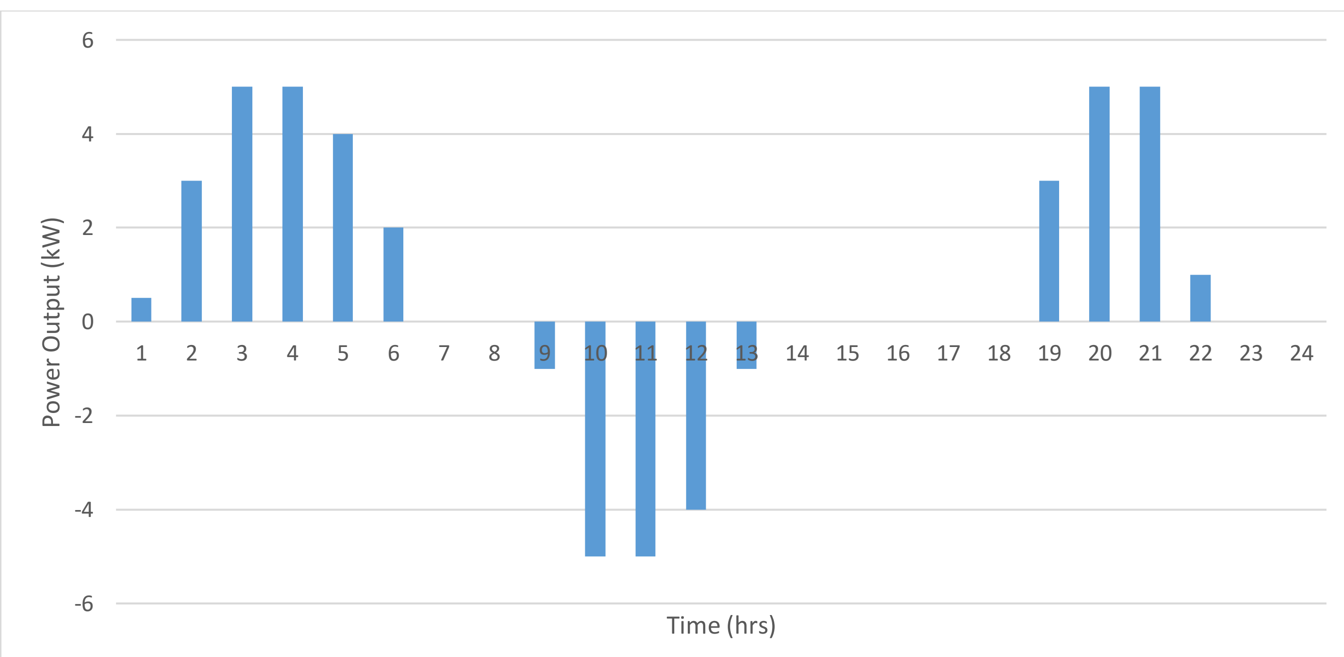

Figure 3: Daily battery Power Output.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IV, April 2025

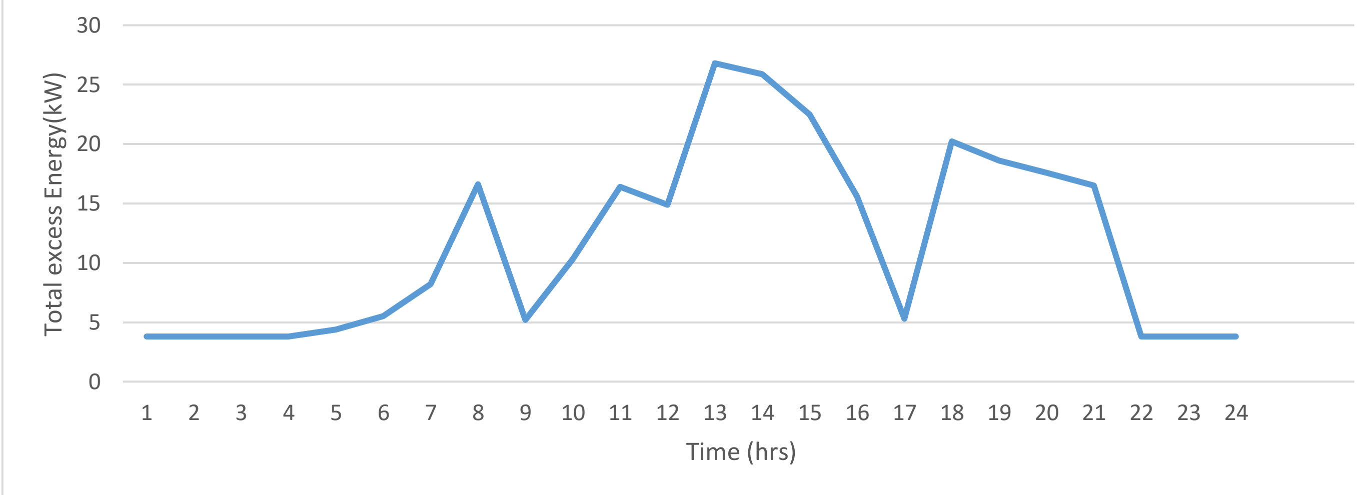

Figure 4: Total Excess Electricity after Local site Consumption

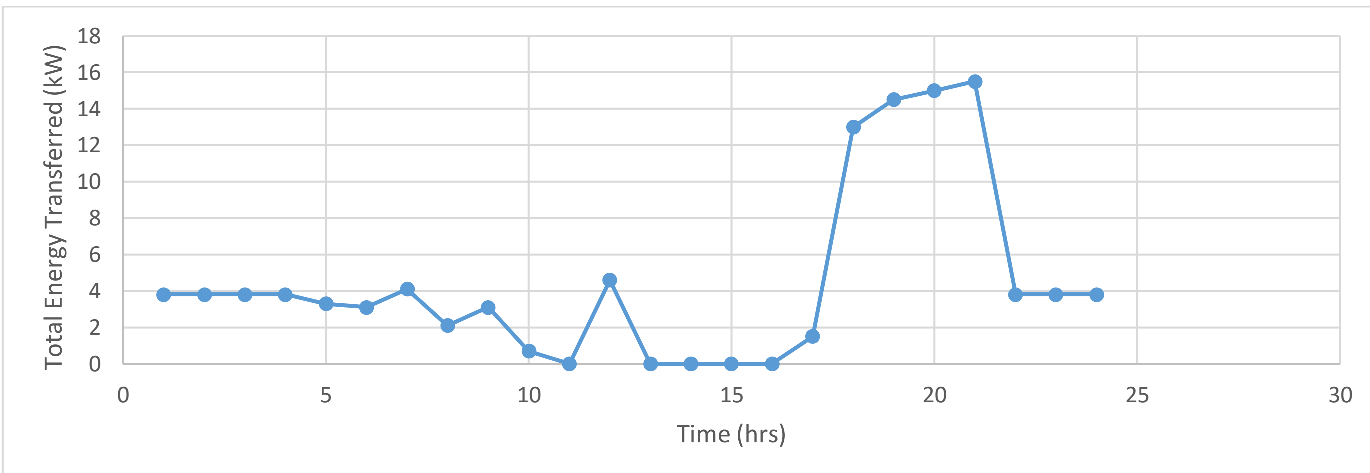

Figure 5: Total Energy Transferred to the Participants.

II. Simulation Results and Discussion

Profit Allocated to each Participant in Micro-grid

The study presents simulations involving MG participants. The optimization problem is addressed using MATLAB software and carried out on an HP laptop equipped with 4GB RAM and an Intel Pentium processor. Figure 4 illustrates the profit outcomes for individual participants under two scenarios: cooperative operation and independent profit maximization within an islanded MG. In this scenario, the fire station earns the least profit, while the restaurant achieves the highest. When comparing profit levels, the fire station sees a 2.8% increase and the restaurant experiences a 2.1% rise as a result of participant cooperation, as depicted in Figure 4.

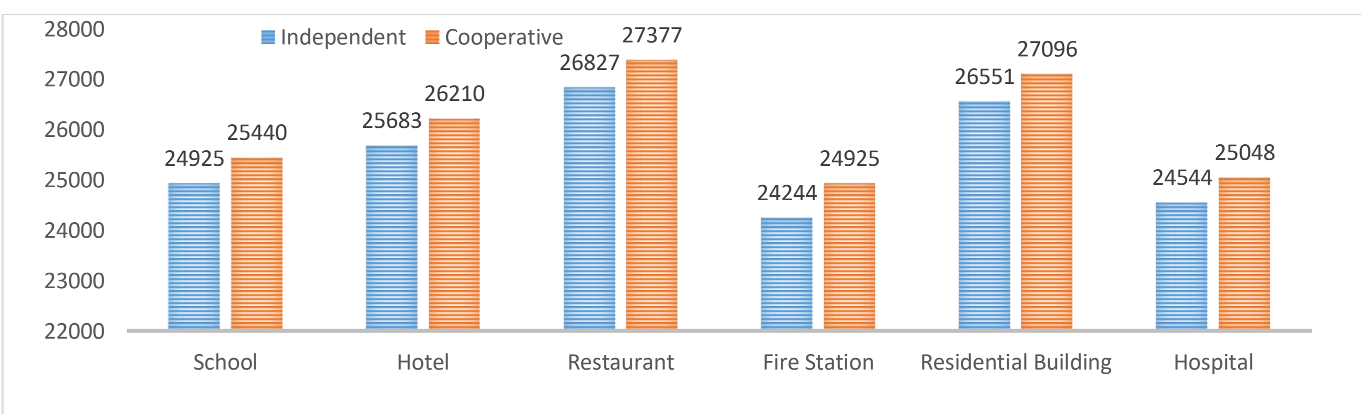

Figure 4: Profits of the MG in both independent and Cooperative operation.

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Electricity transfer between sites

Electricity can be exchanged among microgrid (MG) participants at a mutually agreed rate. In this scenario, a fixed transfer price of 0.039 kWh is used, as referenced in [20] and [22]. Table 6 outlines the optimal hourly electricity transfers between sites. No transfers occur between 1:00 AM and 4:00 AM, as well as from 8:00 PM to midnight, due to the absence of solar generation and insufficient battery reserves to produce surplus energy. However, significant energy transfers take place between 7:00 AM and 10:00 AM, at noon, and from 5:00 PM to 6:00 PM.

Table 7 presents the total optimal electricity transferred over the course of one year among the participants. These transfers are facilitated by variations in peak electricity demand profiles across the different sites. When one participant has excess energy during a certain period, it is shared with others experiencing higher demand. For instance, over the span of a year, the school supplies a total of 328.5 kW of electricity to the residential building, while the fire station contributes 720 kW to the same building, among other examples. It also presents the yearly electricity exchange among the sites. A total of 37,590.5 kW of electricity was transferred over the year, accounting for approximately 8percent of the total electricity demand annually. Meanwhile, consumption with the local sites amounted to approximately 420,000 kW, representing about 92% of the total demand of energy annually. Figure 6 illustrates the contribution of each site to the microgrid's energy demand in islanded mode. The findings suggest that inter-site electricity transfers play a significant role in addressing uncertainties among microgrid participants.

Table 6: Hourly Electricity Transfer between Sites in islanded mode

Time (hr)	Site		Amount of Electricity transferred (kW)
	From	To	
1	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
2	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
3	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
4	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
5	Hospital	Restaurant	2.3
	Residential Building	Restaurant	1
6	Hospital	Restaurant	2.9
	Residential Building	Restaurant	0.2
7	Nil	Nil	0
8	School	Hotel	2.1
9	Residential Building	Hotel	3.1
10	School	Hotel	0.7
11	Nil	Nil	0

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12	Residential Building	Restaurant	4.6
13	Nil	Nil	0
14	Nil	Nil	0
15	Nil	Nil	0
16	Nil	Nil	0
17	Restaurant	Hotel	1.4
	Restaurant	Hospital	0.1
18	School	Residential Building	7.1
	Fire Station	Restaurant	5.5
	Hotel	Restaurant	0.4
19	School	Residential Building	6.8
	Fire Station	Restaurant	5.5
	Hotel	Residential Building	1.2
	Hospital	Restaurant	1
20	School	Restaurant	6.5
	Hotel	Restaurant	0.3
	Fire Station	Residential Building	5.4
	Hospital	Residential Building	2.8
21	School	Restaurant	6.2
	Hotel	Restaurant	0.8
	Fire Station	Residential Building	5.1
	Hospital	Residential Building	3.4
22	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
23	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2
24	Hospital	Restaurant	2
	Residential Building	Restaurant	1.5
	Residential Building	Fire Station	0.1
	Residential Building	Hotel	0.2

Table 7: The energy exchanged between sites operating in islanded mode.

Site		Annual energy transferred (kW)
School	Hotel	1021
School	Restaurant	4636

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School	Residential Building	5001
Hotel	Restaurant	548
Hotel	Residential Building	438.5
Restaurant	Hotel	511.5
Fire Station	Restaurant	4015
Fire Station	Residential building	3833
Residential Building	Fire Station	256
Residential Building	Restaurant	5945
Residential Building	Hotel	1642
Hospital	Restaurant	77045
Hospital	Residential Building	2263.5

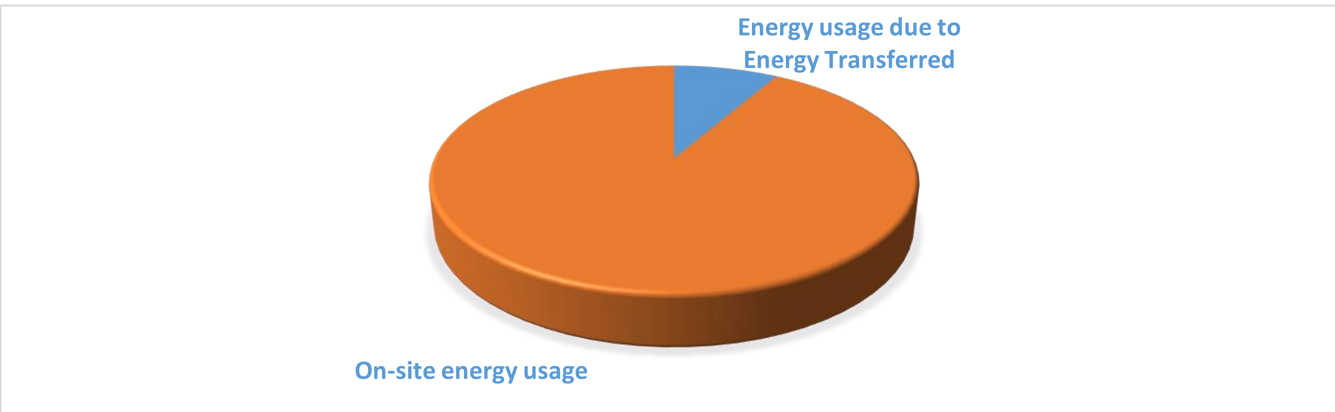

Figure 6: MG Electricity demand Contribution

III. Conclusions

The study investigates how uncertainties are managed in the islanded operation mode of a MG. These uncertainties mainly stem from fluctuating load demands and non-dispatchable source integration. To address this, the study employs CGT for uncertainty modeling, involving six participating sites, each outfitted with a dispatchable energy unit and solar photovoltaic (PV) system. The focus is on optimizing generation scheduling to maximize individual participant profits under uncertain conditions, specifically considering variations in load demand and renewable energy generation. The CGT approach, based on the NBS, is utilized to tackle this optimization challenge.

Energy is distributed among participants as needed throughout the day. Findings reveal that the CGT-based uncertainty management approach yields higher profits compared to when participants operate independently. The effectiveness of CGT over the independent strategy is validated through empirical analysis. Simulation results indicate that while total expenses are higher under the independent approach, cooperative management through CGT leads to increased income. Additionally, cooperation among participants led to an 8% increase in energy transfers between sites. Overall, the study demonstrates that collaborative resource sharing and energy transfers among MG participants result in more favorable economic outcomes.

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