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Peer-to-Peer Electricity Trading in Microgrids with Renewable Sources and Uncertainty Modeling Using IGDT

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Abstract— *Microgrids are known as the main components of energy networks because they can accommodate a large share of renewable energy sources. Peer-to-peer energy trading is one of the most effective ways to implement decentralized patterns in the electricity market. In peer-to-peer trades, each actor negotiates directly with a set of partners without any intermediaries. Peer-to-peer energy exchange methods allow direct energy exchange between producers and consumers. This study tested the peer-to-peer trading method on networks consisting of 4 microgrids. Existing microgrids have different generating sources, such as solar energy, wind turbines, and microturbines, each of which is modeled separately. Moreover, in order to reduce the uncertainty in the production of renewable sources, a battery storage system has been used in this network. Also, to encourage microgrids to use renewable resources, cut-off costs have been considered by these resources. This research uses the constrained optimization method and GAMS software with a Baron solver to optimize the problem. In the end, the uncertainty of producing renewable resources for different modes is examined using the information gap decision theory method. The available results show the power distribution between microgrids and other network components based on the objective function and existing constraints.*

Keywords— Battary Storage, Energy Trading, Microgrid, Peer-to-Peer, Renewable Energy.

NOMENCLATURE

Abbreviations

ADMM	Alternating Direction Method of Multipliers
BESS	Battery energy storage system
DSO	Distribution system operator
EM	Energy management
IGDT	Information-gap decision theory
MG	microgrids
PV	Photovoltaic

Variables

$PB^{dso}_{i,t}, PS^{dso}_{i,t}$	Energy purchase from and sale to DSO for MG i at hour t
$PB_{i,t}, Ps_{i,t}$	Energy purchase from other MGs and sale to other MGs for MG i at hour t
$Pch_{i,t}$, $Pdch_{i,t}$	Charge and discharge rate of battery storage system in microgrid i at time t
$PD_{i,t}$	Load of MG i at hour t
$PG_{i,t}$	Microturbine power output for microgird i at time t
$Pwcut_{i,t}$, $Pwindcut_{i,t}$	Interrupted wind turbine and solar cell energy due to excess production power for MG i at time t
$PWind_{i,t}$	Wind turbine power output for microgird i at time t
$PW_{i,t}$	PV system power output in microgrid i at time t
$K_{(i,\ t)}$	Binary variable
SOC_t	battery storage system state of charge at time t

Parameters

α	Temperature coefficient of solar cells
η	Battery charging efficiency
$\lambda_{i,t}$, $\beta_{i,t}$	Parameters represent the satisfaction level of MG i at hour t
$a_{i,t}$, $b_{i,t}$, $c_{i,t}$	Cost curve coefficients of microturbine in MG i at hour t.
PD^{min}_i, PD^{max}_i	Minimum and maximum load limit of MG i
π^{min}_t, π^{max}_t	Unit energy price of selling power to and buying power from DSO at hour t
G^a_t	Solar radiation at time t
G_{a0}	Reference solar radiation
Pch^{min}, Pch^{max}	Minimum and maximum charging capacity of the battery storage system
P_{max}	Nominal power of solar cell
P_r	Wind turbine rated power
SOC^{min}, SOC^{max}	Minimum and maximum charge levels of the battery storage system
T_c	Ambient temperature
T_0	Reference temperature
V^w_t	Actual wind speed at time i
V_{ci}	Cut-in speed
V_{co}	Cut-off speed
V_r	Wind turbine rated speed
M	Penalty factor

Indices

i	Indices of microgrids
t	Indices of time

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1. INTRODUCTION

Today, we are facing a growing electricity demand, and meeting this demand, considering the reduction of greenhouse gases, we need new sustainable sources, renewable sources such as solar and wind energy. Peer-to-peer energy trading is a new energy management method in electrical energy networks that allows subscribers to exchange electrical energy and other goods and

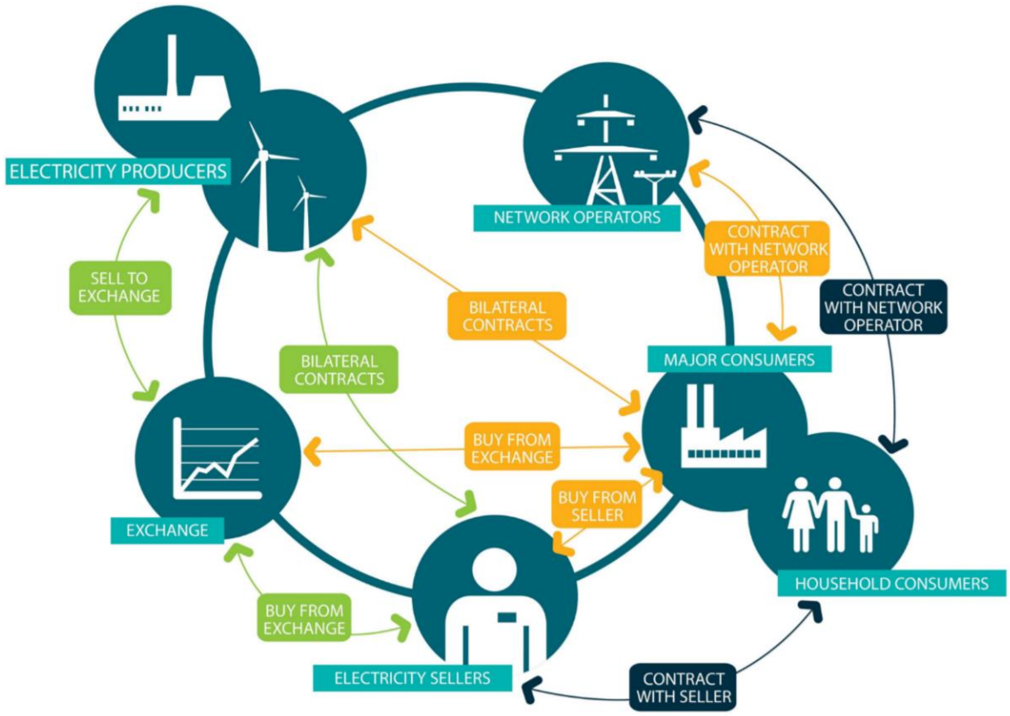


Fig. 1. Concept of electricity trading [1]

services. Fig. 1 shows a simple concept of how to exchange electricity. In this figure, major producers can supply their electricity to the energy exchange or major consumers or to the grid. On the other hand, consumers can get the energy they need from Provide these resources. In recent years, we have seen significant growth in small-scale distributed energy resources, including home and small-scale producers, electric vehicles, energy storage devices, and controllable loads. Using these resources helps meet energy demand and injects clean energy into the grid. Moreover, to encourage consumers to invest in renewable resources, incentives should be provided for them to reap financial benefits and return on the initial investment. The peer-to-peer energy exchange method allows subscribers to actively sell their excess energy in the electricity market or participate in this market by reducing the amount of their energy demand. With this partnership, sellers will benefit from this energy exchange's financial and social welfare benefits by selling extra energy. Buyers can receive clean energy from other members instead of receiving energy from fossil fuels. Also, distribution network providers will benefit from reduced grid losses, peak shaving, reduced investment and grid operating costs, reduced power plant reservations, and increased power grid stability.

Peer-to-peer energy trading makes renewable energy sources such as solar and wind energy more accessible. They also help consumers make better use of renewable energy sources, increase the power system's resilience, and increase the level of access to energy in some areas. Fig. 2 shows an overview of the power system in which different members, such as producer and consumer microgrids, solar and wind farms, and traditional producers are located. These different members are fully connected to each other through the transmission and distribution network and can be participate in peer-to-peer exchange processes. Each component of this power system can transfer this excess energy to other microgrids or distribution systems if excess energy is available to other consumers.

Peer-to-peer energy trading, despite its many advantages, also has many challenges. In the peer-to-peer trading method, because the subscribers exchange energy directly with each other, they are less affected by the central controller, thus creating an unreliable environment, so encouraging subscribers to participate in peer-to-peer energy exchange is a significant challenge. Also, due to the large number of members participating in this market, modeling the decision-making process for various energy exchange parameters is difficult because some decisions conflict with the interests of some participants.

In exchanging electrical energy on a peer-to-peer basis, this exchange mechanism is critical because all the items of this process, such as the market settlement mechanism, pricing, and how to match the energy exchanged between buyer and seller, are necessary. Therefore, a mechanism design can do the above entirely and accurately while being accurate and fast.

In the peer-to-peer energy exchange section, many articles from different aspects have dealt with this issue in [3] presented a decentralized method for the market settlement process by considering the members' privacy, the power losses, and the cost of using other networks. In this article, optimization was considered as the maximization of social welfare. Considering the privacy of members and social welfare is one of the advantages of this article, and the lack of using different energy sources and loads is one of the disadvantages of this method. In [4] proposes a decentralized algorithm for local energy trading in microgrids with an integrated pricing mechanism considering welfare maximization. Considering network voltage management using peer-to-peer energy exchange is one of the advantages of this paper. In [5] proposes a framework for joint scheduling and power trading of a community of prosumers in a transactive energy market. Considering intraday and day-ahead planning is an advantage of this article. In order to consider the privacy issues in [6], a transactive energy market is proposed in which microgrids exchange limited information with the market operator. The use of a reconfigurable distribution network, as well as the consideration of distribution system operators (DSO) and multi-microgrids, are the advantages of this paper. A peer-to-peer energy exchange method for smart microgrids with several renewable energy sources such as biogas, solar energy, and wind energy is presented in [7]. The simultaneous use of different sources of renewable energy is

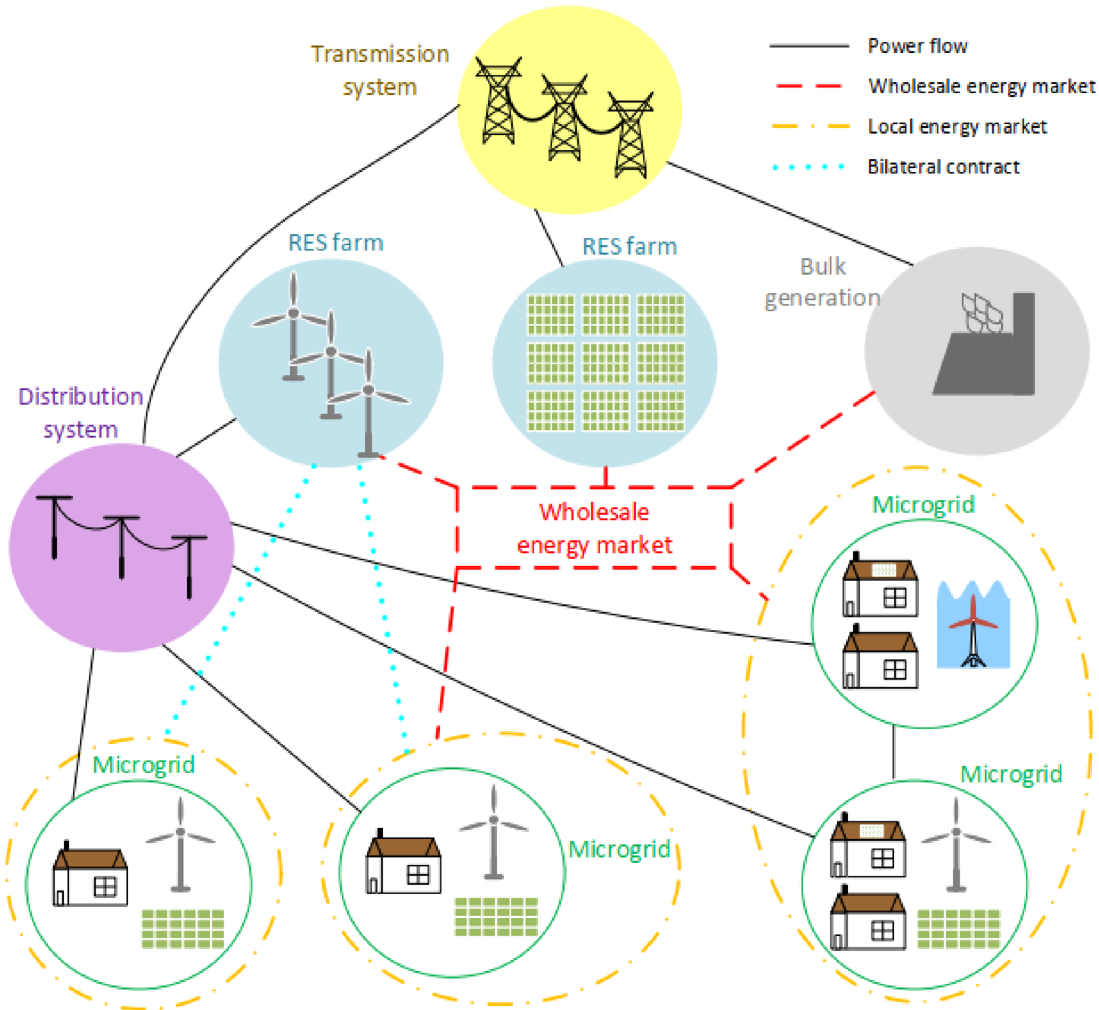


Fig. 2. Trading power between different members in a power network [2]

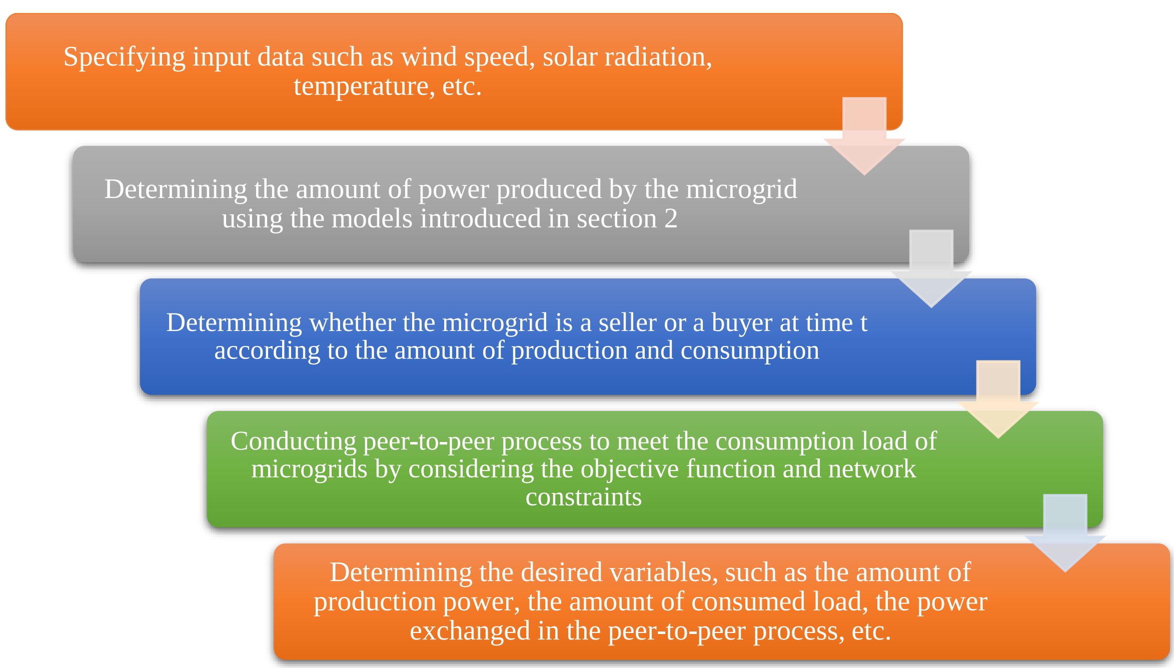


Fig. 3. Solution methodology flowchart

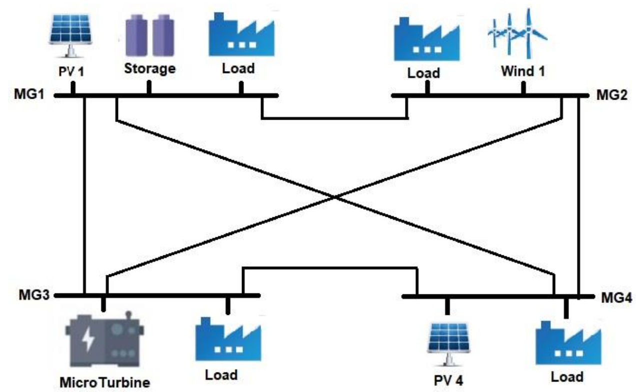


Fig. 4. Topology of network used in study

one of the advantages of this article. This optimization problem is modeled based on Nash bargaining theory and solved using the Alternating Direction Method of Multipliers (ADMM) method. Considering that violating the network constraints is one of the common problems in the peer-to-peer energy exchange process, reference [8] suggests a method that solves this problem by using ancillary services. Also, in this method, the local marginal price is used to obtain the network price. Solving the problem of violating network constraints by using ancillary services is one of the advantages of this article. Considering that the previous works did not provide a simultaneous market settlement mechanism for energy and reserve amounts, reference [9] presented a model considering peer-to-peer energy exchange and reserve to cover the uncertainty of renewable resources and reduce reserve costs. Consideration of planning for reserve amount and uncertainty of renewable resources is one of the advantages of this paper. In [10], the study was conducted to investigate energy management for production and storage resources. The author considered the market price of energy, the prices quoted by distributed generation sources, and electric vehicles in the grid and responsive loads. The advantages of the article are the use of load response. Reference [11] models and solves the EM problem of microgrids from the generation point of view. Incentive-based demand response programs and Comprehensive studying of EM in both intra-day and day-ahead markets are the main contributions of this paper.

The main contributions of this paper can be summarized as follows:

- Modeling of various components in microgrids, such as renewable energy sources and storage
- Designing a mechanism for peer-to-peer trades using the constrained optimization method
- Investigating the uncertainty of renewable energy sources using the IGDT method

The rest of this paper is organized as follows: in Section 2, the modeling of the system, including PV, Wind turbine, BESS model, the objective functions, the technical and economic constraints of the problem, and IGDT. Uncertainty modeling for this problem is presented. Section 3 illustrates the case study and its simulation results, and in Section 4 Conclusion and Recommendations are provided.

2. Problem formulation

In this paper, peer-to-peer energy trading between 4 microgrids that have different sources of renewable energy, such as wind and solar and microturbines and battery storage, is studied. To do this, first, the existing elements, such as wind turbines, battery storage systems, photovoltaic system, and microturbines, are modeled. This research has been done by constrained optimization method in which an objective function has been used, representing the profit obtained from this peer-to-peer energy exchange process. The software used to perform the simulation is GAMS software. GAMS is a powerful software for optimizing and executing mathematical models. The IGDT method is also used to investigate the uncertainty in the amount of power generated by renewable sources.

2.1. PV system modelling

The power generated by photovoltaic systems depends on the temperature and amount of solar radiation on the solar panels and the efficiency of the solar panels themselves.

The model used for the power generated by photovoltaic systems is as follows.

$$Pw_{i,t}=\frac{G_t^a}{G_{a0}}P_{max}\times\left(1+\alpha\left(T_c-T_0\right)\right) \quad (1)$$

This formula calculates the output power of solar panels according to solar radiation data, ambient temperature, and the temperature coefficient of solar cells [12].

In this formula G_t^a is solar radiation at time t (W/m^2), G_{a0} reference solar radiation(W/m^2), P_{max} nominal power of solar cell(W), α temperature coefficient of solar cells (%/$^\circ$C), T_c ambient temperature, T_0 is reference temperature and $Pw_{i,t}$ is PV system power output in microgrid I at time t.

2.2. Wind turbine modeling

Power generated by wind turbines is a function of wind speed. Also, these types of turbines have three modes of power generation according to the nominal wind speed for the turbine and the actual wind speed, so that at speeds less than cut-in speed and speeds higher than cut-out speed, power generation by the turbine is zero. At speeds between cut-in speed and rated speed, the power produced is a ratio of rated power concerning wind speed, and at speeds between rated speed and turbine cut-off speed, it produces its rated power. As a result, the power generation model for the wind turbine is as follows [13].

$$Pwind_{i,t}=\begin{cases}0 & V_t^w<V_{ci}\\ P_r\times\frac{V_t^w-V_{ci}}{V_r-V_{ci}} & V_{ci}<V_t^w<V_r\\ P_r & V_r<V_t^w<V_{co}\\ 0 & V_t^w>V_{co}\end{cases} \quad (2)$$

In this formula $Pwind_{i,t}$ is wind turbine power output for microgird i at time t, V_t^w actual wind speed at time t, V_{ci} cut-in speed, V_{co} cut-off speed, V_r wind turbine rated speed and P_r is wind turbine rated power.

2.3. Battery storage modeling

According to [14], [15], technical limitations of storage and calculating the amount of storage charge at different times are given in Eqs. (3) to (8). Eq. (3) and (4) indicate the initial and storage charges at the end of the day. Eq. (5) indicates the maximum storage speed limit, and Eq. (6) indicates the maximum storage discharge rate limit, and the constraint of the storage charge level is given in Eq. (7). Finally, in Equation(8), a dynamic model for the storage charge amount at different times is presented [14].

$$SOC_{t0}=SOC_0 \quad (3)$$

$$SOC_{t24}=SOC_0 \quad (4)$$

$$Pch_{i,t}\le Pch^{max} \quad (5)$$

$$Pdch_{i,t}\le Pdch^{max} \quad (6)$$

$$SOC^{min}\le SOC_t\le SOC^{max} \quad (7)$$

$$SOC_t=SOC_{t-1}+\sum_i Pch_{i,t}\times\eta-\sum_i\frac{Pdch_{i,t}}{\eta} \quad (8)$$

2.4. Objective Function

The objective function maximizes the profit from peer-to-peer energy exchange among the microgrids in the network. In this function, the load consumed by the microgrids, the amount of microgrids sold to other members, and energy sold from DSO is the main benefit of this peer-to-peer energy exchange. Also, the cost of fuel consumption by microturbines and the penalty coefficient due to power outages from renewable sources are included in this objective function.

In Eq. (9) objective function used in this paper is presented.

$$Max\ U_{(i,t)}\left(P_{i,t}\right)+\pi_t\left(PS_{i,t}\right)-\pi_t^{max}PB_{i,t}^{dso}+\pi_t^{min}PS_{i,t}^{dso} \\ -C\left(PG_{i,t}\right)\ \ -M(Pwcut_{i,t}+pwindcut_{i,t}) \quad (9)$$

$U_{(i,t)}\left(P_{i,t}\right)$ Indicates the amount of load consumed by the microgrids at moment t in Eq. (10) The equation used for $U_{(i,t)}\left(P_{i,t}\right)$ is shown.

$$U_{(i,t)}\left(P_{i,t}\right)=\lambda_{i,t}PD_{i,t}-\beta_{i,t}PD_{i,t}^2 \quad (10)$$

This part of the objective function shows the profit from energy consumption in microgrids, and its purpose is to consume a certain amount of energy according to the conditions in microgrids and their limitations, which should have the following conditions:

1- Microgrids prefer to consume more energy than to reach the target, or the limitations do not allow further growth.

2- According to the type of microgrid function, after consuming energy, the amount consumed will be saturated from one point because due to its positive effect on the objective function, if it is not saturated, the optimal point for the model used will not be found.

$$C\left(PG_{i,t}\right)=a_i\left(PG_{i,t}^2\right)+b_i\left(PG_{i,t}\right)+c_i \quad (11)$$

Equation (11) shows the cost of fuel used by microturbines, which is modeled as a quadratic equation.

2.5. Constraints

The constraints of this paper are related to the technical limitations of the network and the power balance, as well as the limitations related to renewable source and storage.

$$PD_{i,t}+Ps_{i,t}+PS_{i,t}^{dso}+Pch_{i,t}=PG_{i,t}+PWreal_{i,t} \\ +PWindreal_{i,t}+PB_{i,t} \\ +PB_{i,t}^{dso}+Pdch_{i,t} \quad (12)$$

The first constraint is related to the balance of production and consumption in each microgrid, modeled in Eq. (12). Eq. 12 controls the balance of production and consumption in each microgrid. each microgrid's includes its output by the resources available in it, purchases from other microgrids and operators, and the amount of discharge from the existing storage network.

The consumption of each microgrid includes its consumption load, the amount of power sold to other microgrids and operators, and the amount of storage charge of the microgrid is also considered as the consumption and output of the microgrid. This constraint must be in place for all available times and all available microgrids.

$$PD_{i,t}^{min}\le PD_{i,t}\le PD_{i,t}^{max} \quad (13)$$

The Eq. (13) is related to controlling the load consumption of each microgrid. This constraint controls the load consumption of each microgrid within the defined range for minimum and maximum load for each microgrid.

The following constraint is the minimum and maximum power generation by generating sources in microgrids such as solar and wind energy and microturbines.

$$0\le PG_{i,t}\le PG_{i,t}^{max} \quad (14)$$

$$PWreal_{i,t}+PWcut_{i,t}=PW_{i,,t} \quad (15)$$

$$PWindreal_{i,t}+PWindcut_{i,t}=PWind_{i,,t} \quad (16)$$

The constraint (14) is related to controlling the minimum and maximum power produced by the microturbine in microgrid I at time *t*. This microturbine can produce between zero and maximum power. The model controls the amount of power produced according to the conditions.

The constraint (15) is related to the amount of power generated by the solar panels in microgrid I at time *t*. The sum of delivered power and cut-off power equals the total power that these plates can produce.

Constraint (16) is also related to the amount of power generated by the wind turbine in the microgrid I at time *t*. The power generated by wind turbines is not as controllable as the power generated by solar panels. It is also modeled similarly to the power limit produced by solar panels.

$$\sum PB_{i,t}=\sum PS_{i,t} \quad (17)$$

Constraint (17) related to the equality of power purchased from other microgrids and the amount of power sold to other microgrids at time *t*.

$$0\ \le\ PS_{i,t}+PS_{i,t}^{dso}+Pch_{i,t}\ \le K_{i,t}\left(PG_{i,t}+PW_{i,t}+Pwind_{i,t}-PD_{i,t}\ \right) \quad (18)$$

$$0\ \le\ PB_{i,t}+PB_{i,t}^{dso}+Pdch_{i,t}\ \le(1-K_{i,t})(PD_{i,t}-PG_{i,t}+PW_{i,t}+Pwind_{i,t}\ ) \quad (19)$$

Constraints (17) and (18) determine whether the microgrid i is a buyer or a seller at time *t*. The microgrid i at time *t* can sell its excess power to other microgrids if it has excess power, or if it has a shortage of power buys from others. The variable K (i, t) is a binary variable which, if it has a value of 1, is the seller's microgrid and if it has a value of zero, it is the buyer's microgrid.

2.6. IGDT background

The IGDT method is one of the risk control methods that can help in planning and decision-making in the presence of severe uncertainties. The difference between this method and probabilistic methods is that there is no need for the probability density function of uncertainty, which can be very useful in cases where the decision maker's knowledge of the problem's parameters is deficient.

The uncertainty parameter can positively affect the objective function and improve it, or it can negatively affect and cause the value of the objective function to deteriorate.

These two incompatible topics are modeled in the IGDT method using robustness and opportunity.

The IGDT method consists of the following three parts: A. System model B. uncertainty model C. Decision-making model

A) System model

The system model expresses the mathematics of the system and determines how the final deciding factor, for example, profit or loss, relates to the decision quantities and existing factors. For a set of decision variables P and uncertain variable λ, the objective function, F (P, λ) Shows the relationship between input and output for what is being decided. This paper's objective function is to the amount of profit from peer-to-peer energy trading between existing microgrids.

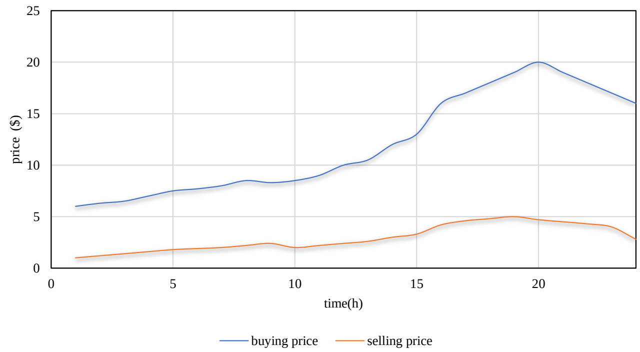


Fig. 5. Trading energy price with DSO

Table 1. Pv system data

	Unit	PV 1	PV 2
Nominal power	MW	5.5	5.5
Reference radiation	W/m^2	1000	1000
Standard temperature	°C	25	25
Temperature coefficient of solar panels	%/°C	0.46	0.46

B) Uncertainty model

In the IGDT method, different models are considered for uncertainty, and depending on the type of uncertainty of the problem, the best model should be selected and used In most power systems studies, the envelope-bound model is used to estimate the uncertainty variable's estimated value. The following is the mathematical expression of this model.

$$U(\alpha, \lambda) = \left\{ u(\lambda) : \left| \frac{u(t) - \tilde{u}(t)}{\tilde{u}(t)} \right| \leq \alpha, \alpha \geq 0 \right\} \quad (20)$$

where α, $u(t)$ and $\tilde{u}(t)$ denote the uncertainty variable, forecasted value and actual value, respectively

C) Decision-making model

In risk-based decisions, the two policies of risk-taking and risk-aversion can be used by the decision-maker. Depending on the company's general policies, this part of the method is determined, and it is determined to what extent the company should follow which policy. in order to mathematically define the model, the Robustness function can be used as risk aversion policies and Opportunity function for risk-taking policies.

Robustness function:

The conservative decision maker tries to make the value of the obtained objective function resistant to any risk of uncertainty. The robustness function is given in Eq. (21).

$$\widehat{\alpha} = Max \ \{\alpha : Max \ C(q, \lambda) \leq r_c\} \quad (21)$$

Table 2. Wind Turbine data

	Unit	Wind 1
Nominal power	MW	5
Nominal wind speed	m/s	14
Cut-off speed	m/s	25
Cut-in speed	m/s	2

Table 3. Microturbine data

	unit	Microturbine 3
Nominal power	MW	4
Cost coefficient (a)	\$/MW^2	0.00037
Cost coefficient (b)	\$/MW	0.068
Cost coefficient (c)	\$	2.02

Table 4. Battery storage data

	Unit	data
Charge capacity	MW	4
discharge capacity	MW	4
Charging efficiency	%	90
discharging efficiency	%	90

In this case, the objective function obtains the maximum acceptable range by considering the constraints of the main problem. In this research, because the objective function is written as a profit function, the resistance function is used to consider the uncertainty and its effect on the objective function.

Opportunity function:

The decision-maker tries to increase the probability of improving the value of the objective function through possible errors in predicting the uncertain parameter.

$$\widehat{\beta} = Min \ \{\alpha : Min \ C(q, \lambda) \leq r_c\} \quad (22)$$

3. SOLUTION METHODOLOGY

In this research, the proposed method is based on constrained optimization. The model used for this work is nonlinear programming mixed with a number, solved using Gam's software and Baron solver. In this model, each microgrid first, according to the amount of power consumed and the amount of power produced by the source in the microgrid, determines its buyer or seller, then according to the microgrid conditions and the existing objective function as a profit from the exchange Peer-to-peer energy is exchanged. Microgrids exchange power with each other as well as with the operator. This power exchange between microgrids is such that the load consumption of microgrids is provided in the whole 24 hours and microgrids make the most use of renewable resources and as much as possible refrain from purchasing power from the operator to create a peer exchange to Peer to be formed between existing members.

Fig 3. Shows flowchart of solution methodology

3.1. Case study

The proposed model and solution method are applied to a 4-Microgrid system. All calculations were performed on a personal computer using a Gams software with Baron solver with Intel Core (TM) i7-4702 CPU and 6 Gb of memory. $\beta_{i,t}$ is set as 0.24 and value of the value of $\lambda_{i,t}$ for microgrids varies from 35 to 45.

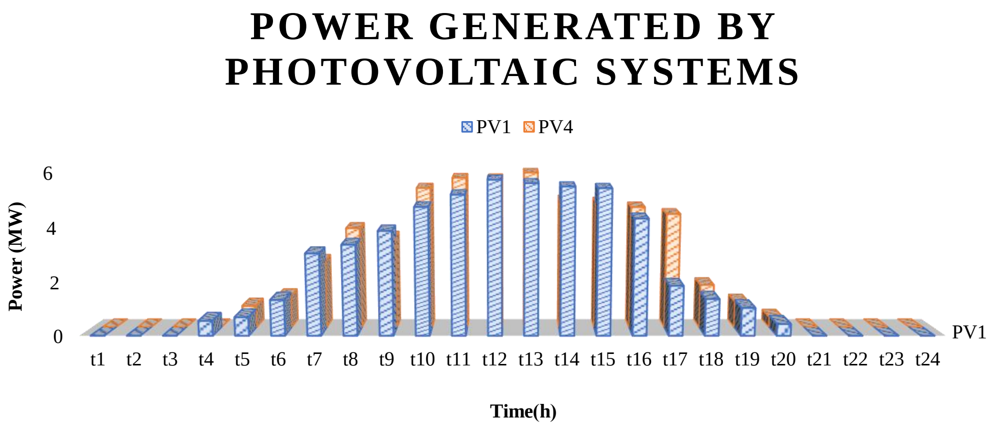
Fig. 4 shows the network used in this study, which consists of 4 microgrids.

In this network, microgrids no. 1 and 4 have a photovoltaic system, microgrid no. 2 has a wind turbine, and microgrid no. 3 has a microturbine, so all microgrids have loaded.

The specifications of the photovoltaic system, wind turbine, and microturbine are given in Tables 1 to 3. Also, battery storage is considered in microgrid no. 1, the specifications of which are given in Table 4.

In this test network, all microgrids are connected to each other in pairs, and the ability to transfer power is established in both directions, and there is no limit to power exchange. Also, a network operator is provided that plays the role of a traditional network. The microgrids can provide their power shortage up to 1.5 MW from this operator. Also, if additional power is not available for consumption in the microgrids or it is not possible to charge in the storage, the microgrids can increase this additional power up to 1.5 MW sell to this network operator. This condition occurs when all microgrids have reached their maximum allowable load and the battery does not have the capacity to charge, so the extra power must either be sold to the operator or disconnected.

The prices used by the microgrids in the network for exchanging, buying, and selling energy with each other during 24 hours are



	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
PV1	0	0	0	0.6	0.7	1.3	3.1	3.4	3.9	4.8	5.2	5.8	5.6	5.5	5.4	4.3	1.9	1.4	1	0.4	0	0	0	0
PV4	0	0	0	0	0.8	1.2	2.5	3.8	3.4	5.3	5.7	5.7	5.9	4.8	4.8	4.6	4.3	1.6	1	0.4	0	0	0	0

Fig. 6. Power generated by photovoltaic systems

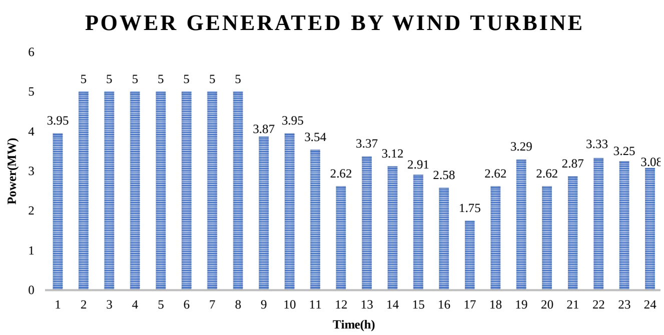


Fig. 7. Power generated by wind turbine

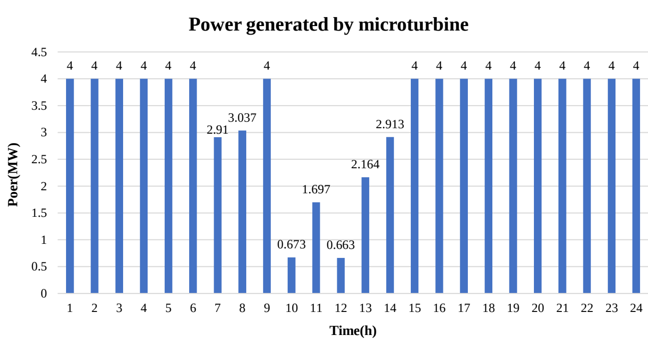


Fig. 8. Power generated by microturbine

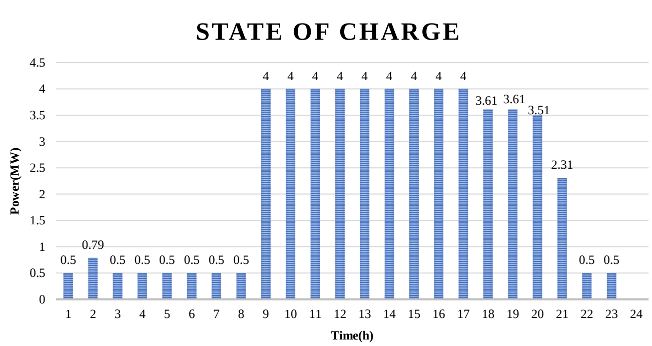


Fig. 9. State of charge

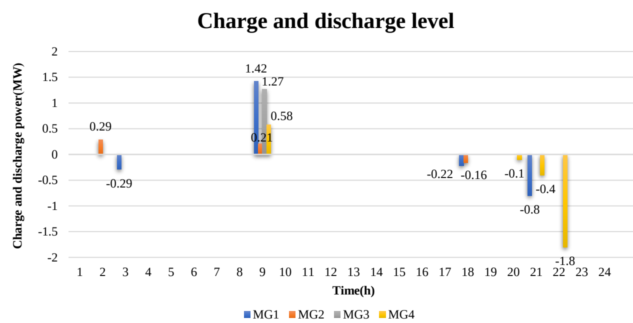


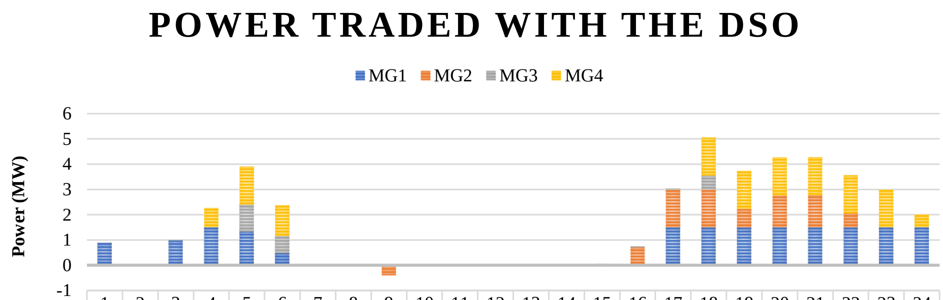
Fig. 10. Charge and discharge level of each microgrid

Table 5. Microgrids trading energy price

Price ($)	Time (h)	Price ($)	Time (h)
7	13	3	1
6	14	4.5	2
8	15	4	3
8.1	16	4.5	4
6	17	5.4	5
7.6	18	5.5	6
9	19	6.1	7
7.8	20	6	8
8.2	21	6.3	9
7.4	22	6	10
7.6	23	6.5	11
9	24	7.5	12

given in Table 5. According to Fig. 5, microgrids must pay more than the time of energy sale to the operator when buying energy from the operator. This situation is due to encouraging microgrids to exchange peer-to-peer with other microgrids. In this way, microgrids are more inclined to buy power from other microgrids because of the low price than the operator. also when selling their surplus energy because the purchase price by the operator is lower than other microgrids, microgrids tend to sell their surplus energy to other microgrids first.

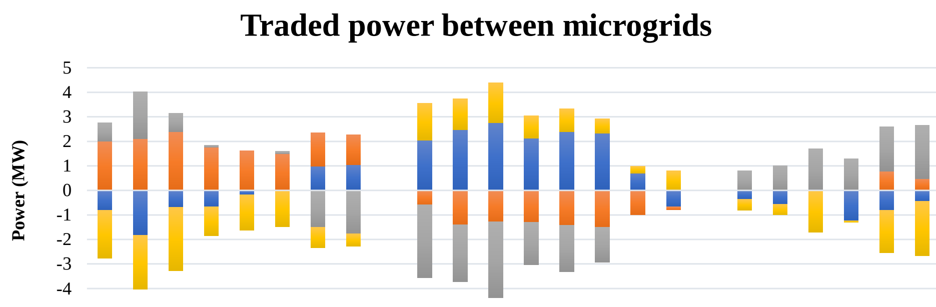
All microgrids have a 24 hours load and the minimum load of each microgrid is according to Table 6. Also, the maximum load of each microgrid is 30% more than the minimum load. At all times, the minimum amount of load consumption of microgrids must be provided from various production sources in the network. If there



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
MG4				0.8	1.5	1.2												1.5	1.5	1.5	1.5	1.5	1.5	0.5
MG3					1.1	0.7									0	0	0	0.6						
MG2									-0							0.7	1.5	1.5	0.7	1.3	1.3	0.6		
MG1	0.9		1	1.5	1.3	0.5											1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Time(h)

Fig. 11. Power traded with the DSO



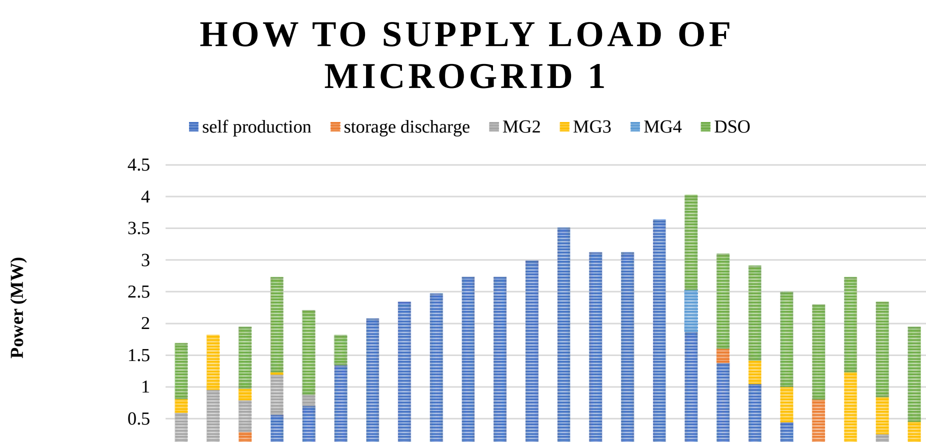
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
MG4	-2	-2	-3	-1	-1	-1	-1	-1		1.5	1.2	1.6	0.9	0.9	0.6	0.3	0.8		-0	-0	-2	-0	-2	-2
MG3	0.8	1.9	0.8	0.1		0.1	-2	-2		-3	-2	-3	-2	-2	-1				0.8	1	1.7	1.3	1.8	2.2
MG2	2	2.1	2.4	1.8	1.6	1.5	1.4	1.2		-1	-1	-1	-1	-1	-2	-1	-0						0.8	0.5
MG1	-1	-2	-1	-1	-0		1	1		2	2.5	2.8	2.1	2.4	2.3	0.7	-1		-0	-1		-1	-1	-0

Time(h)

MG1 MG2 MG3 MG4

*Negative value show energy purchased from other microgrids

Fig. 12. Traded power between microgrids



	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
DSO	0.9		1	1.5	1.3	0.5											1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
MG4																	0.7							
MG3	0.2	0.9	0.2	0															0.4	0.6		1.2	0.6	0.4
MG2	0.6	1	0.5	0.6	0.2																		0.3	0.1
storage discharge			0.3															0.2		0	0.8			
self production				0.6	0.7	1.3	2.1	2.3	2.5	2.7	2.7	3	3.5	3.1	3.1	3.6	1.9	1.4	1	0.4				

Time(h)

Fig. 13. How to supply load of microgrid 1

Table 6. Minimum load of microgrids

Time(h)	Minimum load (MW)			
	MG 1	MG 2	MG 3	MG 4
1	1.3	1.5	2.5	1.5
2	1.4	2	1.6	1.7
3	1.5	2	2.4	2
4	2.1	2.5	3	1.5
5	1.7	2.6	3.9	2.9
6	1.4	2.7	3.6	3
7	1.6	2.8	3.4	2.6
8	1.8	2.9	3.7	3.3
9	1.9	2.5	2.1	2.2
10	2.1	3.5	2.8	2.9
11	2.1	3.8	3.1	3.4
12	2.3	3	2.9	3.1
13	2.7	3.6	3	3.8
14	2.4	3.5	3.7	3
15	2.4	3.4	4.2	3.2
16	2.8	3.3	3.1	3.3
17	3.1	2.6	3.1	3
18	3.1	3.3	3.5	2.8
19	2.6	3.1	3.2	2.9
20	2.5	3	3	2.1
21	2.3	3.2	2.3	3.6
22	2.1	3	2.7	2.6
23	1.8	2.2	2.2	2.5
24	1.5	2	1.4	2.1

Table 7. Photovoltaic and wind turbine data

Time(h)	Temp (°C)		Radiation(W/m^2)		Wind Speed(m/s)
	MG 1	MG 4	MG1	MG 4	MG 2
1	24.7	19	0	0	11.5
2	24.5	19.5	0	0	14.1
3	24.3	20.3	0	0	14.9
4	24.4	21	0	100	15.6
5	24.5	21.5	150	125	19.5
6	26.5	21.7	219	240	20.6
7	27.5	22	467.5	550	14.1
8	22.4	26.4	680	620	14.5
9	28.5	22.6	637.5	700	11.3
10	28.9	23.4	980	860	11.5
11	29	23.7	1050	942	10.5
12	29.7	24	1050	1041	8.3
13	29.8	24.3	1190	1020	10.1
14	29.5	24.8	900	1000	9.5
15	29	25	885	990	9
16	27.7	25	850	790	8.2
17	29	25.1	800	340	6.1
18	27.7	24.9	300	250	8.3
19	26.5	24.8	180	190	9.9
20	24.8	24	70	80	8.3
21	24.6	23.5	0	0	8.9
22	25	23.2	0	0	10
23	24.3	22.7	0	0	9.8
24	24	22	0	0	9.4

is additional power in the network, microgrids can consume up to 30% more than the minimum load.

The data required for photovoltaic systems and wind turbines are given in Table 7.

3.2. Result

In the first part, the existing problem is optimized without considering the uncertainty of the production of renewable resources using the relations mentioned in Section 2. The obtained results show the power exchange between the microgrids in the network, how the power of the microgrids exchanges with

```
**** SOLVER STATUS      1 Normal Completion
**** MODEL STATUS       1 Optimal
**** OBJECTIVE VALUE           0.1259
```

Fig. 14. State of model and solver

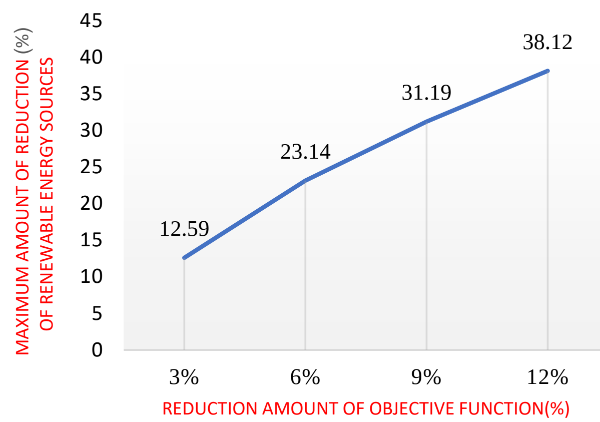


Fig. 15. Maximum amount allowed to reduce the production of renewable resources

the operator, and how the power is produced by the network's production resources and the storage status in all 24 hours.

In the second part, using the IGDT method, the effect of uncertainty of power generation by renewable sources on how to exchange power between microgrids and how to supply the consumption load of microgrids as well as storage status is investigated.

A) Result without considering the uncertainty

The amount of power generated by photovoltaic systems in microgrids 1 and 4 is shown in Fig. 6.

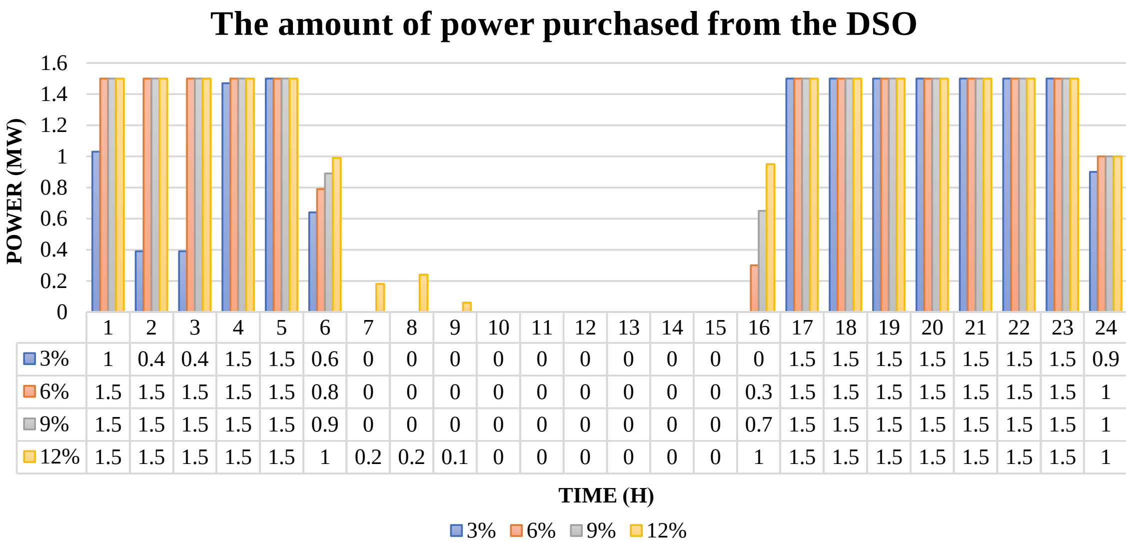
The hour when power generation by photovoltaic sources has reached zero due to lack of sunlight in these hours and according to the amount of production of other generating sources and the consumption of microgrids, the amount of power cut off due to excess power in photovoltaic sources is zero. And all the power generated by the photovoltaic sources is delivered to the grid.

Fig. 7 shows the power generated by the wind turbines in microgrid 2 during 24 hours. When the wind turbine produces its maximum power, the wind speed is faster than the nominal speed of the turbine. Due to network conditions and wind speed, and the total power generated is delivered to the network.

Fig. 8 shows the power generated by the microturbine over 24 hours. According to the output power of the microturbine in Fig. 8, in most cases, the microturbine has produced at its maximum power. In some times when the microturbine has less output than its maximum power, it is mainly due to the penalty coefficient of power cuts from renewable sources such as photovoltaic systems and wind turbines, and also the power generation by microturbines has a fuel cost, so the best-case scenario is that power Buy and consume produced by renewable sources to prevent power outages.

Fig. 9 shows the charge level of the battery storage during 24 hours. Also, Figures 10 show the charge and discharge level of each microgrid at different times.

According to Fig. 10, the microgrids charged the storage at 2 and 9 o'clock, which had a surplus of production, and at other times, when they had a shortage of production, they used the power available in this store. The storage helps to reduce the uncertainty of production resources in such a way that when production is more than needed, microgrids store this extra power in the storage



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3%	1	0.4	0.4	1.5	1.5	0.6	0	0	0	0	0	0	0	0	0	0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.9
6%	1.5	1.5	1.5	1.5	1.5	0.8	0	0	0	0	0	0	0	0	0	0.3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1
9%	1.5	1.5	1.5	1.5	1.5	0.9	0	0	0	0	0	0	0	0	0	0.7	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1
12%	1.5	1.5	1.5	1.5	1.5	1	0.2	0.2	0.1	0	0	0	0	0	0	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1

Fig. 16. The amount of power purchased from the DSO in different situations

and at times when production is lacking for various reasons, they can provide their load this way.
noindent According to Fig. 11, most of the purchases from the operator occurred at night and by microgrids 1 and 4, which is due to the lack of power generation by photovoltaic systems. At these times, microgrids 1 and 4 cannot produce power due to lack of sunlight, and the power generated by microgrids 2 and 3 cannot provide the consumption load of all microgrids, so microgrids that lack power must buy power from DSO.
According to Fig. 12, microgrids 1 and 4, which have a photovoltaic system, in the first and last hours of the day when the solar radiation is zero and the power produced by these microgrids is zero, the power required by the operator and other microgrids. In the middle hours of the day, when the production capacity of these microgrids is at its maximum, to prevent the power cut of these renewable sources, microgrids 3, which have microturbines, reduce production capacity purchase the power produced by these renewable sources. Fig. 12 shows the peer-to-peer energy trading between microgrids in the network. As shown in Figure, the amount of power purchased equals the amount of power sold.

To better understand how to supply a load of each microgrid in the peer-to-peer energy exchange process, we examine how to supply a load of microgrid 1, for example.
Exchange power between different microgrids is based on the amount of excess power of that microgrid and the requested power of another microgrid. The more surplus power of one microgrid has a more significant share of supplying the requested power of other microgrids. Fig. 13 shows how to supply the load in microgrid 1 by different sources in the network. In times when the internal production of the microgrid is not responsible for supplying the load, the microgrid provides power shortages through other sources, such as other microgrids and operators.

B) *Result with uncertainty*

In order to investigate the effect of uncertainty of power generation by renewable sources on the value of the objective function, the IGDT method was used. In this method, the decision-maker announces his desired amount and the maximum acceptable amount to reduce production in renewable sources, which is due to the uncertainty of power production by these sources, is obtained by this method, and the decision-maker can decide based on this information.

In this method, the available information and data are considered predicted data and are solved once without considering the uncertainty of the proposed model. This section was examined in Section 3.2(A), and then, using the IGDT method, the maximum acceptable value for reducing production is obtained based on these data.

In this article, 3%,6%,9%, and 12% are examined to reduce the objective function value. The following are the results of these studies.

We first examine the results of a 3% reduction in the objective function. In this case, the decision-maker wants to obtain the maximum acceptable value for reducing the power generated by existing renewable sources so that a maximum of 3% reduces the existing objective function.
After solving the proposed model, considering the uncertainty of renewable sources, in Fig. 14 the state of the model and the solver state show that the model's state is in the optimal state.
The objective function also obtained the value of 0.1259, which means that the available renewable resources can produce up to 12.59% less than their predicted production value mentioned in Section 3.2(A).

Fig. 15 shows the maximum amount that renewable energy sources can produce less than the predicted amounts of their production to reduce the objective function by the specified percentages (3 to 12 percent).
According to Fig. 15, for a 6% reduction in the objective function, renewable resource production can be reduced to a maximum of 23.14%. In other words, if the amount of energy produced by renewable sources in microgrids decreases more than the percentage determined in Fig. 15, the value of the objective function decreases more than the value determined for it. This value is equal to 31.19% and 38.12% to reduce the objective function by a maximum of 9% and 12%, respectively.
In the following, we examine how to provide power in uncertain conditions and reduce renewable energy production. In these conditions, microgrids show more desire to receive power from the operator because the internal power generation does not meet the consumption load.
Due to the reduction in power generation, microgrids increase the amount of power purchased from the operator to supply their consumption load. According to Fig. 16, for a reduction of 12% for microgrids to compensate for the reduction in power of their products, they buy more power from the operator.
According to the results, using the IGDT method, without using the probability density function to produce renewable resources, the maximum reduction in the production of these resources can be achieved for different percentages that the decision-maker intends and use in decisions.

4. Conclusion and Recommendations

In this research, a mechanism for performing peer-to-peer energy exchanges by considering various renewable sources such as photovoltaic systems, wind turbines, and microturbines in the presence of a network operator was presented. The proposed test network is a small sample of natural microgrids in which each microgrid can have its source of energy and load or storage, so it can be somewhat like reality and provide a suitable model for examining the mechanism. Also, using the IGDT method, the uncertainty in power generation by renewable sources in microgrids.

According to the results of this study, the use of peer-to-peer energy exchange methods can be used as a new solution to decentralize power generation and its benefits, such as increasing the flexibility of renewable resources through member participation in power exchange, providing ancillary services to The power grid used to increase the level of access to energy in areas where it is not possible to build traditional power plants, as well as to manage the balance of production and consumption better because all members are connected.

The research conducted in this article can be developed using the following suggestions:

- Consider reliability in peer-to-peer energy exchange processes
- Consider ancillary services such as voltage and frequency control through peer-to-peer energy exchange
- Consider optimal power flow along with existing technical constraints
- Consider the presence of electric vehicles in the network

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