Micro grid for All India Institute of Medical Sciences, Madurai

C. Palanichamy* and P. Naveen

Multimedia University, 63100 Cyberjaya, Malaysia

*Corresponding author. E-mail: drcpc1119@gmail.com

Abstract

In 2018, the Government of India approved the establishment of the New All India Institute of Medical Sciences (AIIMS) in Thoppur, Madurai, Tamil Nadu, India. As the most important amenity for continuing primary care and rescue response is a healthcare facility, a secure electricity supply becomes an imperative necessity. Hence, as the energy supplier for the new AIIMS, Madurai, this paper proposes a microgrid combined with the utility grid. The microgrid consists of a 4-MW photovoltaic system, a 1.8-MW wind-turbine energy-conversion system, a backup diesel generator capable of meeting the forecasted maximum demand and a 1-MW battery energy-storage system. The AIIMS Microgrid will have a service providing a capacity of 20 MVA following integration with the utility grid. The proposed microgrid would be the first attempt at healthcare facilities in India since its first day of work to ensure the availability of electricity. It would have a 9.8% return on investment, a 13.6% internal rate of return and a payback period of 6.75 years once it is operational, as well as an attractive levelized cost of energy (LCOE) of USD 0.07547/kWh. It would provide an environmentally friendly atmosphere by avoiding an annual emission of 6261132 kg of carbon dioxide, 27362 kg of sulphur dioxide and 12838 kg of nitrogen oxides as compared to power supplied entirely from the utility grid.

Keywords: new healthcare facilities; load assessment; microgrid proposal; optimization
Introduction

Hospitals and healthcare facilities are the foremost energy-intensive consumers of the commercial sector and, as vital components of the delivery system of medical services, they are liable for a considerable portion of total commercial energy consumption in India [1, 2]. For effective functionality, perpetual operations and state-of-the-art medical equipment, most hospitals must have a continuous power supply. Globally, they are under tumultuous pressure to achieve more while controlling costs and limiting waste, and to offer enhanced patient consideration [3, 4].

In India, many healthcare facilities are located near electrical grid networks as the primary power-supply resource. Also, power failures and supply interruptions during high-demand periods have been problematic in grid-connected cities and regions [5]. In one major event, the biggest grid failure in history, over 30 and 31 July 2012 in the northern part of India, massive load demand, poor supply management and interruptions in transmission services led to a recurrent power-grid breakdown that affected 650 million people across the country, home to half of India’s population. By March 2019, the Indian government had granted USD 2.5 billion to provide electricity to all households [6]; access to affordable electricity remains a major concern for Indian health services. Even after the remedial measures, people were unable to ignore the historic grid breakdown and blamed it for the series of major longevity instances around the country, most of which were triggered by the breakdown of life-sustaining equipment such as ventilators and incubators.

Twenty patients died along with eight children, and many others had a tormenting experience when the Kurnool Government General Hospital went into darkness for 12 hours after the power supply had been shut down from 7 p.m. on Thursday, 22 June 2017 to the following morning [7]. More horrible still, no senior specialist, not even the Resident Medical Officer, was in the emergency clinic throughout the blackout. Of the 20 patients reported to have passed on, 4 were ladies. A senior specialist admitted that power disturbance caused the vast majority of deaths. As per source, power was switched off when police outpost personnel snarled electrical connections to high-tension wires on clinic premises to draw power illegally.

On 24 July 2016, 21 patients died from power outages at the state-run Gandhi Hospital, the most prominent 1200-bed hospital in the city of Hyderabad [8]. A few specialists said that power had initially stumbled at around 3 p.m. and then continued to do so on a regular basis. In spite of the fact that there were four generators on standby, the emergency clinic guaranteed that they had peak power generation and could not be used to identify the explanation for the stumbling after electrical cables were later cut off. Deaths occurred in specialty clinics, as well as in the Surgical Intensive Care Unit and the Emergency Ward. These are not just energy challenges for healthcare systems in India; power shortages in a number of countries are still a barrier to effective health services. Energy issues for hospitals vary in low- and high-income countries. The availability of sustainable energy for common medical needs is the key challenge for health facilities in low-income countries, especially those in sub-Saharan Africa [9]. Many healthcare facilities in these countries are facing a shortage of electricity for critical services, such as lighting, heating and medical devices. This would lead to decreased diagnostic capabilities and treatment facilities, shortened working hours during the day and shortages of committed healthcare professionals due to job dissatisfaction [10]. On the other hand, high-income countries are focusing on improving productivity and the practice of renewable energy to minimize energy use, reduce running costs and environmental impacts [11–15].

In the face of rising energy costs, rising demand, the escalating role of power-dependent technology in medical care and rising numbers of aggressive storms all over the world, the issue of resilience keeps several healthcare managers up at all times [16–18]. Thus, the acquisition and appropriate use of electrical energy is a pivotal step for any intricate structure that needs to reach the ideal energy level. Particularly for healthcare facilities, there should be a high level of concern about energy supply and maintenance, as they are the most vital facilities for continuing primary care and emergency care. Since recent incidents have led to power outages, there is no bias that puts hospitals and their patients at serious risk. Hospitals are exploring innovative energy models and highly developed, reliable and cost-effective technologies such as microgrids to address these critical energy concerns [19].

While monitoring and managing energy supply and demand, a microgrid will incorporate and regulate a broad range of energy sources [20–23]. As a result, in an emergency situation, the microgrid will be able to supply electricity to the hospital whenever the adjacent grid breaks down. Whereas the utility is not bound to control blackouts, the microgrid works 24 hours a day and throughout the year [24–26]. The microgrid is constantly on the job, unlike the backup generators that need to be kept under control to ensure they can function in a crisis. In addition, if not required for backup purposes, the microgrid allows the healthcare facility to achieve its cost and sustainability objectives through demand–response, peak shaving and load management, and excess-energy sales to the grid other than the use of on-site generators and energy-storage resources when electricity rates are high on the grid [27, 28].

Microgrid technology is very effective, as can be seen from the installation of California’s leading large-scale microgrid for healthcare services. In 2018, at the Kaiser Permanente facility in Richmond, California, the California Energy Commission issued a USD 4.78 million grant to Charge Bliss, Inc. to develop, build and run the foremost renewable-energy-based microgrid for a healthcare hospital in California [29]. The hospital was the only public...
hospital serving western Contra Costa County to provide the local population with critical care. In addition, the area was affected by a greater degree of environmental contamination and subsequent health consequences. A new microgrid controller was also developed for the project that will isolate the hospital’s life-safety emergency-power division, including emergency lighting and exit signs, and provide emergency power services. The microgrid resulted in an annual output of 395 000 kWh of renewable energy, a 4-hour reduction in demand of 220 kW from the battery and a reduction in emissions of 739 metric tons of CO₂/yr.

The Ministry of Health & Family Welfare, Government of India, approved a project for the development of a new All India Institute of Medical Sciences (AIIMS) in Madurai, Tamil Nadu, with a budget of USD 178 million in 2018 [30]. AIIMS includes the establishment of hospitals, trauma-centre facilities, medical colleges, residential complexes and related facilities/services, mostly based on AIIMS, New Delhi, and six proposed new AIIMS. The aim is to establish the new AIIMS as a nationally significant educational institution to provide quality medical education, as well as tertiary healthcare facilities for the people of Madurai and the surrounding area. The main purpose of this paper is to provide a reliable, economical and efficient power supply based on a microgrid for the new AIIMS Madurai. It is the right time to propose the inclusion of the microgrid, because the project is in the tendering stage. The greatest significance of this suggestion is that AIIMS New Delhi (established in 1956) ranked first in India by the National Institutional Ranking Framework [31], ranked first in South Asia and 231st in the Life Sciences and Medicine category worldwide by QS WUR [32], recognized and introduced the value of the microgrid only in 2017 [33, 34].

The novelty of the proposed microgrid is that it was suggested at the beginning of the approval stage of the AIIMS Madurai itself during the preparation of the infrastructure. Recently, the existing AIIMS in India began planning renewable-energy systems with PV systems only a decade or a few decades after its inception. Having PV alone is unreliable and, in countries like India with four seasons, operating efficiency is <14%, resulting in a higher unit cost of electricity generation. Moreover, because PV systems need vast land, the construction of solar farms without public support is not straightforward. In light of all these issues, a wind turbine (WT), as another renewable-energy system, has been included in this project, as the wind profile in the proposed area is favourable. At this site, a 1-kW WT with a height of 30 m will produce an energy output of 1750 kWh/yr with an attractive payback period of <7 years. The proposed microgrid is such that >50% of its maximum demand could be met by both PV and wind turbines, thus reducing dependence on the utility grid, apart from environmental credits. In addition, the proposed microgrid is based on the smart-grid concept of providing two-way power and communication facilities to enhance the reliability of the power supply at all times. Of course, due to smart-grid technology, the operating and maintenance (O&M) cost of AIIMS is slightly higher than that of conventional microgrid systems.

1 System modelling

AIIMS Madurai will have a hospital capacity of 750 beds with an interim departmental distribution of beds as shown in Table 1.

1.1 Site location

Thoppur village, Madurai-625008, is the proposed location for the new AIIMS. The village of Thoppur is located in the south of Madurai, Tamil Nadu State, India. It is located 20 km from Madurai South Sub-district Headquarters and 20 km from Madurai District Headquarters. As per the Global Positioning System, its coordinates are 9° 52.3’ N (latitude) and 78° 1.5’ E (longitude), respectively. Fig. 1 illustrates the site of the planned Thoppur AIIMS, Madurai. The annual average air temperature over a 30-year period (January 1984 to December 2013) was found to be 27.34°C and the annual average wind speed at 50 m above the surface of Earth over a 30-year period was 4.97 m/s, according to NASA’s Prediction of the Worldwide Energy Resource (POWER) Database [35]. The solar radiation and the clearness index of the proposed site as per the US National Renewable Energy Laboratory database [36] are shown in Fig. 2 and the annual average irradiance value is 5.61 kWh/m²/day.

| Departments | Beds |
|-------------|------|
| a) Speciality Departments | 360 |
| (Surgical & Allied Specialties, Medicine & Allied Specialties, and Obstetrics & Gynaecology) |
| b) Super Speciality Departments | 215 |
| (Cardiology, Cardio-thoracic Vascular Surgery-CTVS, Gastroenterology, Surgical Gastroenterology, Nephrology, Urology, Neurology, Neuro-surgery, Paediatric Surgery, Burns & Plastic Surgery, Medical oncology, Surgical Oncology, Radiation Oncology, Endocrinology and Pulmonary Medicine) |
| c) Other facilities | 175 |
| (Intensive Care Units (ICUs) & Critical Care, Trauma, AYUSH Facilities, PMR Department and Paid Beds) |
| **Total number of beds** | **750** |
1.2 Demand assessment

One of the key tasks for the energy management of the new system is the assessment of demand. Energy consumption depends on activity; climate and changes in occupancy, at different times of the day; days of the week; weather conditions; and seasons. India has four seasons and this is properly considered in the assessment of demand. Besides, the hospital loads are classified as critical and non-critical loads, depending on their importance, and this type of classification has been done during demand assessment in this project to give priority for availability duration. A load diversity varying from 0.5 to 1.0 has been considered. All medical devices, such as ventilators, anaesthesia machines, blood and infusion heaters, MRIs, x-rays and computed tomography scan (CTS), etc., require steady and good-quality electricity supplies for their operation and are considered to be critical loads, while hospital loads, such as heating, ventilating, and air conditioning (HVAC) systems and water heaters, etc., are grouped together as non-critical loads. Modern and sophisticated medical devices with lower energy consumption are chosen. LED lighting fixtures with built-in harmonic-suppression systems are considered for lighting in all areas and buildings in accordance with the National Building Code (NBC) 2016 [37], the Energy Conservation Building Code (ECBC) [38] and the Indian Standard Code. The demand assessment has been estimated on the basis of the covered area of various buildings/blocks as per NBC 2016 considering the lighting load as 13 W per square metre and power load as 55 W per square metre minimum. A 10% load was considered for future expansion. Table 2 shows the different loads and the respective locations and the quantity of the total amount of the connected load requirement in addition to the total demand for kVA at a power factor of 0.9.

1.3 Utility requirement

Tamil Nadu Generation and Distribution Corporation Limited, TANGEDCOUP [39] under state government control has a generation capacity of 18 747.28 MW consisting...
of TANGEDCO state-owned ventures, Central Generating Stations shares and Private Power Purchase. In addition, the state has projects of up to 1 047 961 MW in renewable-energy sources such as wind, solar, biomass and cogeneration. It will supply electricity to meet the electrical load requirements of AIIMS, Madurai, from its nearby 110/11-kV substation located in Kappalur, Madurai, at a distance of <2 km from AIIMS. AIIMS Madurai will have its own 20-MVA distribution substation with 2 × 10 MVA, 11/0.415-KV distribution transformers. The utility has a commercial tariff of USD 0.085/kWh and USD 5/kW. The buy-back tariff for renewable-energy supplies is USD 0.062/kWh, so that consumers can sell their excess energy from renewable energy to the grid.

1.4 Backup power supply

In the event of power failure on the part of the utility, diesel-generator (DG) sets are recommended for backup. The main concern is that the storage of diesel fuel should be there at all times. The main fuel-storage tanks must be tracked and refilled when they run down. Automated control systems are available to inform the generator operator when the level of the tank goes below the specified level. The capacity of the backup power supply has been fixed on the basis of the maximum demand. For the connected load of 14 400 kW, taking into account the average diversity factor of 0.8, the maximum demand is 11 520 kW. As a result, a backup power supply of 12 000 kVA for DGs has been recommended. It is advisable to use a large number

Table 2: Category-wise (power, lighting and residential loads, and total load) demand assessment of AIIMS Madurai

| a) Power loads | kW | Load and location | kW |
|----------------|----|-------------------|----|
| OPD & Diagnostic Block | 550 | Night shelter | 135 |
| Medical equipment | 905 | Auditorium | 98 |
| Hospital Block (720 beds) | 2320 | Fire station | 87 |
| Ayush Hospital (30 beds) | 115 | Dining hall | 75 |
| Medical & Nursing College | 1040 | Kitchen equipment | 44 |
| HVAC | 1925 | Director’s residence and servant quarters | 40 |
| Lifts (56 nos) | 710 | Guest house | 38 |
| Plumbing and pump load | 560 | Mortuary | 32 |
| Apartment blocks | 885 | Waste-management block | 32 |
| PG hostel blocks | 802 | Laundry | 32 |
| Working nurses’ hostel | 420 | Shopping centre | 22 |
| Boys’ and girls’ hostels | 340 | Cafeteria | 14 |
| **Total load in kW** | | | **11 221** |
| **Load in kVA at 0.90 power factor** | | | **12 468** |

b) Lighting loads

| Load and location | kW | Load and location | kW |
|-------------------|----|-------------------|----|
| OPD & Diagnostic Block | 139 | Fire station | 7 |
| Hospital Block (720 beds) | 624 | Dining hall | 19 |
| Ayush Hospital (30 beds) | 30 | Kitchen | 24 |
| Medical & Nursing College | 267 | Director’s residence and servant quarters | 10 |
| Plumbing and pumping house | 7 | Guest house | 11 |
| Apartment blocks | 230 | Mortuary | 11 |
| PG hostel blocks | 207 | Waste-management block | 15 |
| Working nurses’ hostel | 111 | Laundry | 11 |
| Boys’ and girls’ hostels | 85 | Shopping centre | 11 |
| Sports-field lighting | 93 | External lighting | 11 |
| Night shelter | 37 | Cafeteria | 7 |
| Auditorium | 81 | | | 
| **Total load in kW** | | | **2048** |
| **Load in kVA at 0.90 power factor** | | | **2276** |

c) Lighting and power loads of residential blocks

| Residential loads | | |
| Lighting and power loads in kW | 1131 |
| Lighting and power loads in kVA at 0.90 power factor | 1257 |
d) Total load in kW and kVA

| Total connected loads | | |
| Lighting and power connected loads in kW | 14 400 |
| Lighting and power loads in kVA at 0.90 power factor | 16 001 |
of generators rather than a single large-capacity generator in terms of reliability, operating efficiency and economics. The most significant locations to be provided with 100% backup power are:

OPD & Diagnostic Block, Hospital Block (720 beds), Ayush Hospital (30 beds), Medical & Nursing College, HVAC loads, plumbing and pump loads, all chillers and all AHUs, fire station, mortuary, laundry, auditorium, guest house, dining, shopping complex and director’s residence

For providing a 100% backup supply, four 2000-kVA (4 × 2000-kVA) generators are suitable and the strategic location for their placement is near the Hospital Block.

Other facilities and loads are provided with backup power of four 1000-kVA (4 × 1000-kVA) DGs, including: lifts (56 total); apartment blocks; PG hostel blocks; working nurses' hostel; boys' and girls' hostels; night shelter; sports-field lighting; waste-management block; cafeteria; residential blocks; lighting and fan loads; water and firefighting pumps; street lighting; and emergency services. The location for the DGs is near the sports field. All DGs are of an outdoor type with hospital-type silencers and acoustic enclosures. The total capacity of the DG backup power is therefore 12 000 kVA.

1.5 Energy storage

Energy storage is quickly moving forward and becoming a key player in the future of microgrids. In the context of the hybrid renewable-energy concept for the healthcare microgrid, the integration of wind and solar energy becomes inevitable. As both wind and solar have variable outputs, storage technologies have an immense potential to smooth the supply of energy from these sources. This storage option helps operators to dynamically balance energy on the grid by alternatively injecting and consuming excess electricity. Without a balance of supply and demand, the stability of microgrids becomes questionable. Various energy-storage technologies contribute to stability by operating at different stages of the microgrid from generation to end use by customers. Battery storage is preferable in hospitals due to portability, flexibility and economic concerns. The capacity of a storage plant is given as the following expression [40]:

\[ C_{wh} = \left( E_L \times AD \right) / \left( \eta_{inv} \times \eta_{bat} \times \text{DOD} \right) \text{ Wh} \]  

(1)

where \( C_{wh} \) represents the battery capacity (Wh), \( E_L \) represents the average energy load per day, AD represents the number of autonomous days of the battery, \( \eta_{inv} \) represents the efficiency of the inverter, \( \eta_{bat} \) represents the efficiency of the battery and DOD represents the battery-discharge depth.

Battery backup is provided for operation theatres, essential loads and medical equipment of the Hospital, Medical and Nursing College, the Ayush Block, the auditorium and the Computer Centre. It is recommended to use a 4-hour, 1-MWh capacity Li-ion battery [40]. It offers outstanding functionality for microgrid implementation. Depending on the size of the microgrid, the Li-ion battery can be used as an energy-storage system due to its extended size range. Furthermore, its falling price and the recovery of performance and lifetime enhance the applicability of this Li-ion battery.

1.6 Renewable-energy options

Renewable energy is an attractive choice worth exploring, depending on availability, accessibility and cost, policies and incentives, and pricing and regulations for electricity. A variety of renewable options are worth considering: solar, wind and biomass resources. This initiative currently targets both solar and wind energy systems.

At the location of AIIMS Thoppur, Madurai (latitude: 9° 52.3’ N and longitude: 78° 1.5’ E), the annual average solar radiation is found to be 5.61 kWh/m²/day. Fig. 2 shows that, regardless of the four seasons, solar radiation is available throughout the year. The average annual radiation lasts for 5 months (42%) per year and the maximum radiation takes place for a period of 3 months (25%).

The universal method for determining the electricity generated by a photovoltaic system [41] is as follows:

\[ E = A \times r \times H \times PR \quad \text{kWh} \]  

(2)

where \( E \) represents the energy produced (kWh), \( A \) represents the total area of the solar panel (m²), \( r \) represents the solar-panel yield or efficiency (%), \( H \) represents the annual average solar radiation on tilted panels without shading and \( PR \) represents the performance ratio, coefficient for losses (between 0.5 and 0.9, default value = 0.75).

The site is lucrative so that, with a payback period of <7 years, a 1-m² PV panel will generate ~2050 kWh/yr. In view of the yield and the rate of return, a 4-MW PV system with a capacity of ~35% of AIIMS Madurai’s maximum demand has been proposed. While fixing the capacity, the annual solar variation has been duly considered and the backup power supply has been fixed with a diversity factor of 0.8.

The AIIMS site has an average annual wind speed of 4.97 m/s at an anemometer height of 30 m. It lasts for 4380 hours per annum, as seen in Fig. 3. The power output of a WT is given by the expression [42, 43]:

\[ P_T = \frac{1}{2} \times \rho \times A \times v^3 \times C_p \quad \text{Watts} \]  

(3)

where \( P_T \) represents the power output (W), \( \rho \) represents the air density, 1.22 kg/m³, \( A \) represents the turbine swept area (m²), \( v \) represents the wind speed (m/s) and \( C_p \) represents the performance coefficient of the WT.

At this site, a 1-kW WT with a height of 30 m will produce 1750 kWh/yr of energy. Higher WT-generator capacity with higher hub height is an efficient and economical option for better yield. An attractive payback
period of <7 years is feasible with 900-kW capacity WTs. Two such WTs (2 × 900 kW) are proposed for this AIIMS project. Including PV solar and wind power, the contribution of renewable energy to the maximum demand of AIIMS Madurai will be 50.35%.

Since weather (solar irradiance, wind) varies from year to year, a slightly higher capacity to cope with the rise and fall of generation due to year-to-year wind and solar irradiance was considered with a diversity factor of 0.8 when designing the power-generation capacity of the microgrid.

2 Optimization platform

As the AIIMS Microgrid infrastructure has been finalized, the next step is to evaluate its performance and whether or not it can meet the energy requirements of AIIMS Madurai without sacrificing its reliability. To do so, an online platform becomes essential to achieve the objective economically. Computational approaches are usually used to model, test and forecast energy efficiency in the design of microgrid projects. There are a number of software packages available for the optimization mission and it is wise to select the most flexible one.

2.1 DER-CAM

DER-CAM was built by Lawrence Berkeley National Lab, Berkeley, California, USA [44]. It is a decision-support device for decentralized power systems. The important objective of DER-CAM is to conduct a techno-economic comparison of distinct on-site electricity-generation technologies or microgrids and to optimize the costs of on-site electricity generation using linear programming techniques.

2.2 CitySim

Built by the Laboratory of Solar Energy and Physics Buildings (LESO-PB), Switzerland [45], CitySim has a Java-based graphical user interface that supports the decision-making function of surviving urban development. The objective of this instrument is to simulate and optimize the flow of building-related resources (energy, water and waste) and their inter-relationships, as well as to investigate their dependence on urban climates.

2.3 EAM

EAM is used to evaluate the economic viability of microgrids [46]. It is capable of optimizing the capacity of microgrids through the proper choice of equipment selection, power rating, capital and running costs, and lifetime equipment. There is provision for a comparison of the optimized cost of the microgrid against the energy cost of the utility.

2.4 HOMER Grid

Based on software developed by the National Laboratory for Renewable Energy (NREL) [47], HOMER Grid is designed for the economic and engineering assessment of grid-connected and off-grid energy systems. The key capability of HOMER Grid is to simulate the efficiency of any specific configuration of the energy system. However, on specified systems, the programme is also adequately capable of running economic optimization and sensitivity/uncertainty analysis. It is important to note that the optimization is performed on parameters that the designer has control over. Sensitivity analysis is based on factors that are subject to uncertainty or shift that are beyond the control of the designer, like wind speed and the price of fossil fuel. HOMER Grid input data include customer load profiles for electrical and thermal energy, any resources and fuel used by the electrical and thermal power-generation systems, energy-system components, electrical and thermal load curves with a resolution of ≤1 minute, technical efficiency, O&M costs, emission limitations and sensitivity
parameters. HOMER Grid outputs the results of the assessment and analysis in the graph format and in the comprehensive data reports.

Based on the extended facilities, the accuracy of the results and the ease of availability, the HOMER Grid platform was preferred for the design of the microgrid for AIIMS Thoppur, Madurai.

3 AIIMS Madurai Microgrid

HOMER Grid, the identified optimization platform, performs simulation calculations on an hourly basis throughout 8760 hours of the year [48]. Based on the energy balances, the estimations compare the thermal and electrical energy both supplied and required by the system. Based on the energy balances, the estimations compare the thermal and electrical energy both supplied and required by the system. HOMER Grid decides on the optimal configuration of the system as well as analyses of the cost of the system on the basis of these estimates. There was a significant assumption that the energy efficiency of the storage battery remains constant over the life of the battery, while, depending on the battery power and the ambient temperature, it varies, among other factors. Furthermore, the nominal voltage, the power curve, the lifetime curve and the minimum charge state of the battery are considered constant. An interest rate of 6% per year and a 25-year project lifespan are assumed in the computation.

3.1 Daily, seasonal and yearly load profiles

The actual daily-load demand is uncertain but predictable because AIIMS Madurai is in the development process. For AIIMS Madurai, demand is estimated based on data from other AIIMS with the same bed ability and similar location status. Taking into account the number of beds; the number of medical and nursing students; the likely number of outpatients every day; the number of physicians, nurses and support staff; the number of hostel inmates; and the number of campus residents, the head count is ~6200 people. The hourly load for the approximate head counts was reached on the basis of the same reference hospitals, as in Table 3.

Unlike standard commercial loads, for 9–18 hours a day, the hourly load stays at its peak for 10 hours. The minimum load occurs during the early morning and late night, when there will be no outpatients and most loads will be working at less than critical loads; lifts; and medical equipment.

The HOMER Grid database for electricity consumption provided the seasonal and yearly load profiles for AIIMS Madurai Microgrid as in Figs 4 and 5. The most noteworthy month-to-month load utilization would be in August, equal to 11 017.9 kW, and the load factor is found to be 0.43.

3.2 Microgrid architecture

Fig. 6 depicts the proposed architecture for the microgrid with its primary-load requirement. It includes the utility grid as the main electricity supply with a simple tariff, a backup DG, battery energy-storage system (BESS), two WTs each of 900-kW capacity, three PV solar systems ($2 \times 1000$ kW + $1 \times 2000$ kW) with a total capacity of 4 MW and a converter. The WTs and the PV solar systems have their own independent converters. Apart from that, being a critical

| Table 3: Estimated daily-load profile of AIIMS Madurai |
|-------------------------------------------------------|
| Hour and Load in kW                                   |
| Hour | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Load, kW | 2910 | 2910 | 2915 | 2915 | 3015 | 3230 | 4314 | 5380 | 6111 | 6111 | 6111 | 6111 |
| Hour | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| Load, kW | 6111 | 6111 | 6111 | 6111 | 6111 | 6111 | 5901 | 5190 | 3950 | 2935 | 2910 |

Fig. 4: The seasonal load profile of AIIMS Madurai Microgrid. This figure was used with permission from [47].
healthcare facility, to highlight the role of a converter in the microgrid, a separate converter has been included as a reliability concern.

Apart from the utility tariff, the appropriate initial capital cost, replacement cost and operation and maintenance costs of the DG, renewable-energy sources, storage battery and the converter are given in Table 4, which are the inputs for the optimization.

3.3 Optimization options

Microgrid optimization has been carried out with different combinations (or so-called options here) of integrating renewable and backup generation with BESSs. HOMER Grid has the flexibility and suitability to simulate future design configurations in the name of the options:

Reference: Only the utility grid
Option 1: Utility grid, generator backup and WT with battery storage system (Utility, DG, WT, BESS);
Option 2: Utility grid, generator backup and PV solar with battery storage system (Utility, DG, PV, BESS);
Option 3: All—utility grid, generator backup, WT, PV solar with battery storage system (Utility, DG, WT, PV, BESS).

The output performances of all optimization options are compared against the reference on the basis of (i) annualized cost; (ii) electricity production, consumption and sales; (iii) economic; (iv) annual utility bill; (v) fuel consumption; and (vi) emission release.

4 Results and discussions

4.1 Reference option: only with the utility grid

The primary input is the primary-load data from Table 3 and the power-grid tariff as USD 0.085/kWh for electricity and USD 5/kW for demand in order to perform this optimization. The energy buy-back tariff is USD 0.062/kWh for excess-energy sales. Output optimization yields:

- Total electricity production (kWh): 41,062,500
- Total net present cost (NPC) (USD): 52,957,160.61
- LCOE (USD/kWh): 0.09976
- Consumption charge (USD): 3,490,312.50
- Demand charge (USD): 606,155.71
- CO₂ emission (kg/yr): 52,957,160
- Carbon monoxide (kg/yr): 0.0
- Unburned hydrocarbons (kg/yr): 0.0
- Particulate matter (kg/yr): 0.0
- SO₂ emission (kg/yr): 112,511
- NOₓ (kg/yr): 55,024

The optimization indicates the monthly need for grid electricity to satisfy the load demand of the microgrid, as shown in Fig. 7, which incurred an annual USD 4,096,468.21 utility bill.
4.2 Option 1: Utility, DG, WT, BESS

Fig. 8 depicts the microgrid architecture for Option 1 consisting of the 12 000-kW DG, two WTs each of 900-kW capacity, a generic 4-hour 1-MW Li-ion kW battery and the 2880-kW generic system converter. All are integrated with the utility-grid supply system; their relevant data are obtained from the HOMER Grid database and the load and utility-grid data are already available in the optimization platform. The outcomes of the Option 1 optimization are listed in Tables 5–12 with the reference-option comparison.

According to the findings, the DG set had a total fuel consumption of 38 054 L for 32 hours and contributed 137 392 kWh/yr of electricity, with an average electrical output of 4294 kW. Its contribution to the overall output of electricity under Option 1 is just 0.335%. This is because of the major contribution from the wind turbines and the BESS even during demand-management situations to reduce the emission contribution by the DG set. The generated power output per year indicating the minimum (3000 kW), mean and the maximum (7695 kW) values of the DG are shown in Fig. 9. The specific fuel consumption works out to be 0.277 L/kWh and a marginal generation cost of USD 0.236/kWh at a mean electrical efficiency of 36.7%.

Table 4: Optimization input data for DG, WT, PV, BESS and converter

| Component | Initial capital | Replacement | O&M |
|-----------|----------------|-------------|-----|
| Diesel generator (DG) (Auto size Genset., 12 000 kW) | USD 750/kW | USD 500/kW | USD 0.01/operating hour |
| Wind turbine (WT), 900 kW (Enercon E-44, 55-m hub height) | USD 749 700 | USD 749 700 | USD 36 000/yr |
| WT, 900 kW (1) (Enercon E-44, 55-m hub height) | USD 749 700 | USD 749 700 | USD 36 000/yr |
| PV panel, 1 MW (ABB PVS 800–1000) | USD 625 000 | USD 625 000 | USD 25 000/yr |
| PV panel, 1 MW (1) (ABB PVS 800–1000) | USD 625 000 | USD 625 000 | USD 25 000/yr |
| PV panel, 2 MW (ABB PVS 980–2000) | USD 1 250 000 | USD 1 250 000 | USD 50 000/yr |
| BESS (battery) storage, 7030 Ah (generic 4-hour 1-MW Li-ion, 90% roundtrip efficiency) | USD 500 000 | USD 500 000 | USD 5000/yr |
| Converter (generic system converter, inverter 2880 kW and rectifier 2880 kW) | USD 300/kW | USD 300/kW | – |

Utility tariff

Energy: USD 0.085/kWh
Demand: USD 5/kW
Energy buy-back: USD 0.062/kWh

Fig. 7: The monthly utility-grid electricity requirement to meet the load demand of AIIMS Madurai

Fig. 8: The microgrid architecture for Option 1 consisting of Utility, DG, WT, BESS with converter. This figure was used with permission from [47].
Fig. 10 presents the monthly average renewable-energy power generation. Both WTs contribute 3,151,494 kWh annually, which is equal to 7.68% of 41,062,934 kWh/yr, the total electricity generated by the Option 1 microgrid configuration. They operated for 8,109 hours/yr with a LCOE of USD 0.0648/kWh. The annual electricity purchase from the utility grid is 37,774,048 kWh (91.985%). There is an excess of 434 kWh after meeting the microgrid energy requirement, which has been sold to the utility. Fig. 11 portrays the monthly electricity production of the microgrid.

With respect to the reference option, there is a reduction in carbon-dioxide emission by 1,978,346 kg/yr, sulphur dioxide by 8,766 kg/yr and nitrogen oxides by 3,817 kg/yr. The Option 1 has a present worth of USD 1,086,663, an annual worth of USD 84,058/yr, a return on investment of 9.5% and an internal rate of return of 13.0% with a
simple payback period of 6.96 years. The total NPC is USD 43 167 210, the LCOE is USD 0.08132/kWh and the operating cost is USD 2 526 998. There are savings in utility bills on electricity-consumption charges USD –279 545.30 and demand charges USD –61 632.20 against the reference option besides demand-reduction revenue of USD 279 681. As a whole, the economic metrics of Option 1 are attractive when compared with those of the reference option.

### 4.3 Option 2: Utility, DG, PV, BESS

The significant difference between Options 1 and 2 is the addition of PV systems in Option 2 in the place of WTs in Option 1. There are two 1-MW PV systems and a single 2-MW PV systems along with the DG and the BESS with system converter. All are interconnected with the utility main supply as in Fig. 12. As before, the data for the newly added PV systems are obtained from the HOMER Grid database. The renewable-energy-capacity addition is more than double in this option (4 MW in Option 2 versus 1.8 MW in Option 1).

### Tables 5–12

| Category                        | Option 1 (Utility, DG, WT, BESS)       | Option 2 (Utility, DG, PV, BESS)       | Option 3 (Utility, DG, WT, PV, BESS) |
|---------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| Total fuel consumed (L)         | 38 054                                | 43 164                                | 43 974                                |
| Specific fuel consumption (L/kWh)| 0.277                                 | 0.288                                 | 0.289                                 |
| Mean electrical efficiency (%)  | 36.7                                  | 35.3                                  | 35.1                                  |
| Marginal generation cost (USD/kWh) | 0.236                           | 0.236                                 | 0.236                                 |
| Hours of operation              | 32                                    | 44                                    | 46                                    |
| Mean electrical output (kW)     | 4294                                  | 3411                                  | 3305                                  |

References:

Palanichamy and Naveen | 265
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Fig. 9: The DG-generated power output per year indicating its minimum (3000 kW), mean and maximum (7695 kW) values

Fig. 10: The monthly average power output of both wind turbines

Fig. 11: The monthly electricity production of the Option 1 microgrid for a 12-month period
contribution of 0.362%. The PV systems operate for 4376 hours/yr and the LCOE is USD 0.0406/kWh. The utility purchase of energy is 34 142 167 kWh as the major share of 82.28%. In Option 2, the electricity purchase from the utility has been reduced by 3 631.881 kWh (10.64%), which means that the dependence on the utility grid has been decreased.

Fig. 13 presents the annual primary-load variations, the grid purchases and the grid-demand limit. Fig. 14 depicts the demand–response coordination of all the elements of Option 2. The demand incentive is set to USD 35/kW. The load peak is 8000 kW and the demand-reduction revenue works out to be USD 279 681.

There is an excess of electricity production that has been sold to the grid. Option 2 has a return on investment of 9.9% and an internal rate of return of 13.6% with a simple payback period of 6.71 years. The LCOE is USD 0.077532/kWh, whereas, in Option 1, it was USD 0.08132/kWh. There are total savings on utility bills for electricity charges of USD 742 881.37 against the reference option and, with reference to Option 1, the savings are higher by USD 401 703.87. There are considerable reductions on emissions in Option 2 with respect to the reference option such as carbon-dioxide reduction by 4 260 664 kg/yr, sulphur-dioxide-emission reduction by 18 685 kg/yr and nitrogen-oxides reduction by 8604 kg/yr. These reductions are much higher than those of Option 1, too, because of the higher amount of renewable penetration.

### 4.4 Option 3: Utility, DG, WT, PV, BESS

Option 3 is the renewable-energy-enhanced option consisting of both WTs and solar PV systems. The renewable-energy total capacity is 5.8 MW (consisting of 1.8 MW WT and 4 MW PV), which is >52% of the daily maximum demand. All the data are already available in the optimization platform with the support of the HOMER Grid.
database. The demand-management option has been provided as before. The microgrid architecture of this option is shown in Fig. 6. The comprehensive outcome results are presented in Tables 5–12.

In Fig. 15, the monthly total energy production by all the resources in Option 3 is given. The annual energy generation is found to be 41 490 520 kWh, which is the highest generation among all the three options. While comparing the annual utility energy cost among all the options, the reference option incurs the highest utility cost because of no renewables contributed. Among the renewable-integrated Options 1–3, Option 3 has the lowest

![Fig. 14: The demand–response events in Option 2](image)

![Fig. 15: The monthly energy production in Option 3 with Utility, DG, WT, PV, BESS](image)

![Fig. 16: The annual utility energy cost including the consumption and demand charges](image)
utility energy cost, as seen in Fig. 16. In percentage measures, the reference option is 100, Option 1 is 91.985, Option 2 is 82.25 and Option 3 is the lowest, equal to 74.574. Apart from the electricity purchase from the utility, the renewable-energy contribution has a significant impact on the total energy requirement to meet the microgrid energy demand. Fig. 17 portrays the renewable-energy contributions by all options except the reference case, since there is no renewable-energy source. It is a good sign that the grid dependency has been reduced by >25% because of the 25.04% energy production by the renewables (both the WT and PV) and a small contribution of 0.366% by the DG.

The major renewable-energy contribution resulted in environmental friendliness especially in healthcare environments by a reduction in CO$_2$ by 6.261.132 kg/yr, SO$_2$ by 27.362 kg/yr and NO$_x$ by 12.838 kg/yr against the reference option. Among all the options, these are the highest reduction quantities in emissions.

The generic 4-hour 1-MW Li-ion BESS has an autonomy of 0.899 hours, a storage wear cost of USD 0.025/kWh and a usable normal capacity of 4216 kWh. It has a lifetime throughput of 4.452.292 kWh and an annual throughput of 296.819 kWh/yr. The energy-content daily profile of the BESS is shown in Fig. 18. Both the DG and BESS coordinate with the renewable sources (WT and PV) in the demand-management events of the microgrid. Whenever there is no renewable-energy generation, the roles played by the DG and BESS are significant.

On economic metrics, Option 3 has a return on investment of 9.8%, an internal rate of return of 13.6% and a payback period of 6.75 years. Though all the three options have payback periods of <7 years and internal rates of return of ~13.6%, the LCOE is attractive for Option 3 at USD 0.07547/kWh. Besides, the operating cost is much lower in Option 3 and its annualized cost is the lowest among all the options in spite of the addition of 5.8 MW of renewable-energy systems.

Fig. 17: The annual electricity contribution by all the renewable sources in MWh from each option

Fig. 18: The daily energy-content profile of the BESS for a 12-month period
4.5 Utility-grid outage

As the main purpose of the incorporation of the microgrid is to improve the power-supply resiliency, a power-outage case is considered based on the existing state utility grid’s operating conditions. During certain days, there would be a reduction in consumer demand such as 60%, which means that the consumer could make use of only 40% of the sanctioned maximum demand. Another prevailing situation is a 100% planned power cut or power-supply outage for certain hours of a day, such as 13 hours to 17 hours. Under that situation, all consumers in that region are in darkness unless backup power-supply facilities are available for them. The 100% planned outage is considered here as the unexpected power outage due to the grid’s technical functional issues for the simulation purpose.

A 100% power outage of the utility grid for 4 hours during a daytime period has been simulated with the microgrid functioning (as in Option 2: Utility, DG, PV, BESS) without the WTs because of low wind below the minimum in turbine speed. The 100% power outage occurred at 13.00 hours. During that period, the maximum demand of AIIMS was 7000 kW. The microgrid responded and all the loads were served by the battery backup system. Being daytime, there was a PV generation of ~4000 kW; hence, the DG was not triggered. The supply interruption continued for another hour while the AIIMS demand was ~5500 kW. As there was a reduction in PV generation to 3500 kW, the DG has been activated and the loads were met by the backup supply. Likewise, for the continued power outage until 17.00 hour, the generator and the PV generation maintained the continued power supply through the BESS (Fig. 19). Considering the prevailing power-outage situations of the region, the microgrid has been designed to maintain supply reliability even if the utility power outage is up to the maximum sanctioned demand of the microgrid.

4.6 Lessons learned and scope for future energy fields

The proposed microgrid would be the first attempt at healthcare facilities in India since its first day of operation to ensure the availability of electricity. Renewable energy such as solar and wind have been considered for economic and environmental advantages. Biomass, apart from these two, may be the next option in the near future, depending on the production of waste. From a reliable point of view, more types of energy sources would be beneficial. In addition to battery backup, fuel cells could be preferred for backup power supply. Although bilateral power and communication facilities are introduced in the name of smart-grid technology, it is only the initial stage and, depending on the state-of-the-art technological changes, it needs to be modernized.

In this optimization platform, demand management has been duly considered without many grid failures (only one example has been provided). In future work, various magnitudes of grid failures, scheduled power cuts and the energy harnessed from the hospital non-hazardous waste shall be considered.

5 Conclusion

This paper proposed a 20-MVA microgrid for the newly approved 750-bed AIIMS healthcare facility in Madurai.
AIIMS hospitals already in operation, some of which had been established several decades before with no microgrid resources, have now begun to incorporate renewable energy due to energy shortages and grid failures. The authors of this paper considered that it will be economical and environmentally feasible to introduce a microgrid with a utility-grid interconnection option as the electricity supply at the planning stage itself to ensure service continuity and reliability. A detailed load assessment has been carried out considering the number of beds, the medical and nursing students, doctors, nurses and supporting staff, outpatients and visitors, critical and non-critical electrical loads, hostel facilities and resident staff quarters, etc. The demand forecast resulted in 16,000 kVA as the connected load capacity at a 0.90 power factor. Allowing space for future expansion, 20 MVA has been finalized as the capacity of the proposed microgrid.

Within 2-km distance, the state utility grid is available for interconnection as the primary supply. For accommodating renewable energy, the locally available natural resources are considered. The wind speed and solar radiation are favourable; hence, 4 MW of PV panels and 1.8 MW of WTs are proposed for the microgrid with DG and BESS backup. For optimization purposes, the HOMER Grid platform has been used. Various options of renewable capacities were tested and, as a result, a combined 5.8-MW capacity of wind and PV solar generation with 12 MW DG and 1 MW BESS were finalized. On economic metrics, a return on investment of 9.8%, an internal rate of return of 13.6% and a payback period of 6.75 years were achieved besides an attractive LCOE as USD 0.07547/kWh. Avoided annual emissions of 6,261,132 kg of carbon dioxide, 27,362 kg of sulphur dioxide and 12,838 kg of nitrogen oxides have been achieved as compared to the mere utility-grid power supply.

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Conflict of Interest
None declared.

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