Optimal Configuration of Resilient and Reliable Hybrid Power System for Hassled Territories: Gaza Strip a Study Case

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***Abstract*—Power systems could be subjected to partial and/or full damage due to natural or human made causes in stressed territories, which results in tremendous disasters and increases causalities and mortalities. This mandates intelligent design for the power systems in these territories. The article proposes the intelligent Microgrid (MG) for implementing the power system of hassled territories such as Giza Strip in Palestine. The article also proposes the optimal configuration of a MG that fulfils the requirements of a small town/zone. The configuration is implemented via Optimization. The results confirm the applicability of the proposed MG for hassled territories. The proposed MG could result in a sustainable and affordable power supply even during severe and outrages operating conditions.**

***Keywords*—** Renewable Energy Sources, Optimization, Energy, Power System, Sustainability, Gaza.

List of symbols

$P_{PV,h}$ (kW): Power dispatched from PV system at hour h.
$P_{Wind,h}$ (kW): Power dispatched from the wind turbine at hour h.
$P_{BatCharge,h}$ (kW): Power used to charge the battery at hour h.
$P_{BatDischarge,h}$ (kW): Power discharged from the battery at hour h.
$P_{Diesel,h}$ (kW): Power generated by the diesel generator at hour h.
SOC_h (kWh): State of Charge of the battery at the end of hour h.
$U_{Demand,h}$ (kW): Unmet demand at hour h. (This variable ensures feasibility and is penalized in the objective).
$E_{Solar,h}$ (Wh/m^2): Solar irradiance at hour h.
$V_{Wind,h}$ (km/h): Wind speed at hour h.
D_h (kW): Electrical demand at hour h.
η_{PV}: PV panel efficiency.
A_{PV} (m^2): PV array area.
η_{Inv}: PV inverter efficiency.
$P_{Wind,rated}$ (kW): Rated power of the wind turbine.
$V_{Wind,rated}$ (m/s): Rated wind speed of the wind turbine.
$V_{Wind,cutin}$ (m/s): Cut-in wind speed of the wind turbine.
$V_{Wind,cutout}$ (m/s): Cut-out wind speed of the wind turbine.
$P_{Diesel,max}$ (kW): Maximum capacity of the diesel generator.
$C_{Fuel,L}$ (USD/L): Diesel fuel cost per liter.
$R_{FuelCons}$ (L/kWh): Diesel fuel consumption rate.
$E_{Bat,cap}$ (kWh): Total battery energy capacity.
$P_{BatCharge,max}$ (kW): Maximum battery charge rate.
$P_{BatDischarge,max}$ (kW): Maximum battery discharge rate.
η_{Bat} : Battery efficiency (for both charge and discharge, assumed symmetrical).
$SOC_{initial}$ (kWh): Initial state of charge of the battery (at $h = 0$).
SOC_{min_pct}: Minimum allowable battery SOC percentage.
SOC_{max_pct}: Maximum allowable battery SOC percentage.
C_{Unmet} (USD/kWh): Penalty cost for unmet demand.
G is the hourly solar irradiance (W/m²).
η panel is the PV panel efficiency.
A panel is the total area of the PV array (m²).
η inverter is the inverter efficiency.

I. Introduction

The optimum configuration of a resilient and robust hybrid power system in hassled territories is based on several key factors: the integration of renewable energy sources, cost considerations, environmental impact, and system reliability. These aspects are essential in tackling the energy problems, including power outages that occur frequently and high reliance on diesel generators. The operational cost reduction and environmental pollution reduction have also been determined to be a viable solution through the integration of the existing diesel generators and the solar photovoltaic (PV) systems.

The Gaza Strip has adopted hybrid power systems as an answer to resolve its persistent electricity crisis. The combination of renewable energy technologies with diesel power generation systems in hybrid power systems presents a viable option to replace the power transmission infrastructure based on erratic and pricey diesel generators in the Gaza Strip. Nasser Hospital located in the southern Gaza Strip runs its operational processes using a PV-diesel hybrid system which diminishes the requirement for diesel generators. The implemented system cuts operating expenses while reducing environmental pollutants in air[1]. Energy requirements of hospitals in Gaza can be satisfied through hybrid wind-diesel systems which cut down on both power usage and fuel expenses[2][3].The Dier El Balah quarantine center received a hybrid PV wind diesel power system when COVID-19 began spreading in 2020. The designed hybrid system offered dependable cost-efficient power distribution to showcase its flexibility in emergency response operations[4]. Solar-based irrigation equipment demonstrates better economy and sustainability than traditional diesel-powered water systems for cultivation[5]. The planned Gaza Strip wind farm establishment project has the potential to decrease daily CO2 emissions to 484250 kg[6].

Hybrid systems work to enhance energy reliability because they join different sources together which stabilizes renewable variability and maintains uninterrupted power distribution[7][8].

Solar and wind energy show great promise as hybrid system solutions for the Gaza Strip because of its ideal climate conditions. Sustainable investments in renewable power infrastructure systems will create a future of clean energy that minimizes foreign fuel imports and improves national energy stability[9][6][10].

In [11], the proposed solar PV, wind and hydro energy system in combination can offer 100% renewable energy solution without the need for energy storage, as seen in optimal configuration of PV 88 kW, wind 18 kW, Hydro1 215 kW and Hydro2 197 kW. But in small systems still battery banks the most suitable solution. The optimal

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configuration for a PV-wind-hydro system was determined using a multi-objective genetic algorithm MOGA algorithm, achieving a net present cost of 163,238 and a cost of energy of $ 0.35/kWh over 25 years.

Another system produced by feeding the estimated load profile to the HOMER Pro program A standalone hybrid PV/wind/diesel-electric generator system for a COVID-19 quarantine center offers a cost-effective solution for regions with unreliable electricity access. The system consists of solar panels, wind turbines, and diesel generators. The system can achieve a cost of energy as low as $0.348/kWh, reduce emissions by 54.89%, and generate an annual surplus of 212,553 kWh. Despite initial capital costs and maintenance issues, the long-term benefits of this system make it a viable choice for energizing quarantine centers during health crises [12].

There exist multiple barriers that restrict the widespread implementation of hybrid power systems throughout the Gaza Strip. These include both technical elements alongside economic aspects as well as political requisites and fundamental infrastructure concerns. All hybrid power systems need scheduled maintenance procedures to deliver their best possible performance levels. Lack of skilled staff together with limited access to replacement parts in the Gaza Strip leads to system breakdowns and reduced system efficiency[13][7].

The intermittent nature of renewable energy sources, such as solar and wind, necessitates energy storage solutions. The implementation of batteries together with hydrogen storage methods faces major obstacles as their implementation remains too costly and technical to scale up[2].

A proper design and size determination for hybrid power systems demands systematic evaluation of power requirements together with energy source allocations and reserve capacity needs[8][14]. Insufficient system design leads to less efficient operations and a shorter system lifecycle[2][7].

Hybrid power systems find less adoption because the public shows limited understanding regarding their benefits. The public needs detailed knowledge about renewable energy advantages alongside hybrid system capabilities because this education drives their acceptance towards widespread use[9]. Inadequate local institutions coupled with a shortage of technical staff causes problems with planning and maintaining hybrid power systems and their implementation[13][7].

It concluded from the literature [1-8] that the following recommendation are proposed for overcoming the challenges of energy in hassled sites as Gaza.

- Increased financial support from international donors and organizations [6].
- Local staff development through training initiatives that build the technical ability of local workers to design and install and maintain hybrid power systems[13][7].
- The implementation of public awareness campaigns should educate individuals about hybrid power system benefits alongside renewable energy source adoption importance[9].

To overcome the aforementioned power supply limitations, an optimal design for a resilient and reliable microgrid is proposed in this article. This article could claim to have the following contributions. These are:

- Proposing an innovative and simple concept for implementing the electrical power system for stressed territories.
- Adoption of renewable energy as a main power source for microgrids.
- Economic dispatch of microgrids.
- Proposing a new optimization technique for microgrids.

The structure of this manuscript is outlined as follows; section I is the introduction while Section II introduces the proposed microgrid. Section III presents the Methodology. Section IV discuss the results. Section V presents the conclusions.

II. proposed microgrid

Cost of energy (COE) and net present cost (NPC) are key variables for optimal configuration. For example, the low NPC and COE of the PV/Wind/Hydro system has made it economically viable for remote areas [11]. The application of optimization techniques like Dandelion –Optimizer and Giza pyramids construction algorithm assist in finding a balance between cost and reliability by reducing the annualized system cost [15][16]. Emissions reduction is a major consideration, hybrid systems with renewable sources demonstrating reduced emissions versus systems that rely only on fossil fuels [15].

Table1 show the application and components of three major hybrid systems.

TABLE I Application and components of hybrid systems used in Gaza

Application	Key Components	Primary Challenges
Healthcare Facilities	PV-diesel hybrid system	High initial costs, maintenance requirements[1]
Quarantine Centers	PV-wind-diesel hybrid System	Funding limitations, technical complexity[4]
Agricultural Irrigation	Solar PV water pumping	Compatibility with existing AC motor pumps[5]

In this work, we propose a solar PV, wind, diesel generator and batteries hydride microgrid. Fig.1 show the proposed micro grid, where the PV plant and the battery bank in the DC bus linked to the AC bus via DC/AC inverter. The AC bus contains the load, diesel generator and the wind plant.

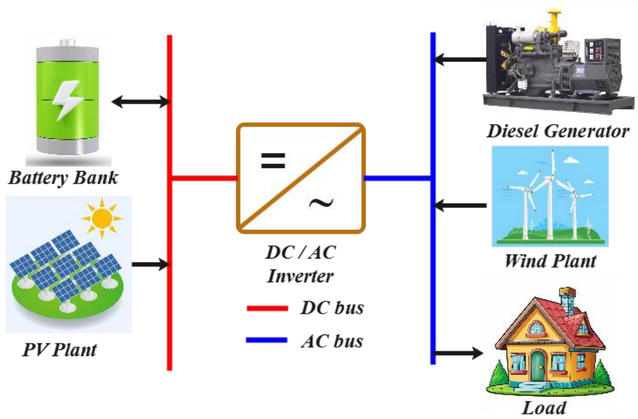

Figure 1. The proposed microgrid.

A. The microgrid dispatch strategy

The simulation tracked key performance metrics, including:

- Hourly and total energy generation from each source.
- Hourly and total electricity demand.
- Hourly battery charge and discharge, and the final Battery State of Charge (SOC).
- Hourly and total diesel fuel consumption and cost.
- Hourly met demand.

A simplified economic assessment was conducted based on predefined capital costs (USD/kW or USD/kWh) and annual operational and maintenance (O&M) costs (USD/kW/year or USD/kWh/year) for each technology.

B. *System Parameters*

The microgrid components are sized and parameterized as follows in Table I:

TABLE II Proposed MG System Parameters

PV System	
Panel Efficiency	20%
Array Area	500 m2
Inverter Efficiency:	96%
Estimated Total PV Capacity	96 kW (approximated DC to AC)
Wind System	
Rated Wind Speed	12.0 m/s
Rated Power	300 kW
Cut-in Speed	3.5 m/s
Cut-out Speed	20.0 m/s
Estimated Total Wind Capacity	300 kW
Diesel Generator	
Capacity	500 kW
Fuel Cost	0.8 USD/liter
Fuel Consumption Rate	0.25 L/kWh
Battery Energy Storage System (BESS)	
Capacity	1000 kWh
Max Charge/Discharge Rate	200 kW
Efficiency	95%
Initial State of Charge (SOC)	50%

III. Methodology

The methodology employed in this work by using Python script for simulating and assessing the Gaza microgrid system. The simulation was conducted over a 24-hour period using simulated weather data for Gaza (solar irradiance and wind speed) and a representative hourly demand profile.

A. Economic Dispatch Algorithm for Microgrid Optimization

Fig.2 show the flowchart of linear programming optimization used for determining the optimal configuration of the proposed MG[17][18] [19]. Linear programming allows decision-makers to identify the optimal solution possible within a series of constraints, which makes it a key process to the allocation of resources and operational effectiveness [20] [21]. Simplex method: is a popular algorithm to use in solving a linear programming problem and so in maximizing profits or minimizing cost [22]. Integer Programming: other special versions such as 0-1 integer programming, mixed integer programming are designed to fit certain optimization problems and these can perform more complicated decision-making situations [19]. Chance of influence in the decision-making process, the issue of linear programming models is that they enable systematic problem solving of a complex issue and thus can be considered an essential component of decision making in the modern world in any field [19][21].

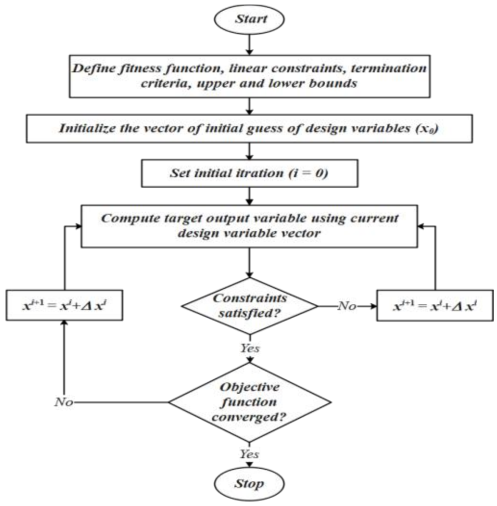

Figure 2. The flowchart of the linear programming

Let h denote the hour, where $h \in \{0,1,\ldots,23\}$.

The primary goal is to minimize the total operational cost over the 24-hour period, which includes diesel fuel expenses and a penalty for any unfulfilled demand.

$$\text{Minimize } \sum_{h=0}^{23}\left(P_{Diesel,h} \cdot R_{FuelCons} \cdot C_{Fuel,L} + U_{Demand,h} \cdot C_{Unmet}\right) \quad (1)$$

The optimal dispatch must adhere to the following operational and physical limitations:

$$P_{PV,h} + P_{Wind,h} + P_{BatDischarge,h} + P_{Diesel,h} \geq D_h - U_{Demand,h} \quad (2)$$

$$\forall h \in \{0,\ldots,23\}$$

$$P_{PV,h} \leq \text{calculate\_pv\_production}\left(E_{Solar,h}, \eta_{PV}, A_{PV}, \eta_{Inv}\right) \quad (3)$$

$$P_{Wind,h} \leq \text{power\_from\_wind\_speed} \quad (4)$$

$$\left(\frac{V_{Wind,h}}{3.6}, V_{Wind,rated}, P_{Wind,rated}, V_{Wind,cutin}, V_{Wind,cutout}\right) \forall h \in \{0,\ldots,23\} \quad (5)$$

$$P_{Diesel,h} \leq P_{Diesel,max} \quad \forall h \in \{0,\ldots,23\} \quad (6)$$

SOC Dynamics:

For $h = 0$ (initial hour):

$$SOC_0 = SOC_{initial} + P_{BatCharge,0} \cdot \eta_{Bat} - \frac{P_{BatDischarge,0}}{\eta_{Bat}} \quad (7)$$

For subsequent hours $h \in \{1,\ldots,23\}$:

$$SOC_h = SOC_{h-1} + P_{BatCharge,h} \cdot \eta_{Bat} - \frac{P_{BatDischarge,h}}{\eta_{Bat}} \quad (8)$$

Battery charge rate limit for each hour h: The rate at which the battery can be charged is limited by its design specifications.

$$P_{BatCharge,h} \leq P_{BatCharge,max} \quad \forall h \in \{0,\ldots,23\} \quad (9)$$

Battery discharge rate limit for each hour h: The rate at which the battery can supply power is also constrained by its design.

$$P_{BatDischarge,h} \leq P_{BatDischarge,max} \quad \forall h \in \{0,\ldots,23\} \quad (10)$$

Battery SOC limits for each hour h: To ensure battery health and operational reliability, its state of charge must remain within predefined minimum and maximum percentages of its total capacity.

$$E_{Bat,cap} \cdot SOC_{\underset{pct}{\min}} \leq SOC_h \leq E_{Bat,cap} \cdot SOC_{max_{pct}} \forall \in \{0,\ldots,23\} \quad (11)$$

Non-negativity Constraints for all variables: All power outputs and unmet demand must be non-negative values.

$$P_{PV,h}, P_{Wind,h}, P_{BatCharge,h}, P_{BatDischarge,h}, P_{Diesel,h}, U_{Demand,h} \geq 0$$
$$\forall h \in \{0,\ldots,23\} \quad (12)$$

Unmet Demand Upper Limit for each hour h: The amount of unmet demand cannot logically exceed the total demand for that hour.

$$U_{Demand,h} \leq D_h \quad \forall h \in \{0,\ldots,23\} \quad (13)$$

A qualitative feasibility assessment was performed, considering factors such as resource availability, land constraints, technological access, grid interconnection possibilities, fuel supply reliability, financial investment risks, environmental regulations, social acceptance, and security considerations.

A. Power Calculation Equations

The AC power output from the PV system is calculated using the following:

$$P_{PV}=G\times\eta_{panel}\times A_{panel}\times\eta_{inverter} \quad (14)$$

Fig.3 show 24 hours example of solar irradiance in Gaza.

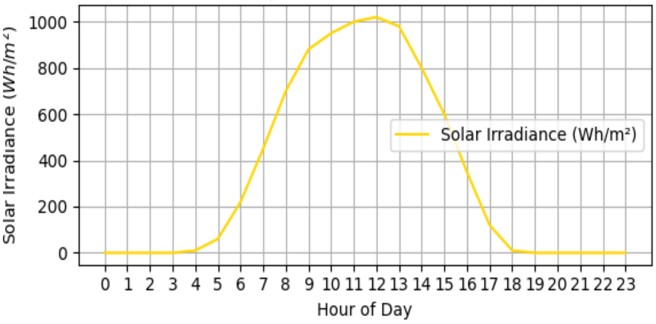

Figure 3. Solar irradiance curve for Gaza City over a 24-hour period

The power output from the wind turbine is determined by a power curve that considers cut-in, rated, and cut-out wind speeds.

$$P_{Wind} = \begin{cases} 0 & \text{if } V < V_{ci} \text{ or } V \geq V_{co} \\ P_r \times \frac{V-V_{ci}}{V_r-V_{ci}} & \text{if } V_{ci} \leq V < V_r \\ P_r & \text{if } V_r \leq V < V_{co} \end{cases} \quad (15)$$

Fig.4 show 24 hours example of wind speed in Gaza.

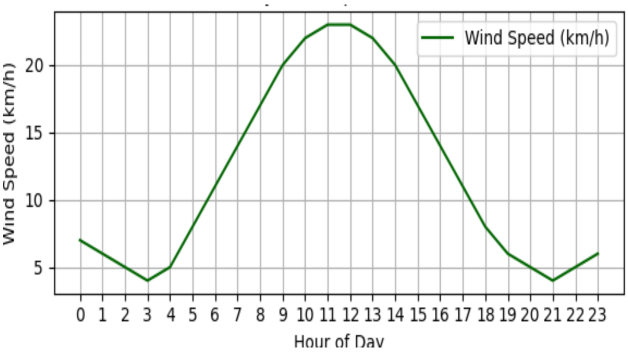

Figure 4. Wind speed curve for Gaza City over a 24-hour period

B. Dispatch Logic

The microgrid dispatch operates hourly based on the following hierarchy:

- Meet demand with renewables: The primary source of power is the combined output from solar PV and wind turbines.
- Battery discharge: If renewable generation is insufficient to meet demand, the battery discharges up to its maximum discharge rate or until its capacity is depleted.
- Diesel generator operation: If demand still exceeds the combined renewable and battery discharge, the diesel generator activates to cover the deficit, up to its maximum capacity.
- Battery charging: If renewable generation exceeds demand, the surplus power charges the battery, up to its maximum charge rate and available capacity.

IV. Primary Challenges and Recommendations

The widespread adoption of hybrid power systems in the Gaza Strip faces significant technical, economic, political, infrastructural, and social barriers. Technically, systems require regular maintenance, skilled personnel, and accessible spare parts; energy storage solutions such as batteries and hydrogen remain costly and technically challenging, and improper system sizing reduces efficiency and lifespan [13][7][2]. Economically, high installation costs, dependence on international aid, and unstable markets hinder viability [1][4][6][9]. Politically and infrastructurally, ongoing conflicts damage energy assets, outdated grids limit integration, and heavy reliance on imported diesel increases vulnerability [6][9]. Socially, low public awareness and weak local institutions restrict acceptance and capacity [9][13][7].

To overcome these issues, strategies include securing greater donor funding [6], developing local technical skills [13][7], conducting public awareness campaigns [9], integrating hybrid systems into national energy policy [6], modernizing infrastructure with smart grids and storage [6], and fostering public–private partnerships [6].

V. Results

The simulation and assessment of a hybrid microgrid system for the Gaza Strip is carried out for providing a reliable and sustainable power supply. The analysis covers capital and operational costs, hourly dispatch logic, and qualitative feasibility considerations specific to the Gaza context.

A. Economic Analysis

The economic analysis provides a preliminary estimation of capital and operational costs Tables III-IV. The capital costs are given in Table III. Operational costs (Annual Estimates) are given in Table IV.

TABLE III Capital Costs of the proposed MG

Component	Capacity	Cost per Unit	Total Capital Cost
Solar PV	96.00 kW	$1,500/kW	$144,000.00
Wind Turbine	300.00 kW	$2,500/kW	$750,000.00
Diesel Generator	500.00 kW	$800/kW	$400,000.00
Battery Storage	1000.00 kWh	$350/kWh	$350,000.00
Total			**$1,644,000.00**

TABLE IV Annual Operational Costs of the proposed MG

Component	Capacity	O&M Cost per Unit	Annual O&M Cost
Solar PV O&M	96.00 Kw	$20/kW/year	$1,920.00
Wind O&M	300.00 kW	$30/kW/year	$9,000.00
Diesel O&M	500.00 kW	$50/kW/year	$25,000.00
Battery O&M	1000.00 kWh	$10/kWh/year	$10,000.00
Total Annual			**$45,920.00**

B. System Performance (24 Hours)

According to the simulation, the total amount of renewable energy produced was 1429.46 kWh and a total amount of diesel energy generated was 0.00 kWh. The contributions of renewable energy sources corresponding to the objective function by a PV of 41%, WT of 34%, batteries of 25%, and DG of 0%. The total demand was 989.00 kWh which results in Cost of Energy (COE) to be: $0.3103/kWh (Assumed Project Lifetime: 25 years)

Fig.5 shows the hourly demand of the load, Table V present a comparison of two MG with our work in methods and result COE.

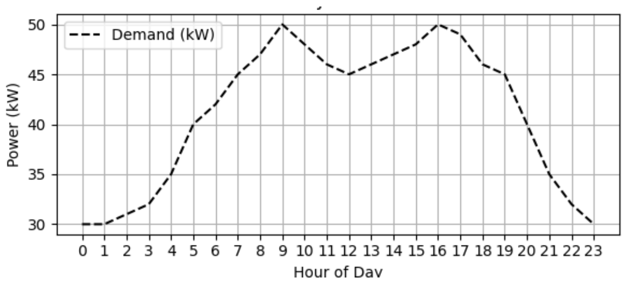

Figure 5. Hourly demand of the load

TABLE V Comparison of two MG with our work based on the COE.

	Method	COE (USD/kWh)
Proposed MG	Linear programming rule based deterministic algorithm	0.3103
A. S. Irshad *et al* MG[11]	multi-objective genetic algorithm MOGA	0.35
COVID-19 quarantine center MG[12]	HOMMER PRO	0.348

Table V shows that the proposed MG has lower cost for the energy as compared with candidates reported in the literature.

The performance of battery storage was 71.87 percent which shows that renewable generation was sometimes higher than the load. The battery effectively stored surplus renewable energy and released at times of low renewable generation and at high demand, Fig.6 show the charge and discharge, indicating it effectively managed daily fluctuations without significant net depletion over the 24 hours, and did not require the diesel generator, The growth in the ratio of SOC by that much (50%:71.87%) indicates that the system also has a potential to be optimized. The selection of the battery capacity was relatively well suited to the demand profile for the day along with the solar and wind resources available.

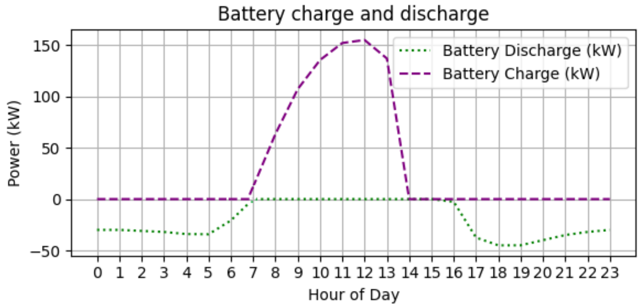

Figure 6. Charging and discharging curve for battery systems in Gaza over a 24-hour period

Fig.7 shows hourly demand and power production of the microgrid, where Night Hours (0-5, 19-23) the solar PV production is zero while wind power contributes, but often not enough to meet demand, requiring significant battery discharge to cover up. In morning/evening transition hours (6-7, 17-18) as solar irradiance increases/decreases, PV output rises/falls. Wind power remains a contributor. The battery plays a crucial role in balancing supply and demand.

charging during surplus and discharging during deficit. The Daylight Hours (8-16) have the highest solar irradiance leads to substantial PV power. Coupled with consistent wind power, the renewable generation often exceeds demand, leading to significant battery charging. The diesel generator providing reliability in case of prolonged low-renewable generation or excessive demand higher than forecasted, or as an emergency.

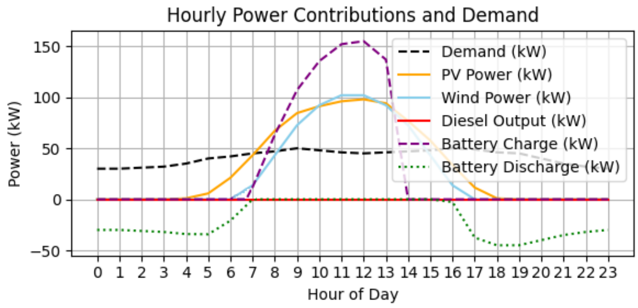

Figure 7. Performance of the proposed MG over 24h

The curves in Figure 7 show the demand and electricity generated by solar cells, wind turbines, and diesel generator throughout a 24-hour period. Figure 7 shows that the batteries are essential for the proposed MG. They store the energy during the surplus production and fulfil the load requirement during the generation shortage.

VI. CONCLUSIONS

The qualitative feasibility assessment identifies several critical challenges specific to the power system for the hassled places, particularly Gaza strip in Palestine.

These must be addressed for the successful implementation of such a power system. These include land constraints, technological access, fuel supply security, financial risks, and geopolitical factors.

The reliance on diesel generation for territories such as Gaza strip is not reliable option. Therefore, it is better to have less share in the electrical power supply. The importance of accurately assessing local renewable resources and optimizing the sizing of the battery storage system for the proposed MG is vital. The economic analysis highlights the substantial capital investment required, necessitating careful financial planning and potential international support.

The simulation results demonstrate the potential for a renewable energy-based microgrid, incorporating battery storage and a diesel generator, to contribute to the electricity needs of Gaza.

The proposed MG enjoys the lowest COE compared to the similar reported approaches as shown in Table V.

FUTURE WORK

This study has demonstrated the technical and economic potential of the proposed hybrid microgrid through simulation, however, practical implementation and validation remain essential to confirm its real-world performance. Due to current logistical, political, and financial constraints in the Gaza Strip, conducting on-site experiments was beyond the scope of this work. Future research will focus on hardware-in-the-loop (HIL) testing of the dispatch control strategy and pilot-scale deployment in comparable off-grid or conflict-affected regions. These efforts will enable the assessment of operational reliability, maintenance requirements, and socio-economic impacts under real-world conditions.

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