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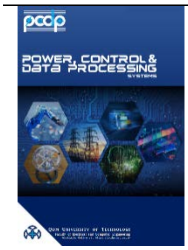

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Management of Distributed Energy Resources for Reducing Environmental Pollution and Enhancing Economic Efficiency

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ABSTRACT

Today, energy management in a microgrid requires development to improve the management of produced and consumed energy while maintaining network balance on both supply and demand sides. This paper proposes an optimal method to reduce microgrid costs, incorporating a diesel generator, wind unit, solar panel, combined heat and power (CHP) unit, and battery storage. The proposed method is solved optimally using the Particle Swarm Optimization (PSO) algorithm. The main objectives of this research include reducing the costs of distributed generation resources, minimizing environmental pollution in the microgrid system, and enhancing network efficiency. To demonstrate the positive impact of the proposed method, various tables and charts related to network requirements, solar radiation angle, and wind speed are utilized. By implementing the proposed method in hybrid microgrids using MATLAB software, the effectiveness of the optimization approach is shown, achieving a 39% reduction in environmental pollution and a 23% reduction in fuel consumption in the optimal state.

Keywords: Renewable Energy, Environmental and Economic Analysis, Sustainable Energy Management, Microgrid, CO2 Emissions

1 Introduction

In smart grid applications, the first step is to create a platform for disconnecting the system from the main distribution network and operating in islanded mode, which presents a significant opportunity for distributed power generation using photovoltaic panels, battery energy storage systems, diesel generators, wind turbines, and CHP units [1]. In [2] examines various loads and distributed energy resources in a microgrid. In ports, microgrids are used to reduce environmental pollution and fossil fuel consumption due to their energy sustainability, high security, and lower maintenance costs [3]. In [4], a unit commitment (UC) problem is addressed in the presence of energy storage systems (ESS) and photovoltaic (PV) arrays, considering battery storage and power injection from the upstream network. This paper employs a multi-source energy management method and the PSO algorithm to simplify and accelerate response to demand while reducing pollution. In [5], an energy hub system is used to integrate electrical, thermal, cooling, and water structures to enhance modern distribution systems and improve efficiency using an LSTM neural network to control and predict groundwater consumption, reducing groundwater extraction. Multi-source microgrids, consisting of two or more renewable energy sources and energy storage systems, are used to mitigate fluctuations in renewable energy sources, improving system performance and flexibility [6]. In [7], a multi-source microgrid including battery storage, solar panels (PV), wind turbines, and diesel generators is utilized. In [8], a scheduling algorithm is applied to energy storage systems. In [9], a mixed-integer quadratic programming (MIQP) optimization algorithm is used for optimizing battery storage systems within operational constraints. In [10], a stochastic planning method for energy storage systems is proposed using Monte Carlo simulation, considering technical and economic uncertainties. Reference [11] examines cost reduction and environmental pollution mitigation, proposing two evaluation methods considering utility rates and transportation constraints to improve distributed energy systems. In [12], a discharge method for energy storage systems is used, considering self-consumption in residential buildings with PV systems to reduce electricity costs.

The Particle Swarm Optimization (PSO) algorithm is much simpler compared to similar optimization algorithms, requires fewer adjustable elements, and offers faster response times, making it suitable for power system network optimization.

In the PSO algorithm, the initial particles are generated based on the size of the distributed energy resources. Additionally, the given input power from the grid must meet the total estimated demand in the microgrid. If the total power generated within the microgrid satisfies the demand, the objective function will be calculated. Each particle improves only its own position and velocity according to equations (1) and (2).

The PSO algorithm parameters in this study include:

- Number of iteration
- ns: 160
- Number of particles: 40
- Learning coefficients (D1 and D2): 2
- Inertia weight: 0.7

The enhanced PSO-based method is implemented in MATLAB for optimal planning and operation of the hybrid microgrid system.

$$L_{t+1}=w\times L_t+D_1(P_{Pbest}-X_t)+D_2(P_{gbest}-X_t) \qquad (1)$$

$$X_{t+1}=X_t+L_{t+1} \qquad (2)$$

In the PSO algorithm, **Pbest** (Personal best) is considered the best individual solution for each particle, while **Gbest** (Global best) represents the best global solution found by the entire swarm.

2 Constraints

The total power generated by the energy sources specified in this article, combined with the energy stored in the battery, must fully supply the microgrid's demand.

The optimization problem constraints include:

1. The power output limits of energy sources,
2. The available energy in the battery,
3. Power balance within the microgrid.

The power output constraint for distributed energy resources (DERs) stipulates that the energy generated by each source at time (t) is bounded by the minimum and maximum power output of the respective energy source model, as defined in Equation (3).

$$P_{Di}^{min}\leq P_{Di}(t)\leq P_{Di}^{max} \qquad (3)$$

The energy stored in the battery depends on the minimum and maximum reliable storable energy limits, as specified in Equation (4):

$$E_{battery}^{min}\leq E_{battery}(t)\leq E_{battery}^{max} \qquad (4)$$

$$E_{battery}^{min}=(1-\mu)\times E_{battery}^{max} \qquad (5)$$

In Equation (5), the minimum Ebattery is calculated as the maximum allowable battery discharge level (μ).

Table1: weakness and strengths of mentioned literatures with proposed method

References	Energy Storage	Renewable Resources	Fixed DER unit	Environment	Load growth
20	✓	Pv/wind	-	-	-
21	✓	Pv/wind	-	-	-
22	✓	Pv/wind	-	✓	-
23	✓	pv	-	-	-
Proposed Method	✓	Pv/wind	Diesel gen.	✓	✓

This paper is organized into four main sections:

- Optimization of battery energy storage systems in hybrid microgrids, considering grid-connected and islanded operation conditions.
- Presentation of an optimization algorithm to simplify the proposed objective function.

- Consideration of economic and environmental issues.
- Analysis of various distributed energy sources to meet consumer needs.

The paper is structured into five sections: Section 1 discusses the components of the hybrid microgrid and their modeling. Section 2 presents the proposed method, tables, charts and required data to evaluate the improvements of the proposed model. Section 3 analyzes the results across seven examined cases, and Section 4 provides the conclusion.

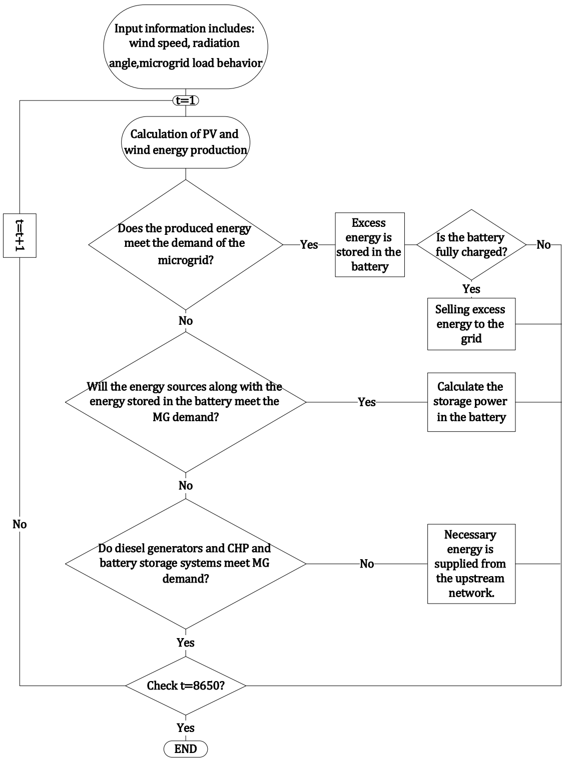


Figure 1: Proposed Flowchart for Microgrid Energy Management Structure

In a microgrid system, all energy produced by distributed resources is stored in the energy storage system (battery), and the exchanged power with the grid is used to meet system demand. Initially, distributed resources supply the entire network load. When the output power of distributed resources exceeds consumption needs, the surplus energy is stored in the battery. If excess power remains, it is sold to the upstream grid. However, when microgrid demand exceeds energy production, the stored energy in the battery is utilized first, followed by the diesel generator and CHP unit. If the combined power production is insufficient, the required energy is sourced from the upstream grid. Figure 1 illustrates the flowchart of the energy management system.

Table 2: Network system equipment costs

model	Capital cost ($/kw)	O&M ($/kw)	Replacement cost ($/kw)
Battery	140	14	140
D.G	200	0.03	200
Wind unit	1740	90	1300
Solar unit	1100	2	1100

The cost per unit of distributed energy resource (DER) includes capital, maintenance, and relocation expenses. The cost data for each energy resource are compiled in Table 2.

3 Modeling of Hybrid Microgrid Components

3.1 Solar Panel (PV)

The power generated from solar energy is directly related to the solar radiation angle and follows Equation (13) [13]:

$$P_{PV}=\alpha_{PV}\times N\times M_{pv}\times \frac{R_t}{R_{tc}} \tag{13}$$

3.2 Battery Energy Storage System

According to Equation (6), the energy produced by the battery at time (t) depends on the previous storage state, total system load, and energy produced by renewable sources:

$$S_{battery}=S_{battery}(t\text{-}1)+\left(\frac{Sr(t-1)-Sl(t)}{\lambda dc/ac}\right)\times \lambda ch \tag{6}$$

In Equation (6), battery charging efficiency, Sr (total energy produced by renewable sources) and Sl (total energy required by the microgrid system) are considered [14].

3.3 Diesel Generator (Dgen)

This system is modeled based on output power, fuel consumption, and Equation (7):

$$F(t)=\beta_1\times P(t)+\beta_2\times P_r \tag{7}$$

Here, P(t) and Pr are the nominal electrical power and power produced by the diesel generator at time (t), respectively. β1 and β2 are fuel consumption curve coefficients, set as β1 = 0.240 and β2 = 0.085 [15].

3.4 Combined Heat and Power (CHP)

The efficiency of a CHP plant can be calculated using Equation (8):

$$CHP=(J_e+E_O)/F_i \tag{8}$$

Here, Eo is the net thermal energy output, Fi is the total fuel energy input, and Je is the electrical energy output [16].

The costs imposed on the microgrid, including power production costs by CHP systems and heat production costs by boilers, are shown in the following equations:

$$N_{CHP}=\left(\frac{Pchp}{\eta_{chp}}*gp\right)+P_{chp}*OM^{chp} \tag{9}$$

$$\eta_{chp}=\frac{1}{\frac{HR^{CHP}}{3600}} \tag{10}$$

$$Cost^{b}=\frac{b_h}{\eta^b}*gp \tag{11}$$

In Equation (9), NCHP is the cost of power production by the CHP system, Pchp is the active power of the CHP system, gp is the gas price ($/kWh), O&Mchp is the operation and maintenance cost of the CHP system ($/kWh), and η is the power efficiency of the CHP system. In Equation (10), HRCHP is the heat produced by the CHP system. In Equation (11), the cost of heat from the boiler, the heat produced by the boiler, and the boiler efficiency are considered [17].

3.5 Wind Turbine (WT)

In Equation (12), the output power is calculated based on power curves. When the wind speed is below the cut-in speed, the generated power is zero due to insufficient wind speed. In the second case, if the wind speed is between the cut-in and rated speeds, the power produced by the wind turbine is a function of wind speed. In the third case, the generated power equals the rated output. In the fourth case, if the wind speed exceeds the cut-out speed, the wind turbine is shut down to prevent mechanical damage:

$$\mathrm{P_w(t)}=\left\{\begin{array}{ll} 0 & s < s_c . s > s_{co} \\ p_w\left(\frac{s-s_c}{s_r-s_c}\right) & s_c \leq s < s_r \\ p_r & s_r \leq s \leq s_{co} \end{array}\right\} \quad (12)$$

Here, *Pw* is the maximum wind unit power (kW), *S* is the wind speed, *Sr* is the rated wind speed (m/s), *Sco* is the cut-out wind speed, and *Sc* is the cut-in wind speed [18].

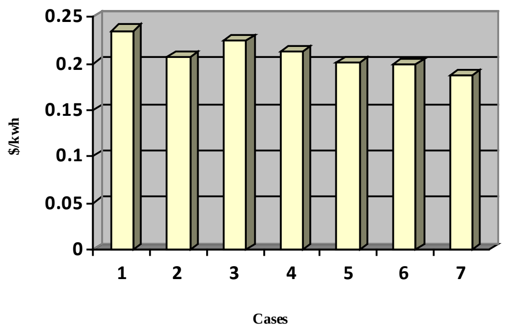
To better illustrate and evaluate the effectiveness of the proposed method, Table 3 provides a comparison based on per-unit cost, fuel consumption, and CO2 emissions among various possible solutions.

Table 3: presents simulation results for various microgrid (MG) configurations [19]

Case	Configuration	Fuel (liters)	Emissions (kg)	Energy Cost ($/kWh)
1	Diesel Generator	3.25	7.121	0.2354
2	Diesel Generator / Main Grid	3.125	6.8425	0.2075
3	Grid / Battery / Wind	0	0	0.2245
4	Grid / Battery / PV	0	0	0.2128
5	Grid / Battery / Wind / PV	0	0	0.2011
6	Grid / Diesel / Battery / Wind / PV	1.431	5.1157	0.1985
7	Grid / Battery / Wind / PV / CHP	1.3987	4.8875	0.1874

The energy cost for various configurations in Table 3 is illustrated in Figure 2(a). It can be concluded from this figure that Case 7 provides the optimal configuration due to its lower energy cost and emissions. The CO₂ emissions are depicted in Figure 2(b), indicating that Cases 3, 4, and 5 result in zero emissions, as they rely solely on renewable sources with no fossil fuel consumption. Compared to Case 1, Case 7 achieves a 39% reduction in CO₂ emissions, equivalent to a decrease of 2.2335 kg.

The improvement of system components in Configuration 7 compared to results obtained by the Genetic Algorithm (GA) is presented in Table 4.



a.

b.

Figure 2: Comparative analysis of different microgrid configurations: a) Total Energy Cost per kWh, b) Total CO₂ Emissions.

Table 4: Optimization of MG Network Components

Algorithm	PV (kW)	Wind (kW)	Diesel Gen. (kW)	Battery (kWh)	Fuel (L)	Cost ($)	CHP (kW)
PSO	440	424	680	772	1.424	20.5	524
GA	436	416	681	770	1.427	20.6	519

The convergence characteristics of the proposed optimal configuration (Configuration 7 from Table 3) are illustrated in Figure 3.

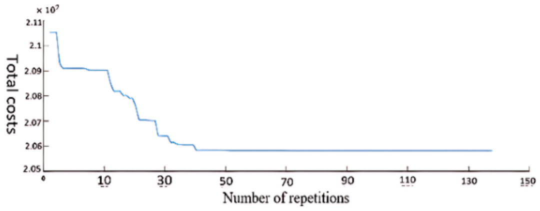


Figure 3: Convergence Characteristics of the Proposed Algorithm (PSO)

The proposed algorithm provides the best solution, optimal results, and fastest response because it reaches the optimal solution with fewer iterations compared to the Genetic Algorithm.

4 Proposed Method

To optimize the sizing of distributed energy units in the microgrid, the Particle Swarm Optimization (PSO) algorithm is used. The optimization focuses on the battery storage system to reduce environmental pollutants, enhance renewable energy efficiency, and lower microgrid system costs. The calculated sizes, combined with the power injected from the main grid, must meet all microgrid demands. However, the obtained sizes are not acceptable if they fail to meet the entire microgrid power demand. If the total power generated in the microgrid meets the required demand, the objective function is used for calculations. In the first stage, excess generated power compared to the network demand is stored in batteries and used during peak consumption periods when energy sources cannot meet the demand. Excess power, if not used, is sold. When the total generated power is less than the network demand, power is injected from the upstream grid. This paper's goal is to reduce the overall system cost, which is calculated using equation (14)

TN=NPV+NWind+NBattery+NGenerator+NFuel+NBuy+NCHP +NCO2- NSell (14)

T_N represents all costs incurred by the system over its useful life.

The system's economic evaluation employs the Net Present Cost (N_{PV}-N_{Wind}-$N_{Battery}$-$N_{Generator}$-N_{Fuel}-N_{Buy}-N_{CHP}-N_{CO2}-N_{Sell}) framework to discount all future cash flows to present value terms, encompassing:

- Capital expenditures (CapEx): equipment procurement, installation, and replacement
- Operational expenditures (OpEx): fuel, maintenance, and grid interaction costs
- Environmental externalities: carbon emission penalties

The Net Present Cost thus provides a holistic metric for comparing alternative microgrid configurations.

In this paper, the goal is to reduce environmental pollutants and the total system cost. The net cost (NC_D) of each distributed energy resource is expressed in Equation (15). In Equation (15), C_D is the initial cost, R_D is the replacement cost, and $O\&M_D$ is the operation and maintenance cost for each distributed energy resource. N_D is the optimal value, R is the system lifespan, L is the lifespan of each distributed energy resource, and I_R is the discount rate [18-25].

$$\mathrm{NCD} = \mathrm{ND} \times \left[C_D + R_D \times \sum_{n=1}^{m} \frac{1}{(1+I_R)^{L\times n}} + \left(O\&M_D \times \frac{(1+I_R)^R-1}{I_R\times(1+I_R)^R}\right)\right] \tag{15}$$

$$\mathrm{N_{Fuel}} = \sum_{t=1}^{7320}[A(t) \times \alpha_{Fuel}] \times \frac{(1+I_R)^R-1}{I_R\times(1+I_R)^R} \tag{16}$$

In Equation (16), the fuel cost and *A(t)* represent the fuel consumption of a diesel generator at time t. The net cost of CO_2 emissions due to fuel consumption (N_{CO2}) is shown in Equation (17), where be is the specific CO_2 emission rate, a constant value of 2.7, and the CO_2 emission penalty is expressed in ($/kg).

$$\mathrm{NC_{CO2}} = \sum_{t=1}^{7320}[b_e \times A(t) \times \beta_E] \times \frac{(1+I_R)^R-1}{I_R\times(1+I_R)^R} \tag{17}$$

$$\mathrm{NC_{buy}} = \sum_{t=1}^{7320} p_{buy}\,(t) \times \beta_{buy} \times \frac{(1+I_R)^R-1}{I_R\times(1+I_R)^R} \tag{18}$$

$$\mathrm{NC_{sell}} = \sum_{t=1}^{7320} p_{sell}\,(t) \times \beta_{sell} \times \frac{(1+I_R)^R-1}{I_R\times(1+I_R)^R} \tag{19}$$

The net cost of energy exchanged with the upstream grid is calculated in Equations (18) and (19). The energy received from the upstream grid at time t and the cost of electrical energy per kWh are considered. In Equation (19), the energy sold to the upstream grid and the cost of sold energy per kWh are calculated.

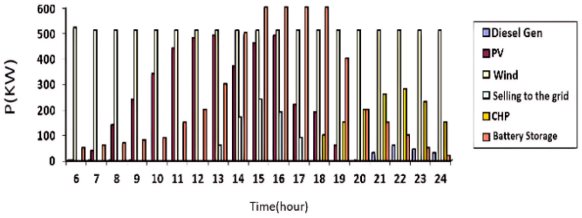


Figure 4: Combined Power Generation over a 24-Hour Period

According to Figure 4, the combined power generation over a 24-hour period on a windy day is shown, where the wind unit generates energy at all times.

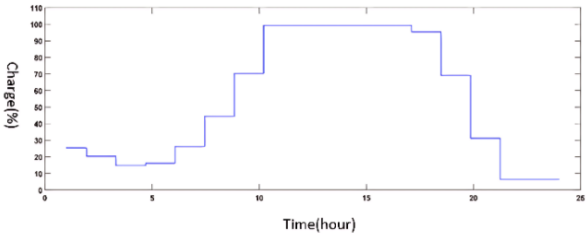


Figure 5: The amount of battery charge for a 24-hour period

In Figure 5 shows the battery charge from 20% to 100% with the lowest level and full charge mode.

Table 5: Effects of Implementing the Battery Storage System on Network Performance

Case	Renewable Impact (%)	Fuel Consumption (Liters)	Emissions (kg)
Diesel Generator	0%	3.25	7.121
CHP	35%	2.42	5.204
Improvement with Battery	23%	1.431	5.1157
Improvement without Battery	17%	1.5429	5.3387

Table 6: The optimal model and its effectiveness on the system

Mode	Fuel(liter)	Emissions (kg)
Diesel Generator	57.78	174
Optimal structure	33.25	120

As observed in Figure 7, we conclude that considering the optimal operating mode for each distributed energy resource (DER) model annually leads to significant fuel consumption reduction. Correspondingly, the reduction in fuel consumption results in a proportional decrease in emissions.

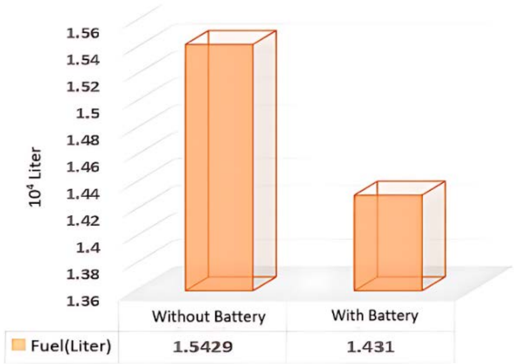


Figure 6: Comparison of Fuel Consumption in Two Scenarios

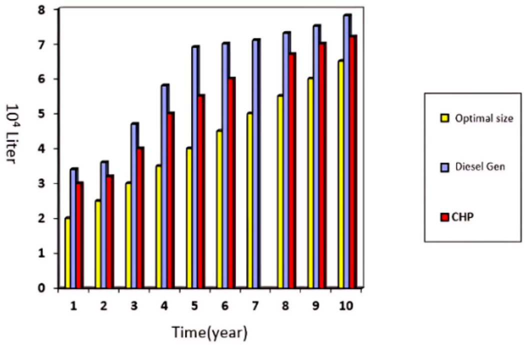


Figure 7: Fuel consumption rate for different operating modes per year

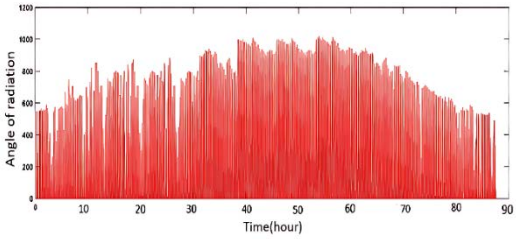


Figure 8: Solar Irradiance over an Annual Period [17]

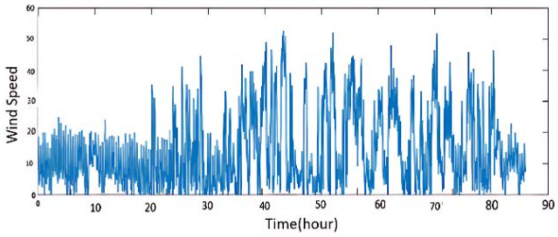


Figure 9: Wind Speed over an Annual Period [17]

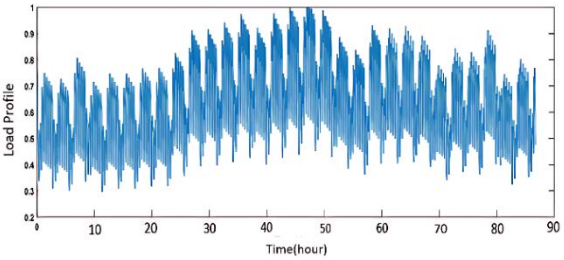


Figure 10: Load Profile over an Annual Period [17]

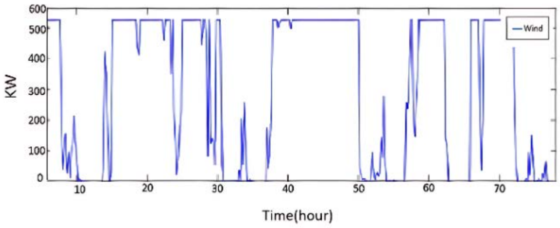


Figure 11: Output Pattern of the Wind Energy Section [18]

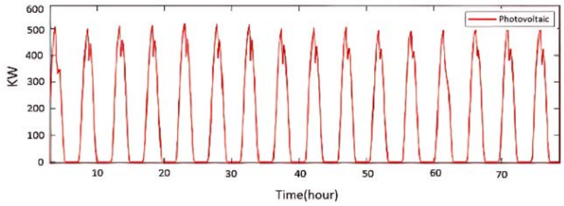


Figure 12: Output Pattern of the Photovoltaic Energy Section [18]

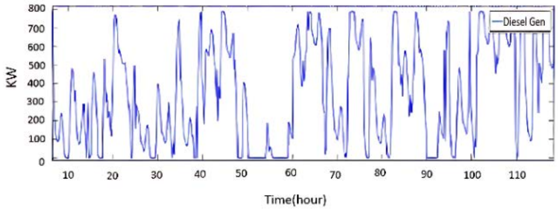


Figure 13: Diesel Generator Energy Output [18]

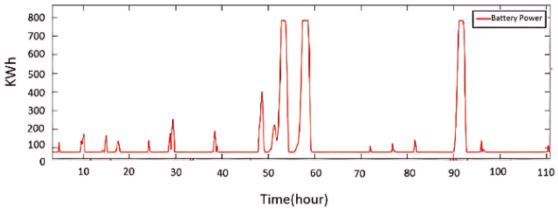


Figure 14: State of Charge (SOC) [18]

5 Results Analysis

The obtained values were analyzed for seven configurations, and the impacts of the energy storage system on system parameters, component improvements, and CO_2 emissions were evaluated. The simulation results are discussed in this section.

5.1 Microgrid Component Improvements

Different configurations of various distributed energy units to meet the demands of load units are classified as follows:

1. Diesel Generator: Has the highest fuel consumption and emissions.
2. Diesel Generator/Main Grid: Produces fewer emissions and consumes less fuel compared to the first configuration.
3. Wind Unit/Main Grid/Battery Storage System: Excess power generated by the wind unit is stored in batteries for injection during peak load periods.

4. Solar Panel/Main Grid/Battery Storage System: Solar panels and the main grid are responsible for meeting consumption needs. Excess power generated by solar panels is stored in batteries.

5. Solar Panel/Wind Unit/Battery Storage System/Main Grid: Power generated by solar panels, wind turbines, battery storage, and the main grid meets network demands. During low consumption periods, excess power from solar panels and wind turbines is used to charge batteries.

6. Solar Panel/Diesel Generator/Wind Unit/Battery Storage System/Main Grid: All mentioned components are responsible for meeting residential or network load demands.

7. Solar Panel/Wind Unit/Combined Heat and Power (CHP)/Battery Storage System/Main Grid: All units supply power to meet consumer needs. Excess power from solar panels, wind units, and CHP is stored in batteries and injected into the network during peak consumption to reduce environmental emissions and fuel consumption.

Based on the above configurations, analyses and results were evaluated in terms of CO_2 emissions, fuel consumption, and energy costs. The cost of each distributed energy unit includes capital, maintenance, and replacement costs. Cost information for each energy source is compiled in Table 2 [19]. Input data, including solar irradiance, financial and economic data, wind speed, and network demand, are sourced from [18]. Solar irradiance, wind speed, and load profile over a one-year period are depicted in Figure 6-8 [17]. Figure 8-13 show the output power of wind, solar, and diesel generator units. As mentioned earlier, excess power from wind and solar units is stored in batteries and injected into the network when needed [18]. Battery energy variations are shown in Figure 14. From Figure 14, it can be inferred that during hours 60 to 70, the total power generated by distributed sources cannot meet network demands, and battery capacity is at its lowest. In such cases, energy is sourced from the main grid to meet network needs.

5.2 Impacts of Battery Energy Storage on the Microgrid

Fuel consumption and CO_2 emissions for different configurations are compiled in Table 5. According to this table, using batteries in the microgrid system reduces fuel consumption by 23% compared to Configuration 1 (Diesel Generator). Without batteries, fuel consumption and CO_2 emissions are reduced to a lesser extent. Figure 6 shows fuel consumption for different conditions. After integrating the battery storage system, annual fuel consumption decreases to approximately 112 liters compared to the scenario without batteries. Implementing the battery storage system and CHP in the microgrid reduces environmental emissions (CO_2) and fuel consumption in diesel generators and CHP. To demonstrate the positive impact of the proposed optimization method, total fuel consumption for different configurations was analyzed and compared. With the optimal model in place over multiple years, fuel consumption is reduced by 33.25 liters, as shown in Table 6.

6 Conclusion

This paper proposes an optimal method for managing electricity in a microgrid with various distributed generation sources. The primary goal of this research is to reduce environmental emissions (CO_2), lower microgrid-related costs, and enhance economic efficiency. Considering configuration 7 according to Table 3 and comparing it with the results of other existing configurations shown in Figure 2, it can be concluded that the proposed configuration takes steps towards reducing costs and CO2 emissions. To achieve these objectives, the Particle Swarm Optimization (PSO) algorithm was used to simplify and solve the proposed objective function. In this paper, the optimal battery storage system was evaluated for different microgrid conditions, and results show that using batteries reduces emissions and fuel consumption. Conversely, not using batteries increases fuel consumption and CO_2 emissions. Simulation results indicate that the new distributed generation model can improve microgrid performance and achieve environmental and economic goals.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

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