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The Best Planning for a Grid-Connected Microgrid Takes into Account Load and Renewable Generation Uncertainty as Well as Battery Storage

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ABSTRACT

One of the finest solutions for supplying electrical energy in rural places is to use hybrid renewable energy. When using renewable energy sources to meet demand, the right capacity of these sources should be chosen because they are dependent on weather and other factors. It is very impressive to take into account the stochastic nature of wind speed and solar radiation when estimating the potential of renewable energy sources like wind and solar. One issue with employing renewable energy like wind and solar in micro-grids is their inherent unpredictability and random stochastic nature, which made planning and forecasting for such resources challenging. To represent uncertainty in both Wind and PV resources, stochastic programming and probability scenarios are used in this project. Gam's software uses mixed integer programming to determine the best way to program a micro-grid that is connected to the main grid. The Virtual Power Producer uses the main control system to manage optimal production and load control.

1. INTRODUCTION

Micro grid is an effective way of implementing small-scale distributed generation resources in large power grids, in order to be able to provide power for growing loads. The micro-grid serves as an accumulation of electric loads and distributed generation resources (mostly renewable resources such as wind and solar) along with energy storage devices, as an integrated system, generating heat and power. Integrated micro-grid with renewable energy resources and small-scale distributed generation is a safe and effective solution to the energy crisis On the other hand, the desire to install energy storage batteries in the grid has increased due to the challenges of fluctuations in wind turbine production units and solar cell production as renewable energy resources in micro-grids and central micro-grid control., This tendency is due to the need for additional energy storage at times of sufficient access to and use of energy resources when needed and inadequate. For this reason, storages capacity have an important role in reducing micro-grid costs. The problem of reducing operating costs in micro-grid is one of the main tools for optimizing the

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management of smart grids or micro-grid control centers, in which efficient output of storage and distributed generation units with regard to all equal and unequal constraints, reducing grid costs.

The fundamental rule of all power systems is to maintain the balance between load and generation. When it comes to rural and remote areas, there is now a trend toward using tiny, isolated power systems rather than centralized power production systems [1].

The micro-grid can be introduced as a low voltage distribution network, which includes distributed generations, storages and loads, and can be exploited either directly or separately from the network [2]. From power system point of view, the micro-grid can be considered as a controlled element that is connected to the main distribution system. The power may come in or out of the micro-grid. From the point of view of the consumer, the micro-grid can not only supply energy, it can also improve local reliability, reduce pollution, and with exploiting distributed resources, storages, and loads it can participate in providing cheap energy [3].

Due to these features, attentions both in industry and academia are increasingly focused on it [4].

In order to achieve these benefits and provide energy in a reliable, economical and consistent way Several resources of distributed generation, storage and load should be exploited in a coordinated manner. To achieve this, the existence of a planning system for micro-grid is important. This planning system should anticipate the output of renewable resources and market prices, and consider technical constraints to plan, as well as specify the connection of the micro-grid to the main distribution system when participating in the electricity market. Significant efforts have been made to optimize planning and management of the micro-grid [5].

Although numerous studies have been done on cost reduction issues, most of them, regardless of the impact of storage optimization size, have been on reducing the operating costs of micro-grids. By using linear programming, the operating cost of the micro-grid has been optimized and the charging status of the storages has improved [6].

An algorithm for optimizing particles swarm in order to reduce the cost of operation in a micro-grid that has been applied to this problem [7].

By an adaptive mesh algorithm, the strategy and effective operating cost reduction for a micro-grid are estimated [8]. Bee mating optimization algorithm is used to reduce the operating cost of a micro-grid, consisting of a photovoltaic system, a wind turbine, a fuel cell, regardless of the technology of storage batteries, in which active power losses and voltage drops and total energy costs are reduced [9].

An algorithm which is expressed as a multi-objective problem has been developed to minimize the cost and pollution of a grid [10].

The best power and pricing for the MG are obtained using a GA-based optimization approach. The production of regional DGs and power exchanges with the main distribution grid are then optimized to maximize the net present value of the micro-grid during interconnected operation using an objective function based on the overall net present value [11].

2. THE SYSTEM UNDER STUDY

This study focuses on the microgrid of a university in Hungary, as illustrated in Figure 1. By leveraging a virtual power plant (VPP) framework and an integrated development system, the objective is to identify the optimal power management strategy within this small-scale network. Effective utilization of the system requires the VPP to access consistent data inputs to determine the contributions from wind power, photovoltaic (PV) systems, fuel cells, and battery charging/discharging operations.

Wind power generation is highly dependent on weather conditions; however, its production can generally be forecasted over a 24-hour horizon, and dispatch decisions are influenced by its competitive pricing. Similarly, PV output can be predicted based on historical sunlight patterns and expected solar conditions across different hours of the day. Fuel cells, while offering a stable output over time, are constrained by the available hydrogen fuel supply. Battery discharge capacity is governed by both its maximum output limits and the current stored energy levels.

Load predictions are made using multiple models, with many loads adjustable through demand-side management (DSM) strategies. To maintain system stability, the VPP can establish reserve margins, typically maintaining at least 10% of the forecasted load as a minimum reserve.

A case study is conducted on this microgrid, which is interconnected with the upstream power grid. The system integrates wind turbines, PV arrays, fuel cells, diesel generators, and batteries, with the microgrid's 24-hour load profile detailed in Figure 2.

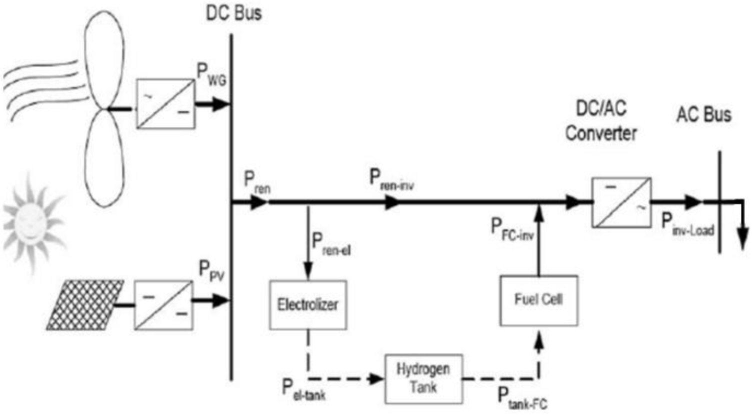

Fig. 1. Under studied micro-grid includes resources like wind, PV, FC and load

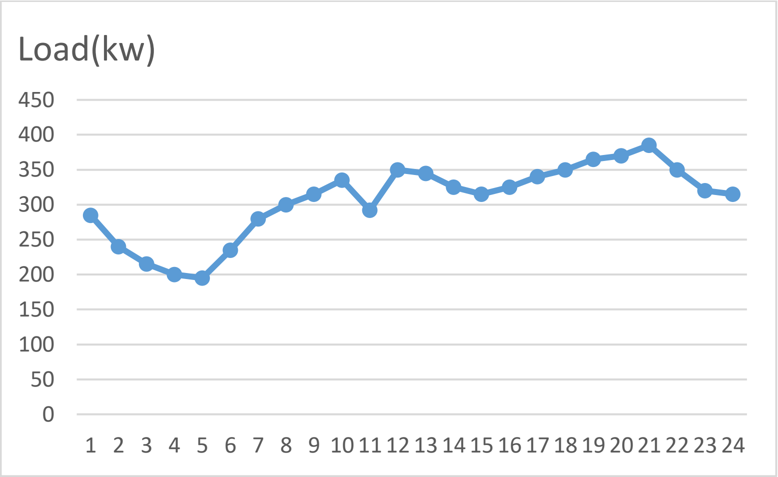

Fig. 2. The micro-grid load pattern in 24 hours

The price of power generation by different units and the cost of undelivered energy are presented in Table 1. These values are assumed to be the same for all study hours and scenarios.

Table 1. Cost of generation power of units

Type of energy	Price(€/kwh)
Wind	0.4
PV	0.4
Fuel cell	0.9
Battery charge	0.4
Battery disCharge	0.6
Undelivered energy	1.5

The electricity selling tariff for a 24-hour period is shown in Figure 3:

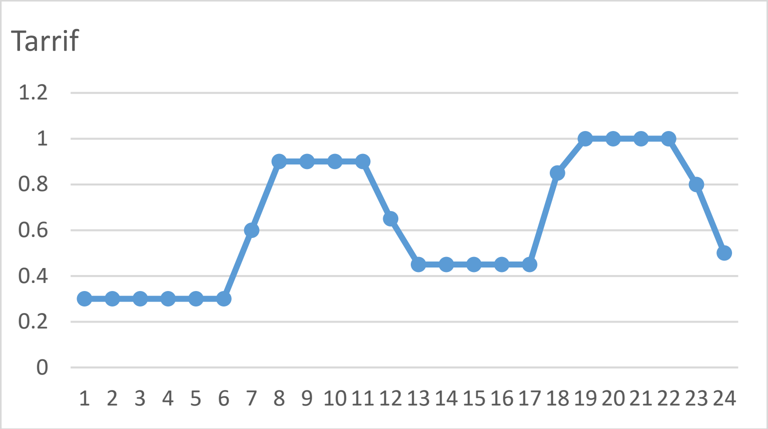

Fig. 3. Power selling tariff

The cost function of the diesel fuel generator is as follows:

$$Cost=\alpha_1*P^2+\alpha_2*P+\alpha_3 \tag{1}$$

For solving the problem, we consider it as a piecewise-linear, containing 100 pieces. The specification of the cost function factors and the minimum-maximum output of the diesel generator are presented in Table 2.

Table 2. Specifications of the cost function of diesel generator

Coefficients	α_1	α_2	α_3	$P_{min(kw)}$	$P_{max(kw)}$
Amount	1.112100	1.2220	3.028	0.1	**0.81**

2.1. Stochastic Programming

Making decision is always a solution to an optimization problem. Now if the inputs of the optimization problem are definite, the decision is optimal and the decision can be made by solving this problem. But the input information is not always definite and it has uncertainties that can be described by the probability distribution function. In such cases, the making decision will not be clear. A solution is the use of expected values, which will be like a definite solution and may not lead to favorable outcomes. But the probabilistic distribution of input information can be estimated with a group of possible events which is likely to occur. This type of programming is called stochastic programming. For example, three sets of input data with three probability occurrence rates, the sum of which will be equal to one, thus we have found an optimal response, this response, while not dependent on any of the inputs solely, is associated with and affects all of them. Since the input information has uncertainty, the objective function is uncertain too and random variables must be classified and each of them must be entered with the probability of its category. Another method for maximizing the objective function is to maximize the expected value for the target function in such a way that the variance is limited. The use of the above-mentioned problem answers is correct when the entire categories of input information are considered with their respective probability. This answer is not the best answer for each entry group, and only when all input groups are considered this answer will be the best answer. The main problem in the Stochastic Programming is its heavy calculations, and these calculations may lead to divergence.

3. PROBLEM FORMULATION

3.1. Random variable

In stochastic programming, each variable with uncertainty is modeled as a random variable, and each random variable is expressed as a series of events or finite scenarios in the form of equations (1).

$$\lambda(ns)=\{\lambda(1),\lambda(2),\ldots,\lambda(ns)\} \tag{2}$$

Each scenario represented by λ (ω) is associated with a probability (π (ω)) which is defined as follows:

$$\pi(\omega)=P(\omega \mid \lambda=\lambda(\omega)) \quad , \quad \sum\pi(\omega)=1 \tag{3}$$

The cumulative probability function of the scenarios can be defined as:

$$F(\eta)=P(\omega \mid \lambda(\omega)\leq\eta) = \sum\_\pi(\omega) \quad , (\omega\in n) \tag{4}$$

The above equations relate to discrete data. To calculate the probability of a discrete random variable, we can use the probability mass function, which is equivalent to the probability density function in the continuous space from the graphical point of view, Pmf is not suitable for displaying discrete variables, and it is recommended to use the adjusted Pdf.

3.2. Objective function

Choosing the appropriate objective function is the most important decision in the optimization problem. Electricity purchasing tariffs (or electricity selling tariffs) are considered in objective function. The main purpose of the cost function is to provide the required power for load with the lowest operating cost. Also, the cost of the diesel generator as well as the cost of the electricity sent to the network is also considered. In addition, the objective function has been rewritten as a stochastic problem with probabilistic scenarios. This objective function is described as follows:

$$\begin{aligned}Cost=\sum_{t=1}^{24} \Big\{ \sum_{s=1}^{Ns} \rho s \times (&Qs(t)+PFC,s(t)\times CFC+Pw,s(t)\times Cw+Ppv,s(t)\times Cpv - PBSC,s(t)\times CBSC \\ &+PBSDC,s(t)\times CBSDC+PUE,s(t)\times CUE-PEE,s(t)\times CEE)\Big\}\end{aligned} \tag{5}$$

Simulation is considered for each specific hour and Ns scenario. Q is the cost of generating power in diesel generator at time t and scenario s.

3.3. Constraints

At any time (t) and in each scenario(s) the balance of power between generators and the load and the grid must be maintained.

$$P_{w,s}(t)+P_{pv,s}(t)+P_{BSDC,s}(t)+P_{FC,s}(t)+P_{D,s}(t)-P_{BSC,s}(t)-P_{EE,s}(t)=P_{Load,s}(t) \tag{6}$$

Power generation of wind turbine should be less than the maximum wind turbine output at any time (t) and scenario (s).

$$P_{W,s}(t)\leq P_{W\ Limit} \tag{7}$$

Power generation of photovoltaic should be less than the maximum photovoltaic output at any time (t) and scenario (s).

$$P_{PV,S}\ (t)\leq P_{PV\ Limit} \tag{8}$$

Power generation of fuel cell should be less than the maximum fuel cell output at any time (t) and scenario (s).

$$P_{FC,S}(t) \le P_{FC\ Limit} \tag{9}$$

Power generation of diesel generator is between its minimum generation and maximum generation.

$$P_{D,S\ Min}(t) \le P_{D,S}(t) \le P_{D,S\ Max}(t) \tag{10}$$

Battery capacity at any time (t) and any scenario (s) is less than its maximum capacity.

$$P_{SB,S}(t) \le P_{SB\ Max} \tag{11}$$

Battery discharge at any time (t) and any scenario (s) is less than the maximum discharge amount of the battery.

$$P_{BSDC,S}(t) \le P_{BSDC\ Max} \times X(t) \tag{12}$$

Battery charge at any time (t) and any scenario (s) is less than the maximum charge amount of the battery.

$$P_{BSC,S}(t) \le P_{BSC\ Max} \times Y(t) \tag{13}$$

In order to eliminate the simultaneous charge and discharge of the battery, and to determine the energy stored in the battery as a time-dependent parameter, the following equation exists:

$$X_s(t)+Y_s(t)=1 \quad , X,Y\in \{0,1\} \tag{14}$$

In other words, at any time (t) and scenario (s), the battery cannot be charged and discharged at the same time. The amount of battery discharge at the moment t and scenario s should be less than the battery storage in the moment before it.

$$P_{BSDC,S}(t) - P_{SB,S}(t-1) \le 0 \tag{15}$$

The amount of battery charge at the moment of t and the scenario of s plus the battery storage in the previous moment should be less than the maximum storage capacity of the battery.

$$P_{BSC,S}(t) + P_{SB,S}(t-1) \le P_{SB\ max} \tag{16}$$

The amount of battery storage at the moment t and scenario of s is equivalent to the battery storage at the moment t-1 plus the battery charge at the moment t minus the battery discharge at the moment t (battery power balance)

$$P_{SB,S}(t) = P_{SB,S}(t-1)-P_{BSDC,S}(t)+P_{BSC,S}(t) \tag{17}$$

The battery storage at zero time is equal to the initial battery power

$$P_{SB}(t=0) = P_{\ initial} \tag{18}$$

The undelivered power at the moment t and scenario s should be less than the amount of load

$$P_{UE,S}(t) \le P_{\ Load(t)} \tag{19}$$

4. STOCHASTIC SCENARIOS IN THE STUDIED GRID

Because solar irradiance and wind speeds fluctuate unpredictably, we adopt a stochastic, scenario-based framework to capture these uncertainties in modeling the power output of both wind turbines and photovoltaic (PV) arrays. In practice, we define three representative weather scenarios each reflecting a distinct combination of irradiance and wind conditions that collectively span the range of likely operating environments. For each scenario sss, we compute the expected power outputs P_s^{wind} and P_s^{PV} using the manufacturers' performance curves and the scenario's meteorological profiles.

To integrate this uncertainty into our optimization, we assign a probability π_s to each scenario, representing its likelihood based on historical weather data and statistical analysis. These probabilities satisfy

$$\sum_{s=1}^{3} \pi_s = 1, \tag{20}$$

ensuring a complete and mutually exclusive partition of the forecast space. Table 3 summarizes the estimated values of π_1, π_2, and π_3. During power scheduling, the micro-grid's objective function and constraint evaluations incorporate these probabilities, effectively weighting each scenario's contribution to expected cost, fuel consumption, and renewable utilization metrics. By optimizing across all scenarios in this probabilistic manner, the resulting generation dispatch plan is robust performing well not only under the most probable conditions but also maintaining reliability and economic efficiency when the weather deviates from the norm.

Table 3. Probability of occurrence of each scenario in each power generation unit

Wind scenarios	**probability**	**PV scenarios**	**Probability**
Scenario1	0.2	Scenario1	**0.15**
Scenario2	0.6	Scenario2	**0.7**
Scenario3	0.2	Scenario3	**0.15**

The new table will include nine scenarios in which probability of occurrence of each scenario is obtained from the product of the probability of previous scenarios in each other. These new scenarios and their probabilities are shown in table4.

Table 4. Scenario probabilities

Final Scenarios	Probability
Scenario1	0.03
Scenario2	0.14
Scenario3	0.03
Scenario4	0.09
Scenario5	0.42
Scenario6	0.09
Scenario7	0.03
Scenario8	0.14
Scenario9	0.03

Scenario 1, combining wind scenario 1 with solar (PV) scenario 1, is defined as the new combined scenario 1. Similarly, combining wind scenario 1 with solar scenario 2 results in the new combined scenario 2, and so forth. The detailed combinations of new scenarios for wind and photovoltaic (PV) systems are presented in Tables 5 and 6, respectively.

Table 5. Wind turbine power generation scenarios

	s1	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**	**s8**	**s9**
t1	97.5	97.5	97.5	130	130	130	156	156	156
t2	112.5	112.5	112.5	150	150	150	180	180	180
t3	105	105	105	140	140	140	168	168	168
t4	120	120	120	160	160	160	192	192	192
t5	75	75	75	100	100	100	120	120	120
t6	90	90	90	120	120	120	144	144	144
t7	112.5	112.5	112.5	150	150	150	180	180	180
t8	135	135	135	180	180	180	216	216	216
t9	127.5	127.5	127.5	170	170	170	204	204	204
t10	120	120	120	160	160	160	192	192	192
t11	90	90	90	120	120	120	144	144	144
t12	97.5	97.5	97.5	130	130	130	156	156	156
t13	112.5	112.5	112.5	150	150	150	180	180	180
t14	132	132	132	176	176	176	211.2	211.2	211.2
t15	138.75	138.75	138.75	185	185	185	222	222	222
t16	90	90	90	120	120	120	144	144	144
t17	97.5	97.5	97.5	130	130	130	156	156	156
t18	105	105	105	140	140	140	168	168	168
t19	127.5	127.5	127.5	170	170	170	204	204	204
t20	142.5	142.5	142.5	190	190	190	228	228	228
t21	90	90	90	120	120	120	144	144	144
t22	127.5	127.5	127.5	170	170	170	204	204	204
t23	97.5	97.5	97.5	130	130	130	156	156	156
t24	112.5	112.5	112.5	150	150	150	180	180	180

Table 6. Pv power generation scenarios

	s1	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**	**s8**	**s9**
t1	0	0	0	0	0	0	0	0	0
t2	0	0	0	0	0	0	0	0	0
t3	0	0	0	0	0	0	0	0	0
t4	0	0	0	0	0	0	0	0	0
t5	0	0	0	0	0	0	0	0	0
t6	3.75	5	6	3.75	5	6	3.75	5	6
t7	7.5	10	12	7.5	10	12	7.5	10	12
t8	22.5	30	36	22.5	30	36	22.5	30	36
t9	45	60	72	45	60	72	45	60	72
t10	75	100	120	75	100	120	75	100	120
t11	97.5	130	156	97.5	130	156	97.5	130	156
t12	105	140	168	105	140	168	105	140	168
t13	112.5	150	180	112.5	150	180	112.5	150	180
t14	105	140	168	105	140	168	105	140	168
t15	97.5	130	156	97.5	130	156	97.5	130	156
t16	75	100	120	75	100	120	75	100	120
t17	45	60	72	45	60	72	45	60	72
t18	22.5	30	36	22.5	30	36	22.5	30	36
t19	7.5	10	12	7.5	10	12	7.5	10	12
t20	3.75	5	6	3.75	5	6	3.75	5	6
t21	0	0	0	0	0	0	0	0	0
t22	0	0	0	0	0	0	0	0	0
t23	0	0	0	0	0	0	0	0	0
t24	0	0	0	0	0	0	0	0	0

5. SIMULATION RESULTS

Simulation is done by using data consist of probability scenarios for wind and the sun, using the objective function, existing data such as the constraints which are proposed power generation, the tariffs for power generation and load. As expected, the result consists of 9 scenarios. For instance, scenario 1 ,4 and 9 are shown in table7, table8 and table9 respectively. The optimal power generation planning in each scenario is based on the generation cost of each generator, which is diesel, wind, photovoltaic, discharger, fuel cell, respectively. In each scenario and at any particular time, all constraints, including the balance of power, are maintained.

Table 7. Power generation of units in scenario1

Hour	Diesel	Wind	PV	Fuel cell	Charge	Discharge	Sell
1	161.8	97.5	0	20.7	0	0	0
2	127.5	112.5	0	0	0	0	0
3	115.6	105	0	0	10.6	0	0
4	115.6	120	0	0	35.6	0	0
5	115	75	0	0	0	0	0
6	136.25	90	3.75	0	0	0	0
7	160	112.5	7.5	0	0	0	0
8	161.8	135	22.5	80	0	0	99.3
9	161.8	127.5	45	80	0	0	94.3
10	161.8	120	75	80	0	0	106.8
11	161.8	90	97.5	80	0	0	139.3
12	147.5	97.5	105	0	0	0	0
13	125	112.5	112.5	0	0	0	0
14	114.95	132	105	0	21.95	0	0
15	115.6	138.75	97.5	0	31.85	0	0
16	161.8	90	75	3.2	0	0	0
17	161.8	97.5	45	35.7	0	0	0
18	161.8	105	22.5	60.7	0	0	0
19	180	127.5	7.5	80	0	50	85
20	180	142.5	3.75	80	0	50	86.25
21	180	90	0	80	0	50	20
22	180	127.5	0	80	0	50	87.5
23	161.8	97.5	0	70.7	0	0	0
24	161.8	112.5	0	45.7	0	0	0

By analyzing the optimal scenario planning, several key factors help validate the simulation results:

- All problem constraints are successfully satisfied.
- Optimal power generation is achieved in each scenario, taking into account the cost hierarchy of the generators namely diesel, wind, photovoltaic (PV), battery discharge, and fuel cell, respectively.
- The scheduling of wind and PV units is closely aligned with the predicted load demand.
- Battery charging consistently occurs during periods of low demand (2:00–5:00 AM and 1:00–3:00 PM), when electricity purchase from the grid is most cost-effective. This strategy is economically justified, as the cost of purchasing energy during these low-demand hours is lower than the potential revenue from selling energy back to the grid.
- Energy sales to the grid are maximized during high-price periods, specifically between 8:00 AM–12:00 PM and 7:00–10:00 PM.
- Maximum battery discharge is used to meet peak load demands between 7:00 PM and 10:00 PM, as well as to supply energy for sale to the grid during the profitable window of 8:00–11:00 AM.

Table 8. power generation of units in scenario4

Hour	Diesel	Wind	PV	Fuel cell	Charge	Discharge	Sell
1	146.4	130	0	0	0	3.6	0
2	98.8	150	0	0	8.8	0	0
3	98.8	140	0	0	28.8	0	0
4	98.8	160	0	0	58.8	0	0
5	97.2	100	0	0	7.2	0	0
6	105.8	120	3.75	0.45	0	0	0
7	122.5	150	7.5	0	0	0	0
8	161.8	180	22.5	80	0	50	194.3
9	161.8	170	45	80	0	50	186.8
10	161.8	160	75	80	0	18.6	165.4
11	161.8	120	97.5	80	0	50	219.3
12	115	130	105	0	0	0	0
13	114.2	150	112.5	0	26.7	0	0
14	114.2	176	105	0	65.2	0	0
15	114.2	185	97.5	0	76.7	0	0
16	135	120	75	0	0	0	0
17	161.8	130	45	3.2	0	0	0
18	161.8	140	22.5	25.7	0	0	0
19	180	170	7.5	80	0	50	127.5
20	180	190	3.75	80	0	50	133.75
21	180	120	0	80	0	50	50
22	180	170	0	80	0	50	130
23	161.8	130	0	38.2	0	0	0
24	161.8	150	0	8.2	0	0	0

Table 9. power generation of units in scenario9

Hour	Diesel	Wind	PV	Fuel cell	Charge	Discharge	Sell
1	119.8	156	0	0	0	4.2	0
2	71.2	180	0	0	11.2	0	0
3	70.8	168	0	0	28.8	0	0
4	70.8	192	0	0	62.8	0	0
5	70.8	120	0	0	0.8	0	0
6	80.6	144	6	0	0.6	0	0
7	89	180	12	0	0	0	1
8	161.8	216	36	80	0	50	243.8
9	161.8	204	72	80	0	50	247.8
10	161.8	192	120	80	0	50	273.8
11	161.8	144	156	80	0	50	301.8
12	101.6	156	168	0	0	0	75.6
13	54	180	180	0	64	0	0
14	54	211.2	168	0	103.2	0	0
15	54	222	156	0	32.8	0	79.2
16	66	144	120	0	0	0	0
17	111.4	156	72	0.6	0	0	0
18	149.2	168	36	0	0	0	3.2
19	180	204	12	80	0	50	166
20	180	228	6	80	0	50	174
21	180	144	0	80	0	50	74
22	180	204	0	80	0	50	164
23	161.8	156	0	12.2	0	0	0
24	139.4	180	0	0.6	0	0	0

6. CONCLUSION

Hybrid power systems integrate multiple components — including generation units, storage systems, control mechanisms, and power management systems — to produce electricity efficiently. As the role of micro-grids continues to expand in the electricity sector, one of the most critical challenges is the optimal distribution of power among the various generation units. Addressing this challenge is essential for ensuring reliability, cost-effectiveness, and sustainability in micro-grid operations.

This paper investigated the optimal planning of a grid-connected micro-grid using a mixed-integer programming approach. The studied micro-grid incorporates renewable energy sources such as wind and solar, alongside batteries and fuel cells. A case study was conducted on a real system at a university in Hungary, with the goal of minimizing operational costs. The virtual power plant (VPP) within the system uses centralized control to manage both power generation and load distribution optimally.

Simulations were performed using GAMS software, applying both the CPLEX solver and a genetic algorithm for comparison. The calculated operational cost over a 24-hour period was $3183 using the proposed method and $3352 using the genetic algorithm — yielding a cost savings of $169 with the proposed optimization approach. These results highlight the efficiency and economic advantages of the proposed method over more conventional optimization techniques.

7. SUGGESTIONS FOR FUTURE WORK

- Incorporate advanced load forecasting methods such as neural networks and time-series models to enhance the accuracy and reliability of generation planning.
- Apply time- and energy-based variable tariffs to promote a dynamic balance between generation and consumption, aligning economic incentives with operational goals.
- Integrate advanced metering infrastructure (AMI) into the simulation framework to enable real-time data exchange and improve control and responsiveness in smart grids and distributed micro-grids.
- Design a secondary control layer to maintain the balance between generated and consumed power, particularly during micro-grid islanding or separation events.
- Develop intelligent loss control mechanisms for the simultaneous coordination of voltage and frequency across the system, ensuring stable and efficient operation.
- Simulate communication links between micro-grid components to better understand the interactions, dependencies, and vulnerabilities across the system, supporting more robust and adaptive control strategies.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFRENCESS

[1] Morais, H., Kádár, P., Faria, P., Vale, Z. A., & Khodr, H. M. (2010). Optimal scheduling of a renewable micro-grid in an isolated load area using mixed-integer linear programming. *Renewable Energy, 35*(1), 151–156. https://doi.org/10.1016/j.renene.2009.02.031

[2] Liu, G., Xu, Y., & Tomsovic, K. (2016). Bidding strategy for microgrid in day-ahead market based on hybrid stochastic/robust optimization. *IEEE Transactions on Smart Grid, 7*(1), 227–237. https://doi.org/10.1109/TSG.2015.2476669

[3] Tsikalakis, A. G., & Hatziargyriou, N. D. (2011). Centralized control for optimizing microgrids operation. In *2011 IEEE Power and Energy Society General Meeting* (pp. 1–6). IEEE. https://doi.org/10.1109/PES.2011.6039737

[4] Agrawal, M., & Mittal, A. (2011). Micro grid technological activities across the globe: A review. *International*

Journal of Research and Reviews in Applied Sciences, 7(2), 147–152.

[5] Gu, W., Wu, Z., Bo, R., Liu, W., Zhou, G., Chen, W., & Wu, Z. (2014). Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review. *International Journal of Electrical Power & Energy Systems, 54*, 26–37. https://doi.org/10.1016/j.ijepes.2013.06.028

[6] Sharma, S., Bhattacharjee, S., & Bhattacharya, A. (2016). Grey wolf optimisation for optimal sizing of battery energy storage device to minimise operation cost of microgrid. *IET Generation, Transmission & Distribution, 10*(3), 625–637. https://doi.org/10.1049/iet-gtd.2015.0429

[7] Moghaddam, A. A., Seifi, A., & Niknam, T. (2012). Multi-operation management of a typical micro-grids using particle swarm optimization: A comparative study. *Renewable and Sustainable Energy Reviews, 16*(2), 1268–1281. https://doi.org/10.1016/j.rser.2011.10.002

[8] Mohamed, F. A., & Koivo, H. N. (2010a). System modelling and online optimal management of MicroGrid using mesh adaptive direct search. *International Journal of Electrical Power & Energy Systems, 32*(5), 398–407. https://doi.org/10.1016/j.ijepes.2009.11.003

[9] Niknam, T., Kavousifard, A., Tabatabaei, S., & Aghaei, J. (2011). Optimal operation management of fuel cell/wind/photovoltaic power sources connected to distribution networks. *Journal of Power Sources, 196*(20), 8881–8896. https://doi.org/10.1016/j.jpowsour.2011.05.081

[10] Niknam, T., Azizipanah-Abarghooee, R., & Narimani, M. R. (2012). An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation. *Applied Energy, 99*, 455–470. https://doi.org/10.1016/j.apenergy.2012.04.017

[11] Mohamed, F. A., & Koivo, H. N. (2010b). System modelling and online optimal management of MicroGrid using mesh adaptive direct search. *International Journal of Electrical Power & Energy Systems, 32*(5), 398–407. https://doi.org/10.1016/j.ijepes.2009.11.003