**ABSTRACT**

To mitigate the hazardous effect of increasing energy demand and global warming, the Renewable Energy Sources (RESs)-based smart microgrids are gaining massive attention. However, intermittency, as well as the volatile nature of RESs, make it a challenging task. To confront the wavering of voltage profile and power flow in microgrids, the Energy Storage System (ESS) and Diesel Generators are being used as a backup power supply. On a national as well as an international scale, a vast list of Universities with a growing number of departments, centers, and hostels add up a mass amount of energy demand. The study of electricity consumption trend in Aligarh Muslim University (AMU) provides vital information to analyze, design, and implement a suitable solution for the deployment of the microgrid. In this work, Polygeneration based on various smart microgrid topologies in both modes of operation (i.e. grid-connected and off-grid mode) is studied. To execute the economic and feasibility analysis, HOMER® is used as simulating and optimizing tool. On the basis of minimum Net Present Cost (NPC) from the various topologies, the best solution is recommended. The obtained results show that the total system cost under solar PV + Battery (PV + B) mode is 1419.6 million INR, which is approx. 64.2% higher as compared to the current existing scenario (864.2 million INR), while, the total system cost under (Grid + Solar PV) G + PV mode is 494.92 million, which is approx. 57.2% lower as compared to the current existing scenario. The comparative study of the environmental and economic structure of proposed topology with existing one reveals that, under the proposed topology, 3.636*10^6 kg of CO₂, 1.578*10^4 kg of SO₂, and 7.7*10^3 kg of NOₓ will be mitigated.

**1. Introduction**

Electric power generation has been a key factor to determine the economic infrastructural growth and industrialization. In India, the total electrical energy installed capacity has reached 303.118GW by 30th June 2016. 70% of total installed capacity comes from fossil fuel-based generating stations (61% coal and 9% natural gas), which raises environmental issues [1]. In regard of the above challenging issues, Renewable Energy Recourses (RES) are gaining massive attention due to various benefits associated such as uncontaminated energy, zero carbon emission, free from dependency on foreign oil, which

| Analysis Parameter | MG Topology | G | DG | G+PV | PV+B | PV+DG | PV+B+DG |
|--------------------|-------------|---|----|------|------|-------|---------|
| Cost Analysis      |             |   |    |      |      |       |         |
| NPC (million)      | 864.2       | 2750 | 494.92 | 1419.6 | 2261 | 1751   |
| COE (INR/kWh)     | 9.02        | 28.91 | 5.41 | 17.02 | 23.77 | 18.41 |
| O&M (million)      | 52.2        | 163.44 | 7.38 | 36.08 | 126.86 | 89.01 |
| PV (kW)            | 0           | 0 | 3886 | 4120 | 1300 | 740 |
| Converter (kW)    | 0           | 0 | 3078 | 2776 | 977 | 1506 |
| Battery (kWh)     | 0           | 0 | 48345 | 9828 |
| Energy Trading     |             |   |    |      |      |       |         |
| Energy Purchased   | 5753283     | 3014812 | 0 | 0 | 0 |
| Energy Sold        | 0           | 0 | 3014499 | 0 | 0 | 0 |
| Renewable Penetration (%) | 0 | 65.6 | 100 | 24.2 | 36.9 |
| Capacity Shortage (%) | 0 | 0 | 10 | 0.1 | 0.1 |
| Emission Analysis  |             |   |    |      |      |       |         |
| CO₂ (1000*kg/year) | 3636        | 6046 | 0.2 | 4638 | 3225.1 |
| CO                 | 0           | 45.73 | 0 | 35.08 | 24.40 |
| SO₂                | 15.78       | 14.8 | 0.00086 | 11.38 | 7.91 |
| NOₓ                | 7.7         | 51.9 | 0.00042 | 39.87 | 27.72 |
also enhances economical infrastructure [2]. Despite such tremendous attributes, REs are volatile and intermittent in nature due to dependency on meteorological conditions, which causes fluctuation in output power/voltage profile [2]. So, in order to overcome volatile and intermittent nature of RES energy storage systems like a battery, supercapacitor and the flywheel are being used. Deployment of Microgrids is the only optimum, feasible, secure, and reliable paradigm to overcome the increasing demand for sustainable development. As being smart in nature, Microgrids are capable to operate in both modes i.e. grid-connected (Grid-tied/Grid-interactive) as well as in islanding mode. During a faulty condition on grid side, smart microgrids change the mode of its operation from grid-connected to islanding to serve the critical or emergency loads like hospitals, central jail etc. [1–6].

In [2], the detailed study of microgrid feasibility, design, and implementation for a residential hostel at AMU has been done, the presented work considered peak load during the night-time that affects the size of battery storage. However, this work analyzes the day-based peak load of the commercial building. In [7], a PV-based residential microgrid as home-to-grid back-up power has been analyzed. The authors in [3] have been discussed the detailed contribution of Microgrid for EV energy management system.

In [8], the author presented and analyzed the potential impact of the rooftop solar system in grid-connected mode on electric distribution utility for the time horizon of 24 h; the energy demand and load profile was taken from electric DU in the province of Agusan del Norte. The obtained result helps in energy management for higher renewable energy penetration in the grid. In [9], a hybrid PV- and wind-based microgrid system to meet the load demand of a water distillation plant is discussed; the swarm optimization is implemented to achieve the minimum life cycle cost and losses. In [10], the author presents a novel method to extract the maximum power point of a 10.2 kW PV panel based on convergence rate and efficiency. Further, the obtained results have been discussed with fuzzy logic-based control algorithm. In [11], a PV system to feed the electric demand of the technical CAD laboratory is designed and economic analysis is explained; the obtained results show that the per unit cost is higher than the present utility provider but in future with decreasing cost of solar PV system will be favored. The author in [12] presented a homer-based hybrid PV solar and wind system in a grid-connected mode with bi-directional power flow; the analysis shows the feasibility and economic applicability. The [13] presents a feasibility study of electricity generation from the two micro-turbine mounted on the moving car by taking the drag forces into consideration. The analysis was verified by comparing the simulation and experimental results. A techno-economic analysis of a wind-based power generation system in off-grid mode has been presented in [14].

To maximize the generated torque from the wind turbine a novel optimization technique based on three variable system (airfoil type, attack angle, and chord) rather than two (airfoil type, attack angle) or one (airfoil type) is used [15], the obtained result shows the fine increment in the generated torque (i.e. 7.7–22.27 for two variable while 17.91–24.48 for 3 variable system). To install the wind plant at various locations of the Gulf of Guinea, the author in [16] has presented wind energy potential analysis. Annually and monthly, the assessment of the wind speed was performed and the obtained result was compared with the 13-year available data. In this paper, various topologies of microgrid are analyzed in order to find out the best possible configuration in terms of achieving various desirable objectives like better economical configuration as well as a reduction in global warming, Carbon footprints, and other environmental problems.

2. Electricity Consumption in AMU

The study of electricity consumption trend in A.M.U. provides vital information that can be used to analyze, design, and implement a suitable solution for the deployment of a microgrid that can cut down the electricity usage from the conventional grid and GHS emissions, thus saving the environment. This analysis can also be implemented for other institutes.

A.M.U., which is run by central government, has a student strength of approx. 39000. Latitude and Longitude coordinates of Aligarh are 27.8800° N and 78.0800° E, respectively. Total installed capacity of A.M.U. is 13.63 MVA as shown in Table 1; it has 12 faculties which include more than 110 departments and centers. Their consumption is approx. 65%, while 16 halls of residence consume

Table 1. Feeder description of AMU.

| University feeders | Capacity (kVA) |
|--------------------|---------------|
| Feeder 1           |               |
| A                  | 1000          |
| A-1                | 630           |
| F                  | 800           |
| F-1                | 400           |
| Feeder 2           |               |
| B                  | 1000, 630 &400|
| E-1                | 630           |
| E-2                | 630           |
| J                  | 630           |
| Feeder 3           |               |
| E                  | 1000          |
| DQ                 | 100           |
| NTH                | 400           |
| Feeder 4           |               |
| C                  | 1000          |
| C-1                | 630           |
| D                  | 630 & 1000    |
| H                  | 630           |
25% of total consumption, annual electricity consumption from FY 2011–2012 is shown in Figure 1, which explains the how the energy consumption, as well as Cost of energy (CoE), rising year-by-year. The study of energy consumption, as well as well rising pattern of CoE, reveal that in last five-year energy consumption has increased from 23.11 to 29.05 million units (MU), which is 25% higher than the energy consumption during 2011–2012, with yearly rising average % of 6.2, while the CoE has increased from INR 5.2 (in 2011–2012) to INR 9.08 (2015–2016), which is approx. 74.6% higher [2,9]. One unit represents 1kWh.

UPPCL sanctioned a load of 6.1 MVA to A.M.U. campus. But due to increase in load demand, University consumption overshot the limit of 7.952 MVA in Nov 2013 followed by 8.176 MVA in Sep. 2015 [17].

2.1. Considered Load Profile

To analyze the various microgrid topologies, the load profile of medical college and the medical colony is considered. The variation of month-wise daily average load profile (hourly basis) is shown in Figure 2, which explains that during the winter and summer season, the load is higher except the July due to summer vacation. The monthly average consumption is shown in Figure 3. The daily average energy consumption in 15762kWh/day, the average load is 656.77 kW, peak load is 1686.3 kW, and the load factor is 0.39. After analyzing the Figures 2 and 3, it is also revealed that the load profile is highly fitted for solar PV-based microgrid because the Aligarh’s geographical location is in such a way that it generates more power during the April to September while less amount of generated energy in other months, except the July month due to summer vacation. So, in July, good amount of energy be will be fed back to the grid.

3. Component Modeling

3.1. Solar PV System

PV panel size, solar radiation, clearing index, and PV cell temperature are the factors which affect the electrical power output solar PV module. The PV power output of each set of microgrid can be calculated as follows [18]:

$$PV_i = PV_{STC} \frac{G_{ING}G_{STC}}{(1 + k(T_c - T_r))} \times A$$  \hspace{1cm} (1)

where $PV_i$ is the output power of each microgrid set, at a particular incident irradiance $G_{ING}$, the $PV_{STC}$ is the maximum power output at Standard Test Condition (STC), $G_{STC}$ is irradiance at STC (i.e. 1000 W/m²), $k$ is the temperature coefficient of power, $T_c$ is the PV module temperature, $T_r$ represents the reference temperature, and $A$ is the total surface area (m²) of PV module.

3.2. Charge Controller

To avoid overcharging of energy storage devices, a charge controller is utilized to sense when the storage devices are completely charged and to stop the further energy flow from the generating source. The mathematical model of the charge controller is given below:

$$E_{CC\cdot OUT}(t) = E_{CC\cdot IN} \times \eta_{CC}$$  \hspace{1cm} (2)

$$E_{CC\cdot IN}(t) = E_{REC\cdot OUT} \times E_{SUR\cdot DC}(t)$$  \hspace{1cm} (3)

where $E_{SUR\cdot DC}(t)$ is excess energy from power generating sources, $E_{CC\cdot OUT}(t)$, $E_{CC\cdot IN}(t)$ is energy output and input.
3.5. Diesel Generator System

Due to intermittent RESs, there is a chance of complete and partial outages of these resources due to which diesel generators are required for meeting the electricity demand of the primary load. The mathematical model is as follows [21]:

\[
C_{gen,\text{fixed}} = C_{\text{om,gen}} + \frac{C_{\text{rep,gen}}}{R_{\text{gen}}} + F_0 Y_{\text{gen}} C_{\text{fuel,eff}}
\]  (7)

where \( C_{\text{om,gen}} \) is operation and maintenance cost (INR/ hour), \( C_{\text{rep,gen}} \) is replacement cost (INR), \( R_{\text{gen}} \) is generator lifetime (hours), \( F_0 \) is fuel curve intercept coefficient (fuel/ hour/kW), \( Y_{\text{gen}} \) is generator capacity (kW), and \( C_{\text{fuel,eff}} \) is effective price of fuel (INR/quality of fuel). It includes the cost penalties associated with the emission of pollutants from the generator.

3.6. Battery Bank System

Battery bank size, the battery charge, and discharge rate are the main influencing power output factors associated with the battery bank system. Batteries are essential in a hybrid power system in order to store excess electricity generated by renewable sources and during high power demand periods. The equation for calculating the state of charge (SOC) is as follows [20]:

\[
SOC(t) = (1 - Q)SOC(t - 1) + \frac{P_{\text{dch,eff}} \Delta(t) e_{\text{dch}}}{E}
\]  (8)

The equation for calculating the life of battery bank (in years) is as follows [21]:

\[
R_{\text{batt}} = \min \left( \frac{N_{\text{batt}} Q_{\text{lifetime}}}{Q_{\text{thrpt}}} R_{\text{batt,f}} \right)
\]  (9)

The equation for calculating the wear cost of the battery is as follows [21]:

\[
C_{\text{bw}} = \frac{C_{\text{rep,batt}}}{N_{\text{batt}} Q_{\text{lifetime}} \sqrt{\eta_{\text{rt}}}}
\]  (10)

where \( \text{SOC}(t) \% \text{SOC}(t-1) \) is state of charge at time \( t \) and \( (t-1) \), \( Q \) is hourly discharging rate, \( E \) is total energy, \( e_{\text{dch}} \) is efficiency of charge and discharge, \( N_{\text{batt}} \) is number of batteries in a battery bank, \( Q_{\text{lifetime}} \) is lifetime throughput of a single battery, \( Q_{\text{thrpt}} \) is total amount of energy that cycles through the battery bank in one year (annual throughput), \( R_{\text{batt,f}} \) is maximum life regardless of throughput (float life of the battery), \( C_{\text{rep,batt}} \) is replacement cost of the battery bank, and \( \eta_{\text{rt}} \) is round-trip efficiency.

Figure 3. Monthly energy consumption of 2016.
4. Availability of RESs

Aligarh is located at the coordinates 27.88° N 78.08° E. It has an elevation of approximately 17 metres (587 feet) and lacking from hydro-based RESs. However, the availability of solar irradiance is quite good as compared to wind sources. The solar irradiance and wind-speed data were taken from NASA metrological center. The maximum-recorded Daily Solar Radiation was found 7.03 kWh/m²/day in the month of May, followed by 6.77 in April. While minimum recorded solar irradiance was 3.51 kWh/m²/day in December, followed by 3.62 kWh/m²/day on Jan.

The minimum and maximum recorded wind speed were 2.7 and 6.02 m/s during the month of Nov and June. The detail variation solar irradiance corresponding to the clearing index and wind speed are given in Figure 4 [22]. The clearness index is defined as the ratio of the global radiation at ground level on a horizontal surface and the extra-terrestrial global solar irradiation [23].

5. Optimizing Tool

HOMER® microgrid analysis tool is used for the simulation of various microgrid topologies in order to find out the optimal and economical solution among various microgrid topologies considered in this paper. HOMER® uses the hourly load profile of one day for each month while they use the monthly average solar irradiance, clearing index, and wind speed. Using the monthly average of available data, HOMER® generates the hourly solar PV irradiance and wind speed. The Figures 5 and 6 shows the hourly generated solar irradiance and wind speed. HOMER® simulates various system configurations according to specified technical constraints and gives a result based on Net Present Cost (NPC) of the system. HOMER® calculates NPC using the equation [21].

\[ C_{\text{NPC}} = \frac{C_{\text{ann,tot}}}{\text{CRF}(i, R_{\text{proj}})} \]  

where \( C_{\text{ann,tot}} \): Total annualized cost, \( i \): discount rate, \( R_{\text{proj}} \): Project Lifetime, \( \text{CRF}(i, R_{\text{proj}}) \): Capital Recovery Factor.

Possible decision variables in HOMER® include the size of the PV array, the number of wind turbines, the number of batteries, and the size of the ac–dc converter. The details regarding the HOMER® are given in [21].

6. Result and Discussion

In this case study, 25-year project life is considered. To incorporate the time flow effect on cash flow, 6.75% interest rate and 3.17% inflation rate are taken. As AMU comes under the category commercial load, 9.08 INR/kWh grid purchasing and 7.5 INR/kWh grid feeding cost are considered.

At the end of FY 2014–2015, the Central Electricity Regulatory Commission (CERC) declared INR 691 lac per MW as Benchmark Capital Cost (CC) of solar PV project in India [24]. But further, it depends on the site location, state regulations, and other parameters. So, in order to consider the worst scenario and excellent quality of microgrid system components, INR 90000 per kW for solar PV as CC and same as Replacement Cost (RC) is considered with 0.5% of the CC per annum as the operation & maintenance cost (O&M). The details of other system components such as Converter, Battery, Diesel Generator (DG), and Wind Turbine are given in Table 2.

The detailed analysis of the various microgrid topologies in term of different combination of the distributed generator system, with and without the energy storage system (battery) by taking both modes of operation (i.e. grid-connected and islanded) in consideration is carried out.

The summary of the detailed result is discussed in Table 3, which comprises component capacity, energy analysis (i.e. total generation from various DGs, capacity shortage, and grid sale & purchase energy), economic analysis (i.e. detailed variation of Capital Cost (CC), Replacement Cost (RC), Operation & Maintenance cost (O&M) and Salvage Cost (SC)), and emission analysis (i.e. mitigation of CO2, SO2 and NOX). The detailed analysis revealed that the PV system in grid-connected (i.e. G + PV) mode is most preferable. But after considering the intermittency of the PV system, a battery storage system is incorporated which raises the COE, NPC, and operating cost to another extent. Figure 7 shows the total monthly energy purchase (EP), energy sold (ES), and net energy trading (NET) under G + PV microgrid topology. The negative axis indicates the selling of surplus energy. From the

![Figure 4. Monthly average solar global horizontal irradiance & corresponding clearing index, and wind speed.](image-url)
Figure 7, it is revealed that amid the Feb, March, April, July, Oct, and Nov the generated power is higher than the load demand. While, in the rest of months the NET is positive, which means the load demand, is higher than the generated power, so the deficit power will be procured from the grid. Figure 8 shows the comparative study of the current system (i.e. grid-dependent system) with G + PV (i.e. PV system in grid-connected mode) and PV + B (i.e.

**Table 2.** Component cost.

| Components | Life time | CC | RC | O&M/C (/Y) |
|------------|----------|----|----|------------|
| PV         | 25Y      | 90000 | 90000 | 450        |
| WT         | 20Y      | 60000 | 55000 | 600        |
| C          | 15Y      | 7500  | 7500  | 75         |
| B          | 6Y       | 9000  | 7000  | 270        |
| DG         | 15000 h  | 30000 | 28000 | 2628       |

**Figure 5.** Hourly variation of solar irradiance throughout the year.

**Figure 6.** Hourly variation of solar irradiance throughout the year.

**Table 3.** Detail analysis of various microgrid topology.

| Analysis parameter / MG Topology | G | DG | G+PV | PV+B | PV+DG | PV+B+DG |
|----------------------------------|---|----|------|------|-------|---------|
| Cost analysis                    | NPC (million) | 864.2 | 2750 | 494.92 | 1419.6 | 2261 | 1751 |
|                                 | COE (INR/kWh)  | 9.02 | 28.91 | 5.41 | 17.02 | 23.77 | 18.41 |
|                                 | O&M/C (million) | 52.2 | 163.44 | 7.38 | 36.08 | 126.86 | 89.01 |
| System capacity analysis        | PV (kW) | 0 | 0 | 3886 | 4120 | 1300 | 1750 |
|                                 | DG (kW) | 0 | 0 | 1580 | 0 | 0 | 740 |
|                                 | Converter (kW) | 0 | 0 | 3078 | 2276 | 977 | 1506 |
|                                 | Battery (kW) | 0 | 0 | 0 | 48345 | 0 | 9828 |
| Energy trading (kWh/y)          | Energy Purchased | 5753283 | 0 | 3014812 | 0 | 0 | 0 |
|                                 | Energy Sold | 0 | 0 | 3014499 | 0 | 0 | 0 |
| Renewable penetration (%)       | 0 | 0 | 65.6 | 100 | 24.2 | 36.9 |
| Capacity shortage (%)           | 0 | 0 | 0 | 10 | 0.1 | 0.1 |
| Emission analysis (1000*kg/year)| CO2 | 3636 | 6046 | 0.2 | 0 | 4638 | 3225.1 |
|                                 | CO | 0 | 45.73 | 0 | 0 | 35.08 | 24.40 |
|                                 | SO2 | 15.78 | 14.8 | 0.00086 | 0 | 11.38 | 7.91 |
|                                 | NOX | 7.7 | 51.9 | 0.00042 | 0 | 39.87 | 27.72 |
was also carried out. The study revealed that under the proposed topology 3.636*10^6 kg of CO2, 1.578*10^4 kg of SO2, and 7.7*10^3 kg of NOx will be mitigated. Detail of break-up cost is given in Table 3.

Figure 9 shows the performance of battery SOC throughout the year. The battery characteristic consists of 80, 10, 90% as initial, minimum & maximum SOC with charging and discharging efficiency of 85%. Amid the Feb, May, June, August, Sep, and December the battery was highly used which indicates that the generated power by the solar was not sufficient to meet the load demand. The battery was being charged from the grid and the surplus power from the daytime and being discharged to meet the load demand.

7. Conclusion

In this paper, various microgrid topologies in both modes of operation (i.e. islanding as well as a grid) with and without the storage system were analyzed. Detailed of energy consumption and COE rising pattern is discussed, which revealed that the consumption has been increased by 35% in the last 5 years while COE energy is increased by approx. 75%. To execute the economic and feasibility analysis HOMER® is used as simulating and optimizing tool. Based on Net Present Cost (NPC), the detailed analysis reveals that G + PV in grid-connected mode and PV + B in off-grid mode are the most optimal solution for microgrid deployment at AMU. The techno-economic assessment reveals that total system cost under PV + B mode is 1419.6 million INR which is approx. 64.2% higher as compare to the current existing scenario (864.2 million INR), while the total system cost under G + PV mode is 494.92 million, which is approx. 57.2 % lower as compared to the current existing scenario.

A comparative study of the environmental and economic structure of proposed topology with existing one demonstrating a mitigation of approx. 3.636*10^6 kg of CO2, 1.578*10^4 kg of SO2, and 7.7*10^3 kg of NOx per year.
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