Hybrid Solar PV/Biomass Powered Energy Efficient Remote Cellular Base Stations

Md. Sanwar Hossain*‡ (*Student Member, IEEE*), Md. Fayzur Rahman**

*Department of Electrical, Electronic and Communication Engineering, Military Institute of Science and Technology (MIST), Dhaka-1216, Bangladesh

**Department of Electrical and Electronic Engineering, Green University of Bangladesh (GUB), Dhaka-1216, Bangladesh

(sanwareee@gmail.com, drfayzur@eee.green.edu.bd))

‡ Corresponding Author; Md. Sanwar Hossain, Tel: +8801719452910, sanwareee@gmail.com

Received: 15.02.2020 Accepted:09.03.2020

Abstract- Bangladesh is a tropical and fourth rice-producing country in the world. Bangladesh has enough potential to produce electricity from solar photovoltaic (PV) and biomass. The aim of this work is to analyze the feasibility of hybrid solar PV and biomass generator (BG) based supply systems for providing sustainable power to the off-grid macro cellular base stations (BSs). The technical and economic aspects of the introduced system have critically been examined using the Hybrid Optimization Model for Electric Renewables (HOMER) optimization software under a wide range of network configurations. Besides, the wireless network has extensively been evaluated using Matlab based Monte Carlo simulations in terms of performance metrics such as throughput and energy efficiency, considering the dynamic traffic profile. Numerical results demonstrate that the hybrid solar PV/BG system is an attractive solution to the challenges of developing a green cellular network in the context of geographical location like Bangladesh for several advantages. The research finds that the hybrid supply system has sufficient excess electricity and backup capacity that increase the system reliability. It also identifies that the proposed system indirectly minimizes CO_2 emission by reducing the biomass burning in cooking purposes. Finally, the outcome of the hybrid solar PV/BG system has been compared with those of other supply schemes for justifying the system validity.

Keywords Solar energy, biomass energy, hybrid supply system, energy optimization, sustainability, green cellular network, energy efficiency.

1. Introduction

In recent years, energy consumption by the cellular networks has become a major concern due to the significant increment in data rate and the negative impact of this network on economy and ecology [1–3]. Base stations are the main electricity consumer in the cellular network, which consumes around 57 % of the total energy [1]. Basically, the remote cellular base stations are powered by pollutant diesel generator (DG) in areas where the grid connection is not available imposing immense pressure on fossil fuel as well as mobile operators [1], [2]. Moreover, the transportation of diesel is quite difficult and expensive in remote areas due to its geographical features. To tackle these ever-increasing energy demand, telecom operators are continuously searching for sustainable and secure energy sources, which will considerably minimize the capital cost and environmental impacts [3]. Authors in [4] reported that the annual energy consumption by the mobile industry has increased from 219 TWh in 2007 to 519 TWh in 2019, and it is speculated that the demand rises at a yearly rate of 10 %. This heavy demand for electrical energy imposes a higher amount of operational expenditure (OPEX) and capital expenditure (CPEX) on network operators. According to [5], the global operational expenditure for the telecom industry was allocated around twenty billion dollars in 2014. Apart from the economic aspects, the cellular network has a significant influence on environmental pollution. According to [1], the information and communications technology sector are responsible to emit 51 % of the total carbon footprint, and it is assumed that the amount of carbon dioxide (CO_2) ejaculated by the telecommunication sector will rise to 179 $MtCO_2$ by 2020. Additionally, remote stand-alone DG operated base stations upturn the burning of diesel, which significantly reduces fossil fuel preservation and increases the OPEX and carbon contents.

Harvesting energy from the locally available renewable energy sources (RES) is becoming popular technology and is being considered as a mature technology for a number of reasons [1], [6], [7]. Firstly, it reduces the sole reliance on fossil fuel. Secondly, renewable energy sources are widely available throughout the world. Thirdly, a huge amount of green energy can be generated from renewable energy sources by minimizing the costs of generating electricity and reducing carbon contents. Despite the above potential benefits, there are some challenges of harvesting energy from the RES including the weather condition and the dynamic nature of renewable energy sources, which may cause energy deficiency or outage [1], [3], [8]. Due to the outage, the quality of services (QoS) may be degraded. However, the combined utilization of different renewable energy sources or the integration of renewable energy sources with the non-renewable energy sources/electrical grid or renewable energy sources with sufficient energy storage devices can provide a better QoS. This is now, the main objective of the renewable energy powered cellular BS to develop a green mobile communication with a minimum net present cost.

1.1 Opportunities and Potential of Renewable Energy

The selected location of this work is off-grid rural areas of Bangladesh, which has a huge scope of generating electricity from locally available renewable energy sources. The most available renewable energy sources in Bangladesh are solar, wind, biomass, etc. These resources have not extensively been applied for generating electricity. Moreover, the research and development in this area are not yet saturated. The potential of solar and biomass (agriculture residue) energies in Bangladesh is explored in this subsection.

(i) Solar Energy

Bangladesh is a tropical country, whose geographical position is between 33º and 39º N latitude and between 124º and 130º E longitude. As a tropical country, Bangladesh has enough potential to harvest renewable energy from the sunlight. As reported by [9], [10] the average sunlight intensity and clearness index are respectively 4.59 kWh/m^2/day and 5.3; the highest solar intensity is 4 kWh/m^2/day in May and the lowest solar intensity is 6.5 kWh/m^2/day in June. With the help of this higher solar radiation profile and modern technology, Bangladesh has the capability of producing around 70 PWh electrical energy, which is 3000 times higher than the total electricity demand of the country [10].

The monthly solar intensity profile considering the average daily solar radiation rate is shown in Fig. 1 for the selected location of Bangladesh. The amount of energy harvested from the solar system depends mainly on the geographical position, weather condition, material of the module, module tilt, and tracking system [1].

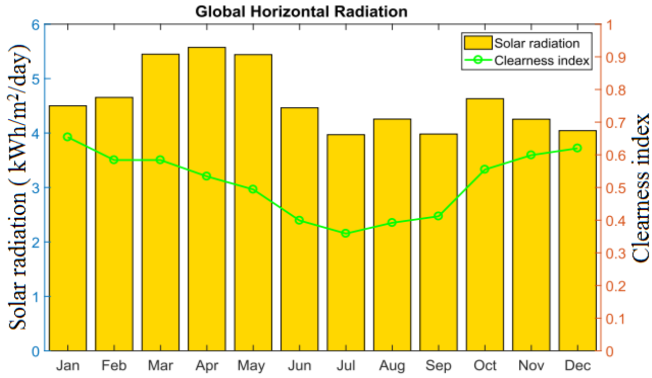


Fig. 1. Solar radiation profile of the selected area.

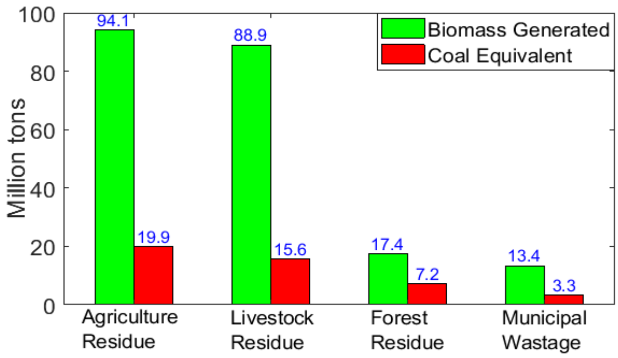


Fig. 2. Biomass energy potential of the selected area.

(ii) Biomass Energy

Bangladesh has enough potential for harvesting energy from biomass resources. The most available biomass sources of the country mainly include agriculture residue, animal dung, poultry dropping, etc. As an agricultural country, agriculture residue is the main source of biomass, wherein rice husk plays a significant role. As mentioned by the 'Rice Mills Owners Association' in Bangladesh, there are around 540 rice mills throughout the country, and the average capacity of the mills is 30 tons/day, which has the potential of producing 171 MW per day [11], [12]. According to [11], Bangladesh had approximately 90.21 million tons of biomass available whose energy potential was 1,344.99 PJ equivalent to 373.71 TWh of electrical energy in fiscal year (FY) 2012-2013. Authors in [12] studied that Bangladesh will able to generate 7,682 GWh energy from the rice husk with a total capacity of 1,066 MW in 2030.

Fig. 2 depicts the usable amount of biomass from different resources and their potential in coal equivalent. It is clearly observed that, among the different types of biomass resources, agriculture residue has the highest level of potential.

1.2 Contributions

The main concern of this work is to introduce a hybrid solar PV/BG system for developing green mobile communication with guaranteed quality of services. The key challenges and potential solutions for designing a hybrid solar PV/BG system are critically analyzed in 20 years. For justifying the effectiveness the optimal criteria have been evaluated and compared under various aspects.

The unique contributions of this work can be summarized as follows:

(i) To propose a hybrid solar PV and biomass-based supply system with sufficient energy storage devices for sustainable powering the remote cellular macro base stations.

(ii) To examine the techno-economic feasibility of the suggested system using HOMER optimization software in the context of different system bandwidth and transmission power.

(iii) To evaluate the performance of the wireless network in terms of performance metrics that are throughput and energy efficiency considering the dynamic nature of traffic.

(iv) To compare the implications of choosing a hybrid PV/BG system with respect to the other system in terms of performance parameters.

The rest part of the manuscript is organized as follows: Section 2 contains the literature review. Section 3 includes system modeling for the hybrid PV/BG enabled macro cellular network. In Section 4, cost modeling and optimization formula are presented. Section 5 outlines the system configuration. The results and discussions of the proposed system are demonstrated in Section 6 with insightful comments. Finally, Section 7 concludes this paper addressing the major findings.

2. Literature Review

Recently, the renewable energy-focused supply system has been considered as a promising solution for developing a green cellular network. As a consequence, harvesting energy from the locally available renewable energy sources has been extensively analyzed by telecom operators and researchers [1–3]. Being inspired by the above potential benefits Nokia Siemens has already developed a hybrid solar PV and wind turbine (WT) powered green cellular BS in the rural areas of Germany [13]. Ericsson [14] has also installed wind energy focused off-grid BS for avoiding the grid energy. In addition, a diesel generator based hybrid supply system has been established by the Huawei technology in remote areas of Africa and the Middle East [15]. Authors in [16] proposed a hybrid solar PV and WT scheme for powering the 3G cellular BS in remote areas of India. In these papers, the technical and economic feasibility of the system has been thoroughly studied for identifying the key challenges and optimal solutions. Reference [17] introduced a standalone solar PV enabled off-grid cellular BS by addressing the optimal system architecture and control strategy. The technical and economic feasibility of installing hybrid solar PV/DG enabled global systems for mobile communication (GSM) base stations in Nigeria has been extensively evaluated in [18]. Reference [19] analyzed the optimal criteria for installing a solar PV/WT/DG system for powering the off-grid BS in Spain. Authors in [20] examined the feasibility of deploying solar PV and wind energy focused macro BS in off-grid sites of Nepal. Reference [21] studied the key aspects and challenges of utilizing the hybrid solar PV/WT power system for off-grid cellular networks in Congo. Prabodh *et al.* [22] studied the deploying of three types of hybrid power system such as (i) solar PV/battery, (ii) solar PV/fuel cell (FC) and (iii) solar PV/FC/battery system for powering the off-grid BS in India. Reference [23] determined the mathematical modeling and size optimization of a hybrid (Solar & Hydro) and the DG system to feed the stand-alone BS site in Nigeria. Alsharif *et al.* evaluated the technical, economic and environmental aspects of installing the solar PV and hybrid solar PV/wind-powered third-generation cellular BSs in rural sites of South Korea [24]. Authors in [25] examined the feasibility of combining the locally available renewable energy sources with the public utility grid system in Malaysia for powering the cellular BS with green energy and minimizing pressure on the grid. In this work, the authors investigated the potential of locally available renewable energy sources and proposed three types of supply systems: (i) solar photovoltaic/electric grid, (ii) wind energy/electric grid, and (iii) solar photovoltaic/wind energy/electric grid. For powering the rural base stations in Malaysia, authors in [26] investigated the feasibility of utilizing solar energy with the traditional DG set. The concept of placing DG as a primary source is not effective, but it plays a significant role in combination with renewable energy sources. Reference [27] discussed the optimal criteria for installing a solar PV enabled off-grid BS in Pakistan with a DG as a secondary source of supply. Authors in [28] propose a hybrid solar PV and DG powered GSM base station for remote areas in Bangladesh in the context of the dynamic traffic pattern. The idea of design and techno-economic analysis of hybrid solar PV/WT supply for powering the off-grid cellular network with excess electricity sharing to the neighboring BS in Bangladesh are discussed in [29]. Moreover, [30] discussed the policies and strategies for renewable energy development in Indonesia.

3. System Modeling

In this section, the architecture and mathematical modeling of the major parts of the proposed system are provided.

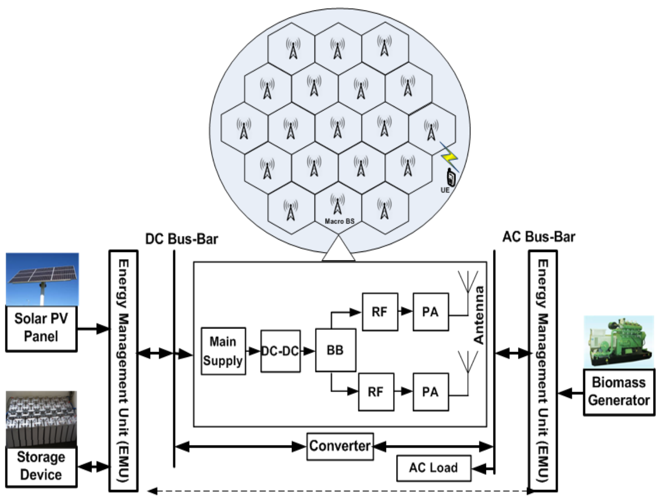


Fig. 3. Layout for the hybrid solar PV/BG system.

Fig. 3 represents the layout of the hybrid solar PV/BG enabled macro base station in the context of green mobile communication. At present, macro base stations are being installed with the Remote Radio Head (RRH) unit [29], [31]. In the macro base station, RRH potentially reduces the line loss and increases the quality of services by replacing the coaxial cable with an optical fiber link. Remote Radio Head is connected with the baseband and power amplifier unit. It is mentioned that no cooling system is required for the RRH enabled macro BS.

3.1 BS Model

The optimal architecture of a hybrid supply system depends heavily on the mathematical modeling of the BS load requirement. A macro base station with hexagonal shape has been considered in this work as shown in Fig. 3. A typical base station primarily consists of different types of power-consuming equipment such as DC-DC regulator, baseband unit (B), radio frequency (RF) unit, power amplifier (PA) unit, and transceiver (TRX) unit [31]. The amount of power consumed by the different parts of a BS is summarized in Table 1. Moreover, the dynamic traffic profile of the selected area is shown in Fig. 4. The total power consumption of a BS as a function of traffic intensity can be modeled as follows [31]:

$$P_{in} = N_{TRX}(P_1 + \Delta_p P_{\max}(\chi - 1)) \text{ if } 0 < \chi \le 1 \tag{1}$$
$$= N_{TRX} P_{sleep} \qquad \text{if } \chi = 0$$

where $P_1 = P_0 + \Delta_p P_{\max}$ is the maximum power consumption of a BS, N_{TRX} is the total number of the transceiver, Δ_p is the load dependency power gradient and P_0 is the consumption at idle state [31]. The scaling parameter χ is the load share, where $\chi = 1$ represents a peak load system and $\chi = 0$ represents an idle system [31]. Furthermore, a BS without any traffic load enters into sleep mode with lowered consumption, P_{sleep} [31].

The peak power consumption of the BS sector is calculated as follows [31]:

$$P_1 = \frac{P_{RF} + P_B + P_{PA}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{2}$$

where P_B is the baseband power consumption, P_{PA} is the power consumption of power amplifier and P_{RF} is the radio frequency power consumption. In addition, σ_{DC}, σ_{MS} and σ_{cool} respectively represent the losses in DC-DC regulator, main supply, and active cooling system [31].

The power consumption of power amplifier mainly depends on the maximum transmission power per antenna ($P_{\max}$), feeder losses (σ_{feed}) and the efficiency of the power amplifier (η_{PA}) which can be formulated as follows [31]:

$$P_{PA} = \frac{P_{\max}}{\eta_{PA}(1-\sigma_{feed})} \tag{3}$$

The amount of power consumption for other system BW as a function of transceiver antenna (N_{TRX}) can be expressed as follows [31]:

$$P_B = N_{TRX}\frac{BW}{10MHz}P_B^{'} \tag{4}$$
$$P_{RF} = N_{TRX}\frac{BW}{10MHz}P_{RF}^{'} \tag{5}$$

where $P_B^{'}$ and $P_{RF}^{'}$ respectively represent the power consumption by the baseband and RF for the given 10 MHz system bandwidth as obtained from Table 1 [31]. The key parameters of the macro with and without (w/o) RRH base stations are shown in Table 2.

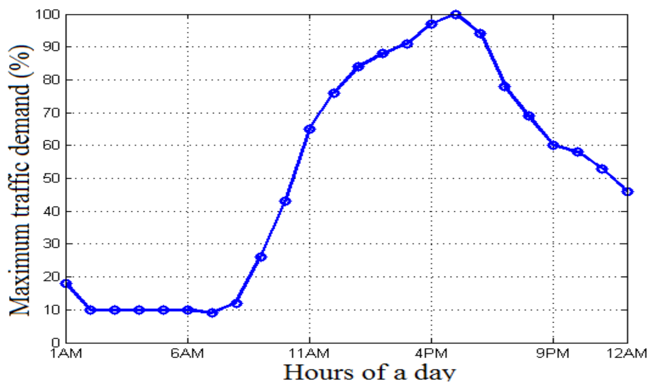


Fig. 4. Dynamic traffic intensity for the selected area.

Table 1. Power consumption parameters of a macro BS under BW=10 MHz [31].

Components	Parameters	with RRH	w/o RRH
BS	P_{max} [W]	20	20
	Feeder loss σ_{feed} [dB]	0	3
PA	Back-off [dB]	8	8
	Max PA out [dBm]	51	54
	PA efficiency, η_{PA} [%]	31.1	31.1
Total PA [W]		64.4	128.2
RF	P_{TX} [W]	6.8	6.8
	P_{RX} [W]	6.1	6.1
Total RF, P_{RF} [W]		12.9	12.9
Baseband (B)	Radio (inner Tx/Rx) [W]	10.8	10.8
	Turbo code (outer Tx/Rx) [W]	8.8	8.8
	Processors [W]	10	10
Total B, P_B [W]		29.6	29.6
DC-DC	σ_{DC} [%]	7.5	7.5
Cooling	σ_{Cool} [%]	0	10
Main Supply	σ_{MS} [%]	9	9
Sectors		3	3
Antennas		2	2
Total Power [W]		**754.8**	**1350**

Table 2. Macro base station key parameters [31].

BS Type	N_{TRX}	P_{TX} [W]	P_0 [W]	ΔP	P_{sleep} [W]
with RRH	6	20 and 40	84	2.8	56
w/o RRH	6	20 and 40	130	4.7	75

3.2 PV Model

The solar PV module collects solar energy and converts it into DC electrical energy. Multiple solar cells are connected in series/parallel to form a solar PV array for harvesting more energy. HOMER determines the energy generated by the solar PV module using the following formula [1]:

$$E_{PV} = R_{PV} \times PSH \times \eta_{PV} \times 365 \ \ day/year, \tag{6}$$

where R_{PV} is the rated capacity of the solar PV module in kW. PSH is a peak solar hour in an hour which is equivalent to average daily solar radiation in kWh/m^2/day. η_{PV} is the derating factor which refers to the relationship between the actual and target yield, and this factor is called the efficiency of the solar PV module. The output power of the solar PV modules mostly depends on the solar radiation profile, geographical location, DC-DC loss factor, tracking mode and the tilt of the solar PV module [1]. To generate a given maximum power (P_P), the required number of PV module can be expressed as [2]:

$$N_{PV} = \frac{P_P}{P_{nom}}, \tag{7}$$

where P_{nom} is the nominal power of the solar PV module.

3.3 BG Model

The key parameters of the biomass generator and their specifications are provided in Table 4. Power generation from the biomass gasifier system depends on the various factors such as the calorific value of biomass (CV_{BM}), biomass availability (T_{BM}), the operating hour of the biomass generator per day and overall conversion efficiency of biomass gasifier system (η_{BM}). This process can be expressed as follows [11], [12]:

$$P_{BM} = \frac{T_{BM}(tons/year) \times CV_{BM} \times \eta_{BM} \times 1000}{365 \times 860 \times (operating \ \ hour \ \ per \ \ day)}. \tag{8}$$

Annual energy production of a biomass gasifier based system can be estimated as [11], [12]:

$$E_{BM} = P_{BM}(365 \times 24 \times capacity \ \ factor), \tag{9}$$

where the capacity factor is the ratio of actual electrical energy output to the maximum possible electrical energy output over a given period. In this work, the set capacity factor is 0.05.

3.4 BB Model

The battery bank is a storage device that provides backup power during the deficiency/outage of renewable energy. In a hybrid solar PV/BG system, backup power supplied by the BB depends mainly on the state of charge (SOC) and depth of discharge (DOD) of the battery [1]. Battery state of charge is the indicator of charging and discharging level of the battery expressed in percentage. The depth of discharge of a battery bank determines how deeply the battery is discharged. Battery DOD can be formulated as follows [1]:

$$B_{DOD} = \left(1 - \frac{B_{SOC\min}}{100}\right). \tag{10}$$

Battery bank autonomy (B_{aut}) is one of the key factors that determines the battery backup time in hours. HOMER optimization software determines the B_{aut} based on the following equation [1]:

$$B_{aut} = \frac{N_{batt} \times V_{nom} \times Q_{nom} \times B_{DOD} \times (24h/day)}{L_{BS}}, \tag{11}$$

where L_{BS} is the average daily BS load in kWh.

Battery lifetime (L_{batt}) depends mainly on two factors: battery float life and lifetime throughput. In other words, batteries die either from the use or from old age. Battery lifetime plays a significant role to minimize the total replacement cost within the project duration. Based on the two factors, the overall lifetime of a battery can be determined as follows [1]:

$$L_{batt} = \min\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right), \tag{12}$$

where $Q_{lifetime}$ represents the lifetime throughput of a single battery measured in kWh. The annual battery throughput measured in kWh/year is represented by Q_{thrpt}. The battery float life (year) is represented by $R_{batt,f}$ [1].

3.5 EE Model

In this work, the term ‘energy efficiency’ is defined as the ratio of total network throughput to the total power consumed by the network. Energy efficiency measures the performance of the wireless network, which is expressed as the number of bits transmitted per Joule of energy. According to Shanon’s information capacity theorem, total achievable throughput in a wireless network at time t can be modeled as follows [2], [28]:

$$R_{total}(t) = \sum_{k=1}^{U}\sum_{i=1}^{N} BW \log_2(1 + SINR), \tag{13}$$

where N is the number of transmitting BSs and U is the total number of user equipment (UEs) in the wireless network. Thus, the EE metric denoted as η_{EE} for time t can be modeled as follows [2], [28]:

Table 3. Technical parameters for the Monte-Carlo simulation setup [32].

Parameters	Value
Resource Block (RB) bandwidth	180 kHz
System bandwidth, BW	5, 10, 15, 20 MHz
Carrier frequency, fc	2 GHz
Duplex mode	FDD
Cell radius	1000 m
BS Transmission Power	43 & 46 dBm
Noise power density	-174 dBm/Hz
Number of sectors	3
Number of antennas	2
Reference distance, d0	100 m
Path loss exponent, α	3.574
Shadow fading, σ	8 dB
Access technique, DL	OFDMA
Traffic model	Randomly distributed

$$\eta_{EE} = \frac{R_{total}(t)}{P_{in}}, \tag{14}$$

where P_{in} is the total power consumed in all the BSs at time t and can be calculated by using (1).

The performance metrics such as throughput and energy efficiency of the introduced networks are evaluated with the help of Monte-Carlo based Matlab simulation. The simulations are performed by averaging above 10,000 iterations considering the dynamic traffic profile. It is also considered that each user is associated with at least one resource block (RB). Table 3 summarizes the key parameters of the Monte-Carlo simulation setup.

4. Cost Modelling

In HOMER, the net present cost (NPC) represents the present value of all the associated costs that occur over the project duration. The total NPC of the system includes a capital cost (CC), replacement cost (RC), cost of electricity (COE), operation and maintenance cost (OMC), fuel cost (FC), and salvage value (SV). Thus, the NPC of the system can be modeled as follows [1]:

$$NPC = \frac{TAC}{CRF} = CC + RC + OMC + FC - SV, \tag{15}$$

where TAC is the total annualized cost and CRF is the capital recovery factor. The capital recovery factor is a function of annual real interest rate (i) and project lifetime (N) that can be modeled as follows [1]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}. \tag{16}$$

Salvage value is the leftover cost that remains in hand after the project completion. HOMER calculates the salvage value based on the following equation [1]:

$$SV = C_{rep}\left(\frac{C_{rem}}{C_{com}}\right), \tag{17}$$

where C_{rep} is the replacement cost of the component, C_{rem} is the remaining lifetime of the component, and C_{com} is the lifetime of the component.

The cost of electricity (COE) determines per unit cost of electricity in \$/kWh. Cost of electricity is the ratio of the total annualized cost to the total annualized electricity generation (E_{gen}) by the system which can be expressed as follows [1]:

$$COE = \frac{TAC}{E_{gen}} = \frac{NPC \times CRF}{E_{gen}}. \tag{18}$$

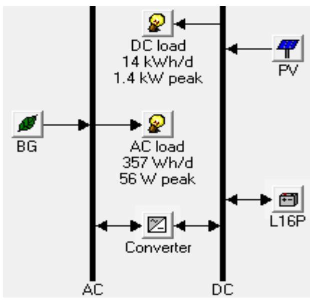
The problem of designing a hybrid energy system is considered as an optimization problem with the objective function of minimizing NPC, which is subject to various design and operational constraints. In other words, our prime goal is to minimize the energy shortage through maximum utilization of solar and biomass energy in conjunction with a battery bank, which in turn reduces NPC. The objective function of the proposed system can be expressed as follows [2]:

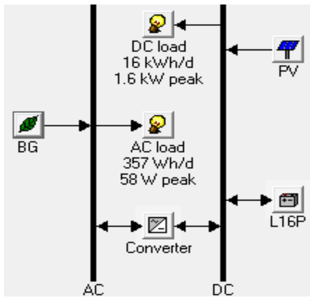
$$\text{minimize} \quad NPC, \tag{19a}$$
$$\text{subject to} \quad E_{PV} + E_{BG} > E_{BS}, \tag{19b}$$
$$E_{PV} + E_{BG} + E_{batt} = E_{BS} + E_{losses}, \tag{19c}$$
$$E_{Excess} = E_{Gen} - E_{BS} - E_{losses}, \tag{19d}$$

where E_{losses} is the total losses of the system which occurs mainly in the battery and converter.

5. System Configuration

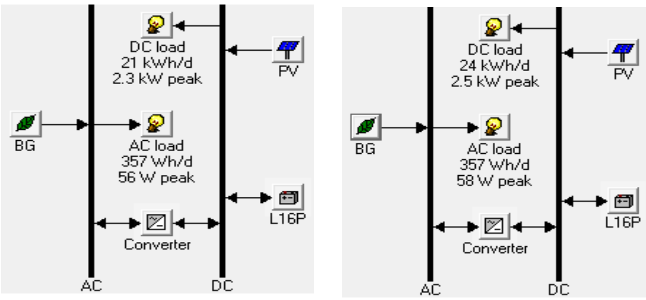
This section highlights the schematic diagram of the proposed system and the specifications of the major components used in the simulation setup. Fig. 5 and 6 illustrate the HOMER layout of the hybrid solar PV/BG system for Long Term Evaluation (LTE) macro under different network conditions. Besides, the daily DC load profile of the macro with and without RRH base stations are respectively illustrated in Fig. 7 and 8 under 10 MHz bandwidth. Remote macro BS also contains a 30W AC lamp which is usually used from six PM to six AM. The key features of the components used in the HOMER simulation setup are summarized in Table 4.





(a) with RRH (b) w/o RHH

Fig. 5: Layout in HOMER for the macro base station under P_{TX}=20 W.



(a) with RRH (b) w/o RHH

Fig. 6: Layout in HOMER for the macro base station under P_{TX}=40 W.

Table 4: Technical parameters and their value for the HOMER simulation setup [1], [10], [11].

System	Parameters	Value
Resources	Solar radiation	4.59 kWh/m²/day
	Biomass available	9 tons/day
	Interest rate	6.75 %
PV	Operational lifetime	25 years
	Derating factor	0.9
	System tracking	Two-axis
	Initial cost	\$1/W
	Replacement cost	\$1/W
	OMC cost/year	\$0.01/W
BG	Efficiency	30 %
	Operational lifetime	25,000 h
	Initial cost	\$0.66/W
	Replacement cost	\$0.66/W
	OMC cost/year	\$0.05/h
	Fuel cost	\$30/t
Battery	Round trip efficiency	85 %
	B_{SOCmin}	30 %
	V_{nom}	6 V
	Q_{nom}	360 Ah
	Lifetime throughput	1075 kWh
	Initial cost	\$300/unit
	Replacement cost	\$300/unit
	OMC cost/year	\$10
Converter	Efficiency	95 %
	Operational lifetime	15 years
	Initial cost	\$0.4/W
	Replacement cost	\$0.4/W
	OMC cost/year	\$0.01/W

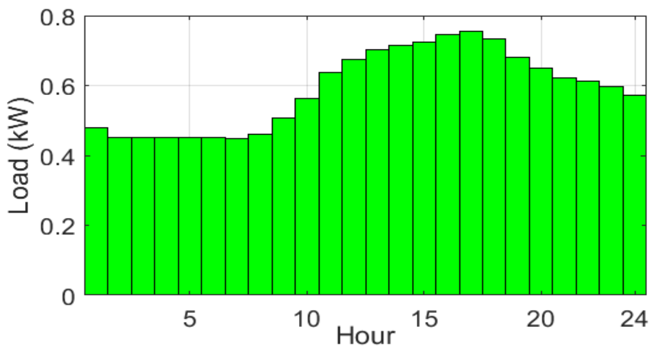


Fig. 7: DC load profile for the macro with RRH base station.

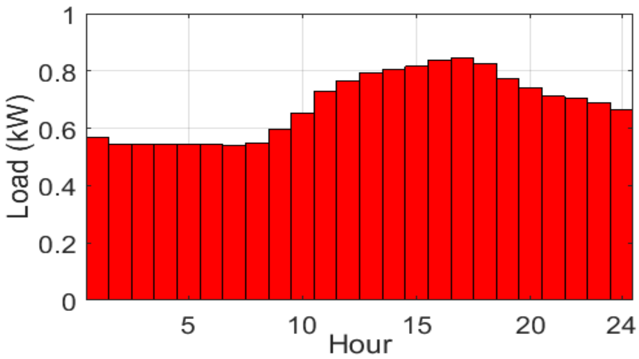


Fig. 8: DC load profile for the macro w/o RRH base station.

6. Results and Discussions

This section discusses several key parameters of the proposed hybrid solar PV/BG system to investigate the feasibility. The performance parameters are (i) Optimal System Architecture, (ii) Energy Yield Analysis, (iii) Energy Efficiency Analysis, (iv) Economic Yield Analysis, (v) Greenhouse gas (GHG) Analysis and (vi) Limitation Analysis. Moreover, it compares the performance parameters of the hybrid solar PV/BG system with the other systems for justifying network validity.

6.1 Optimal System Architecture

The optimal architecture of the hybrid solar PV/BG system for with and w/o RRH macro BS is summarized in Table 5, Table 6, and Table 7. This result has been found simulating the hybrid solar PV/BG system in HOMER optimization software under different transmission power (P_{TX}) and system bandwidth (BW). According to Table 1, macro BS without RRH consumes more power than the BS with RRH. As seen from Table 5 and Table 6, macro BS without RRH requires a large number of the solar PV module to cope up with the higher energy demand. Table 5, Table 6 and Table 7 also show that the size of the solar PV module increases linearly with the increment of transmission power and system bandwidth. This happens because a higher value of P_{TX} and BW upholds the base station energy requirement. The optimal size of the BG, battery, and converter are in a smaller range and remain constant for all configurations. It means that the solar PV/BG system is technically feasible and can meet the BS energy requirement satisfactorily for different network settings.

Table 5: The optimal size of the hybrid solar PV/BG system under P_{TX}=20 W.

BW (MHz)	PV (kW)		BG (kW)		Battery (units)		Converter (kW)	
	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH
5	2.5	3	1	1	64	64	0.1	0.1
10	3.5	4	1	1	64	64	0.1	0.1
15	3.5	4	1	1	64	64	0.1	0.1
20	5	5	1	1	64	64	0.1	0.1

Table 6: The optimal size of the hybrid solar PV/BG system under P_{TX}=40 W.

Radiation (kWh/m^2/day)	PV (kW)		BG (kW)		Battery (units)		Converter (kW)	
	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH
4.5	4.5	5.5	1	1	64	64	0.1	0.1
5	4.5	4.5	1	1	64	64	0.1	0.1
5.5	4	4.5	1	1	64	64	0.1	0.1

Table 7: The optimal size of the hybrid solar PV/BG system for macro with RRH base station.

BW (MHz)	PV (kW)		BG (kW)		Battery (units)		Converter (kW)	
	20W	40W	20W	40W	20W	40W	20W	40W
5	2.5	3.5	1	1	64	64	0.1	0.1
10	3.5	5	1	1	64	64	0.1	0.1
15	3.5	5.5	1	1	64	64	0.1	0.1
20	5	6	1	1	64	64	0.1	0.1

The rated value of the solar PV module is 3.5 kW at P_{TX}=20 W and BW=10 MHz. According to (7), the required number of Sharp ND-250QCs solar PV module is 14: as connected 2 in series and 7 in parallel. The nominal rated voltage of the Trojan L16P battery is 6 V; hence, a 48 V DC bus–bar connected in series is used. As a consequence, the total of 64 battery units is connected 8 in series and 8 in parallel.

6.2 Energy Yield Analysis

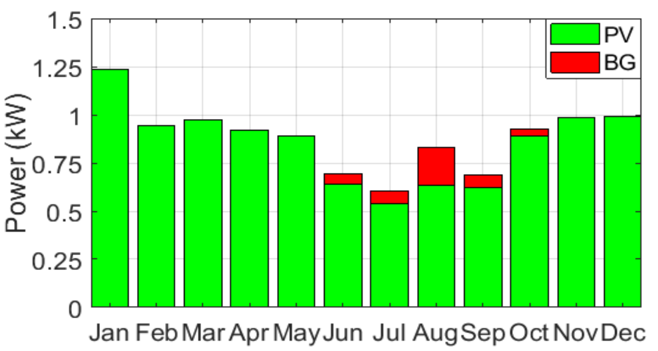


Fig. 9: Energy contribution for macro with RRH base station under P_{TX}=20 W.

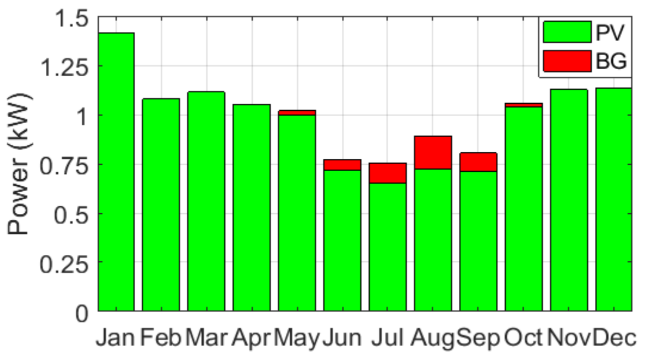


Fig. 10: Energy contribution for macro w/o RRH base station under P_{TX}=20 W.

In this subsection, the annual energy generated by the solar PV module and BG is discussed based on the optimal system architecture. Moreover, BG lifetime, annual energy breakdown, BB throughput, and BB autonomy have critically been analyzed under a different network configuration.

The monthly statistics of power production by the solar PV and BG are presented in Fig. 9 and 10, respectively, for macro with RRH and without RRH base station. These figures have been found under 10 MHz bandwidth for the average solar of 4.59 kWh/m^2/day and available average biomass of 9 tons/day. Fig. 9 and 10 indicate that the maximum power contribution occurred by the solar PV module because of the tropical weather of the country. Moreover, macro without RRH enabled hybrid solar PV/BG system produces 7 % more power than the macro with RRH enabled hybrid system.

(i) Solar PV array

According to Table 5, the hybrid solar PV/BG system requires a 3.5 kW size solar PV module for macro with RRH base station under P_{TX}=20 W and BW=10 MHz. The annual energy generated by the 3.5 kW solar PV module can be determined using (6) in the following way:

$$E_{PV} = 3.5\ kW \times 4.59\ kWh/m^2/day\ \times 0.9\ \times 365\ day/year$$
$$= 5{,}277.35\ kWh/yr$$

Additionally, a dual-axis tracking mode of solar PV module increases the total amount of energy by 43.4 % resulting in 7,567 kWh/yr. In a similar process, generated energy through all other configurations is calculated. The annual energy generated by the solar PV for different network configurations is illustrated in Fig. 11. All the curves follow a similar pattern of increasing trend corresponding to the system BW and transmission power. Moreover, higher solar energy generation is found for the higher value of P_{TX} and without RRH configuration as explained in the subsection of monthly power contribution.

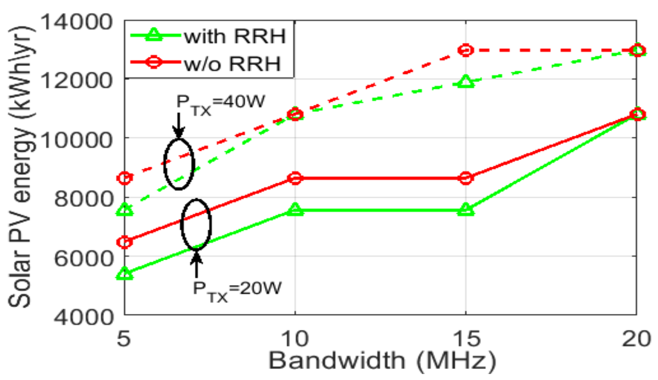


Fig. 11: Energy generation by the solar PV module.

(ii) Biomass Generator

The hybrid solar PV/BG system requires 1 kW size BG for the macro base station under all network configurations. The annual energy generated by the 1 kW BG can be determined using (8) and (9) as follows:

$$P_{BM} = \frac{0.314\ \ t/year\ (BM_{TA}) \times 3{,}411.33\ \ KCal/Kg\ \ (CV_{BM}) \times 0.30\ \ (\eta_{BM}) \times 1000}{365 \times 860 \times 2.0547\ \ (operating\ \ hour\ \ per\ \ day)}$$

$$= 0.498\ \ kW$$

$$E_{BM} = P_{BM}(365 \times 24 \times capacity\ \ factor) = 0.498 \times 365 \times 24 \times 0.05 = 225\ \ kWh/yr$$

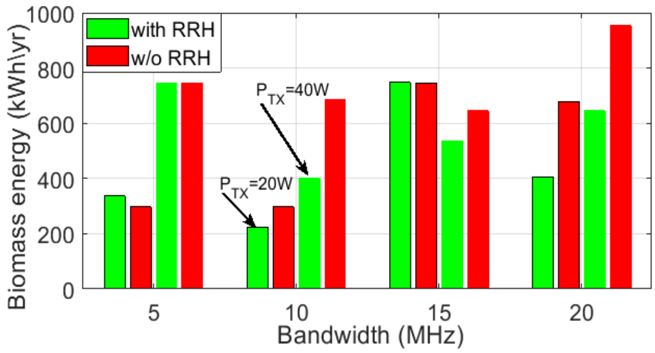


Fig. 12: Energy generation by the biomass generator.

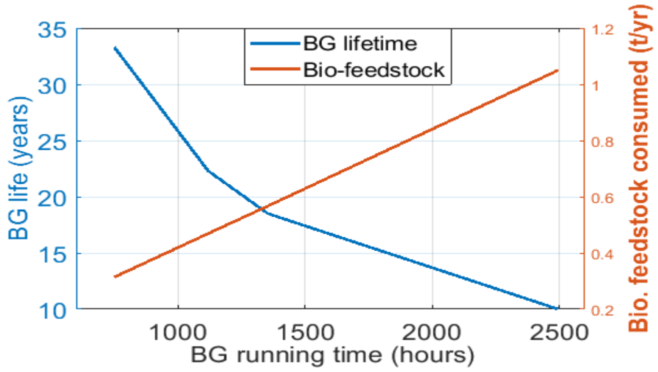


Fig. 13: BG lifetime vs BG operating hours.

Fig. 12 compares the annual energy generated by biomass generators for different network configurations. Likewise, higher P_{TX} and higher system BW exhibit a higher amount of biomass energy generation to meet the higher amount of energy demand as shown in Fig. 11. Due to cost optimization, there is no fixed trend of biomass energy generation between with RRH and without RRH configuration. But in most cases, energy generation from the BG is higher for macro BS without RRH configuration. Fig. 13 demonstrates the variation of BG lifetime and bio-feedstock consumption with respect to the BG operation hours. In line with our expectation, a higher amount of BG running time incurs a higher amount of bio-feedstock consumption which subsequently decreases the BG lifetime.

(iii) Excess Electricity

HOMER calculates the battery losses (B_{losses}) 466 kWh/yr and converter losses (C_{losses}) 280 kWh/yr for macro with RRH base station under BW=10 MHz and P_{TX}=20 W. Annual excess electricity (E_{Excess}) of the hybrid system can be determined by using (19d) as follows:

$$E_{Excess} = 7{,}567\ \ kWh\ \ (E_{PV}) + 225\ \ kWh\ \ (E_{BG}) - 4{,}952\ \ kWh\ \ (E_{BS})$$
$$- 466\ \ kWh\ \ (B_{losses}) - 280\ \ kWh\ \ (C_{losses}) = 2{,}094\ \ kWh/yr$$

Similarly, the annual excess electricity generation for all other network configurations can be found. The annual energy breakdown for macro base stations with RRH and without RRH are respectively demonstrated in Fig. 14 and 15. All the data presented in these figures have been derived from average solar radiation and the average biomass available. It is clearly seen that macro BS without RRH has a higher amount of energy generation, losses, BS demand and excess electricity as mentioned before. It is mentionable that a higher value of E_{Excess} ensures the reliability of the hybrid supply system by providing sufficient backup power during the deficiency/outage of renewable energy generation. The total annual electricity generated by macro solar PV/BG system with RRH is 7,792 kWh, wherein solar PV produced 7,567 kWh and BG produced 225 kWh. On the other hand, total annual electricity generated by macro solar PV/BG system without RRH is 8,921 kWh, where 8,648 kWh comes from solar PV module and 272 kWh comes from BG. Fig. 16 also reveals that the integration of RRH with the macro BS can save the annual energy up to 17.13 % and 13.60 % respectively for P_{TX}=20 W and P_{TX}=40 W.

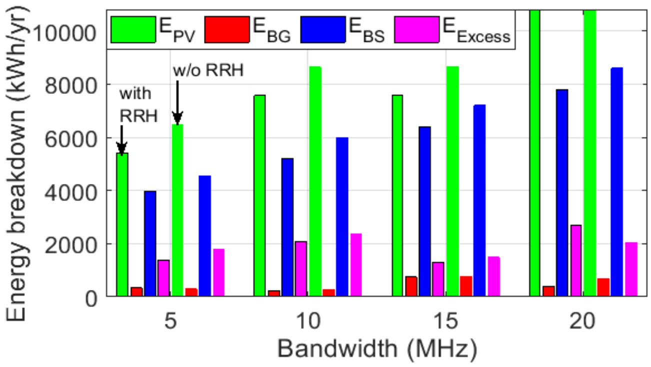


Fig. 14: Annual energy breakdown for the macro base station under P_{TX}=20 W.

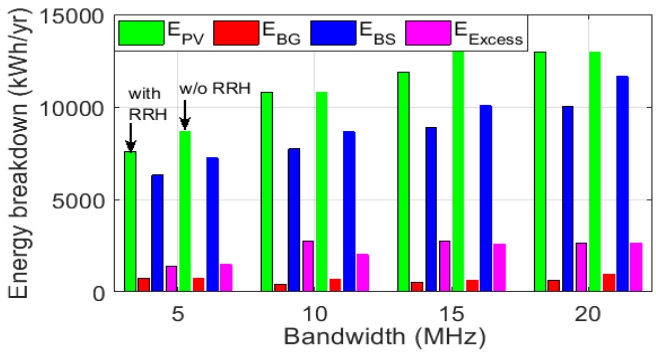


Fig. 15: Annual energy breakdown for the macro base station under P_{TX}=40 W.

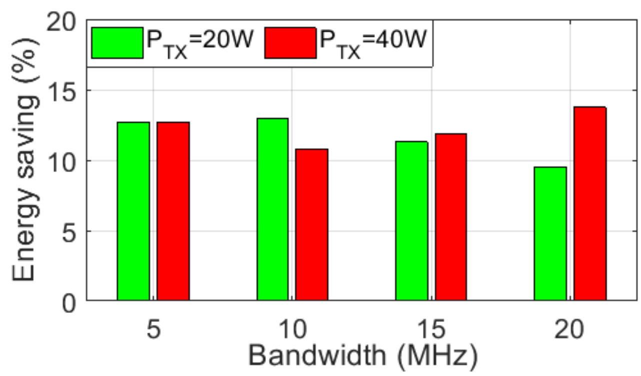


Fig. 16: Percentage of energy-saving by with RRH.

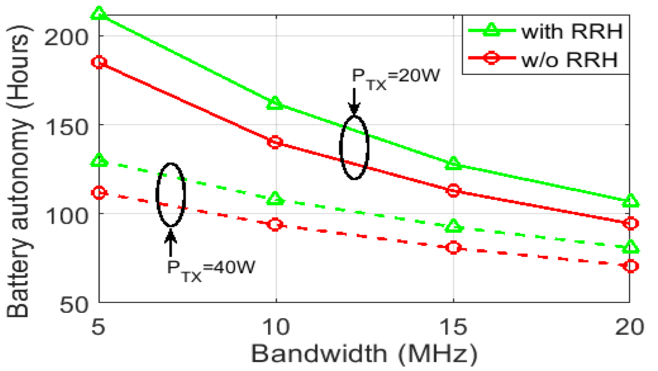


Fig. 17: Battery bank autonomy.

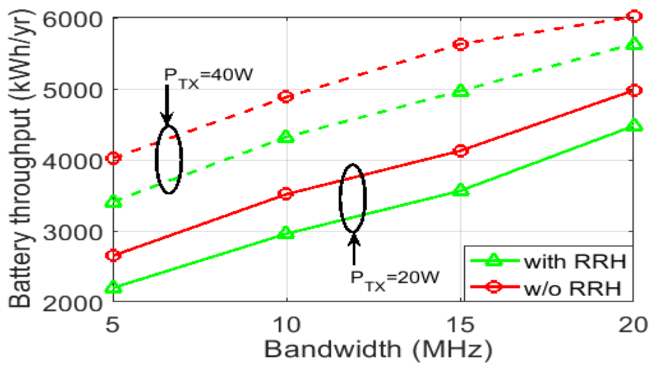


Fig. 18: Battery bank throughput.

(iv) Battery Bank

The battery bank can support the macro with RRH base station load autonomously 162 and 108 hours respectively for P_{TX}=20 W and P_{TX}=40 W. HOMER determines the battery bank autonomy using (11) for P_{TX}=20 W and BW=10 MHz as follows:

$$B_{aut} = \frac{64\ (N_{batt}) \times 6\ (V_{nom}) \times 360\ \ Ah\ (Q_{nom}) \times 0.7\ \ (B_{DOD}) \times (24h/day)}{14.336\ \ kWh\ (L_{BS})}$$

$$= 162\ \ kWh$$

In a similar way, the battery bank autonomy for all network setup can be calculated. A quantitative comparison of BB autonomy and BB throughput is respectively shown in Fig. 17 and 18 for diverse network configuration. A higher value of B_{aut} is always desirable which provides backup power for a long time and enhances the system reliability. According to the definition, a higher value of P_{TX} and system BW considerably reduces BB autonomy and increases the BB throughput. As a consequence, the macro BS with RRH has higher B_{aut} and lower B_{thp} than those without RRH. Moreover, a constant value of battery lifetime is found of all configuration due to the smaller amount of energy variation.

6.3 Energy Efficiency

In this subsection, the throughput and energy efficiency performance of the wireless network has been extensively analyzed for different network configurations. In this work, a two-tier 19 macro base stations with hexagonal shape have been simulated using Matlab based Monte-Carlo method keeping the dynamic traffic profile of Fig. 4 in mind.

The term ‘throughput’ is used to measure the number of bits transmitted per second. A higher value of throughput is highly desirable for making 4G/5G communication. The variation of throughput performance over 24 hours for the proposed network is illustrated in Fig. 19. Moreover, the throughput comparison between macro base station with and without RRH under different transmission power is pictured in Fig. 20. As is seen, the throughput is largely influenced by the variation of system BW. Additionally, a large number of RBs are allocated for running the BS at higher system BW. It is also obvious that there is no significant difference between the throughput performance of the macro base station with and without RRH.

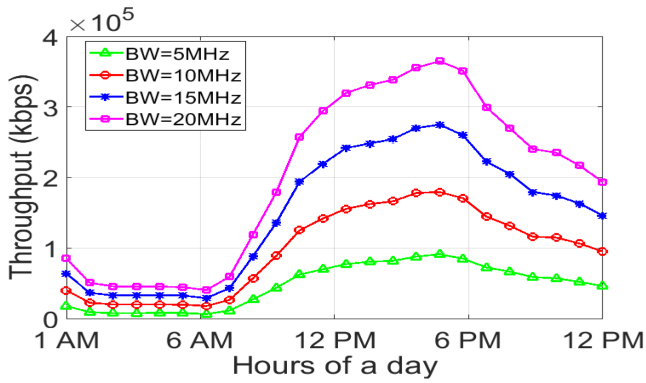


Fig. 19: Throughput comparison with respect to BW.

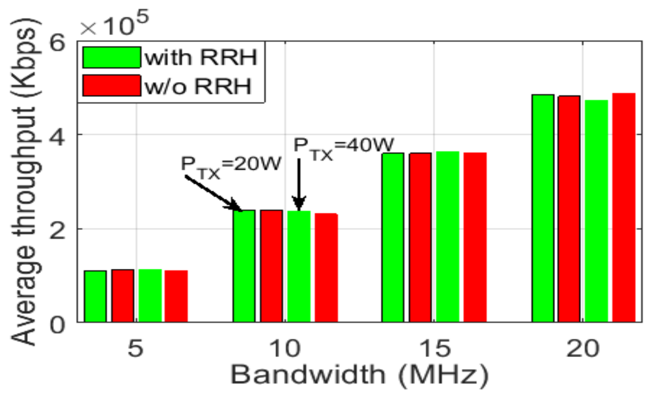


Fig. 20: Throughput comparison with respect to BW.

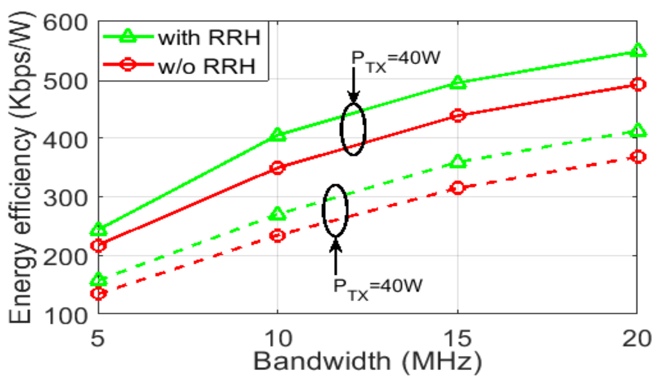


Fig. 21: Energy efficiency comparison with respect to BW.

Table 8: Individual cost breakdown for the hybrid solar PV/BG system under P_{TX}=20 W and BW=10 MHz.

Components	CC ($)		RC ($)		OMC ($)		FC ($)		SV ($)		NPC ($)	
	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH
PV	3,500	4,000	0	0	378	432	0	0	-190	-217	3,689	4,215
BG	660	660	0	0	81	98	102	123	-71	-49	771	832
Battery	19,200	19,200	9,991	9,991	6,914	6,914	0	0	0	0	36,105	36,105
Converter	40	40	15	15	11	11	0	0	-7	-7	59	59
Total cost	23,400	23,900	10,006	10,006	7,384	7,455	102	123	-268	-273	40,624	41,212

Fig. 21 depicts a quantitative comparison of energy efficiency performance with the system BW for different network settings. According to (14), energy efficiency is directly proportional to the throughput performance and inversely proportional to the BS power consumption. As a consequence, a lower value of system BW and transmission power offers higher energy efficiency performance. In the end, the macro base station with RRH has better energy efficiency performance than the one without RRH.

6.4 Economic Yield Analysis

This subsection provides the economic analysis of the hybrid solar PV/BG system considering the average solar radiation of 4.59 kWh/m^2/day and average biomass available of 9 tons/day. Different types of costs such as capital cost (CC), replacement cost (RC), cost of electricity (COE), operation and maintenance cost (OMC), fuel cost (FC) and salvage value (SV) that occurred within the project lifetime are critically analyzed based on the average biomass price of $30 per ton.

Table 8 summaries the individual cost breakdown for the different types of components under the P_{TX}=20 W and BW=10 MHz. The total NPC throughout the project lifetime is $40,624, which is calculated as follows: capital costs of $23,400 + RC costs of 10,006+OMC costs of $7,384 + fuel costs $102− salvage value of $268 = $40,624. As seen from Table 8, the economic feasibility of a solar PV/BG mostly depends on the capital cost of the battery bank and solar PV module. It is also seen that the macro base station system without RRH involves a higher amount of CC, OMC, and NPC due to the higher amount of energy demand, as discussed in the energy yield analysis section.

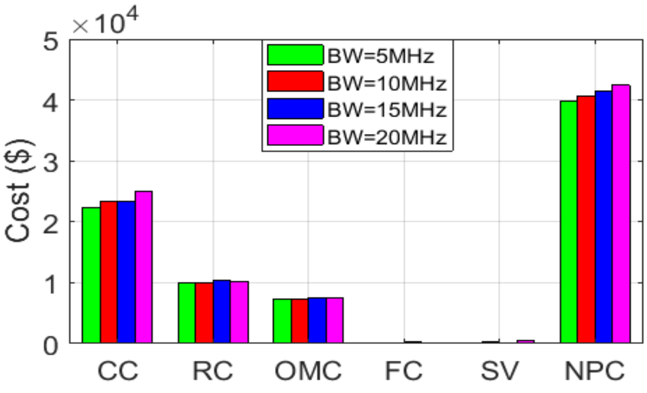


Fig. 22: Individual cost analysis for macro with RRH enabled hybrid solar PV/BG system under P_{TX}=20 W.

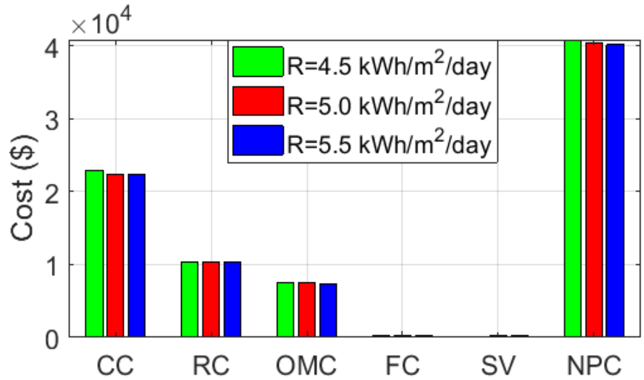


Fig. 23: Individual cost analysis for macro w/o RRH enabled hybrid solar PV/BG system under P_{TX}=20 W.

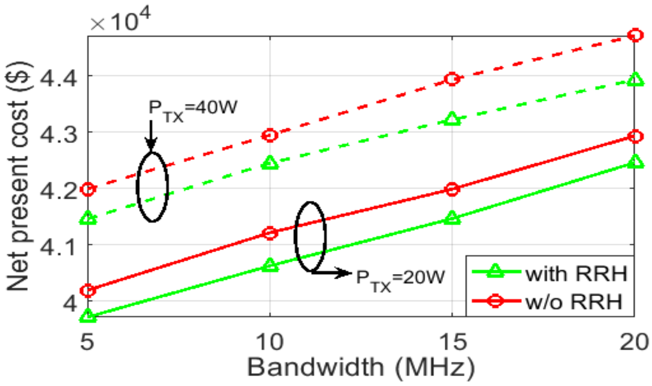


Fig. 24: Net present cost comparison with respect to BW.

Fig. 22 and 23 compare the different types of costs, considering the variation of system BW and solar intensity. All the curves depict that CC is the highest level of the cost paid at the beginning of the project, while RC is just after the CC due to the smaller lifetime of the huge amount of battery units. Moreover, a higher value of system BW has a negative impact on the cost parameters. On the other hand, solar radiation has a smaller amount of effect on the cost parameters.

An extensive comparison of net present cost between macro base station with and without RRH is demonstrated in Fig. 24 and 25 taking the influence of system BW and transmission power into account. As is seen, all the NPC curves follow a similar pattern of upward trending with respect to the system BW and P_{TX} to reach the maximum value. This is happening because of uplifting the energy requirement by a higher value of system bandwidth and transmission power. In light of this, a higher amount of energy demand by macro BS without RRH is not cost-effective as compared to with RRH. Moreover, Fig. 25 illustrates the effect of NPC on the biomass price. In line with our expectations, higher biomass prices incur higher NPC.

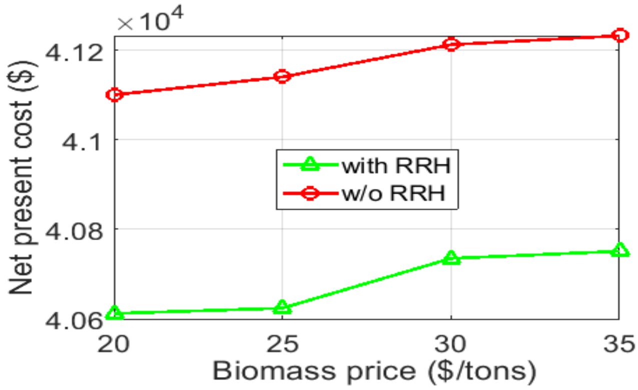


Fig. 25: NPC vs biomass price.

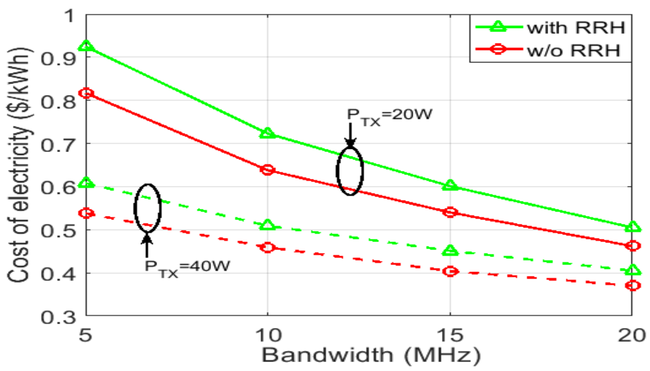


Fig. 26: Cost of electricity comparison.

Fig. 26 summarizes the per-unit cost of electricity generation for the macro base stations with and without RRH. The annual energy requirement for the macro without RRH is higher than with RRH; thus, the macro base station with RRH can attain lower COE. However, the RRH enabled macro hybrid solar PV/BG system is more cost-effective than without RRH.

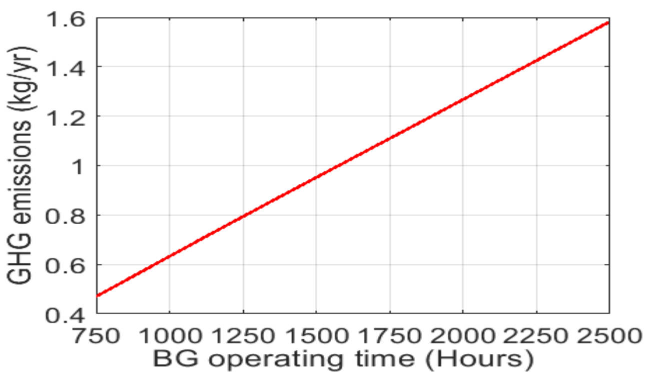


Fig. 27: GHG vs BG operating hours.

6.5 GHG Analysis

The hybrid solar PV/BG system emits a lesser amount of carbon content during the processing of biomass. The operating time of BG is directly related to greenhouse gas emissions, as pictured in Fig. 27. Additionally, the impact of running biomass generator for a long time in case of macro BS both with and without RRH under different system bandwidth is counted in Fig. 28. Due to the cost optimization, there is no fixed trend of running the BG as well as GHG emissions under different system BW. As a consequence, macro BS with RRH and without RRH produces nearly the same amount of carbon content. Finally, a higher volume of BG running time enhances the system reliability, though there is a significant increment in greenhouse gas emissions.

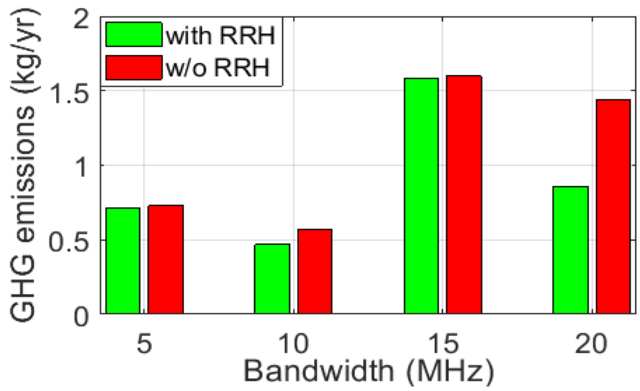


Fig. 28: GHG comparison with respect to BW.

6.6 Limitation Analysis

The major limitations of the hybrid solar PV/BG system are summarized below.

(i) The installation of the hybrid solar PV/BG system requires a greater amount of biomass, land, and water, which are not available throughout the world.

(ii) Energy harvesting from biomass involves a small amount of greenhouse gas emissions, though a higher volume of carbon contents can be maintained at a lower value due to technological advancement.

(iii) The installation of the hybrid solar PV/BG system requires a sufficient number of battery units. So, there may be a loss of load probability due to the older age of the battery bank.

6.7 Feasibility Comparison

This subsection compares the techno-economic feasibility of the proposed hybrid solar PV/BG system with the other systems. The comparison is made in terms of performance parameters to justify network validity.

The techno-economic feasibility of the hybrid supply system mainly depends on the proper dimensioning of the system. Table 9 summarizes the optimal system of the different supply schemes under P_{TX}=20 W and BW=10 MHz. It is clearly seen that the macro without RRH configuration involves a higher value of system components for all supply systems. It happens because of the higher amount of energy demand for macro with RRH configuration. The feasible range of hybrid solar PV/BG system justifies its selection as proper in comparison with other systems.

Table 9. Optimal size comparison among the different supply scheme under P_{TX}=20 W and BW=10 MHz.

Supply scheme	Optimal sizing	
	Macro with RRH	Macro w/o RRH
Stand-alone PV	PV=3.5 kW, Conv.=0.1 kW, N_{batt}=64	PV=4 kW, Conv.=0.1 kW, N_{batt}=64
Stand-alone DG	DG=1.5 kW, Conv.=1.3 kW, N_{batt}=64	DG=1.5 kW, Conv.=0.8 kW, N_{batt}=64
Hybrid PV/DG	PV=4 kW, DG=1 kW, Conv.=0.1 kW, N_{batt}=64	PV=4.5 kW, DG=1 kW, Conv.=0.1 kW, N_{batt}=64
Hybrid PV/WT	PV=1 kW, WT=1 kW, Conv.=0.1 kW, N_{batt}=64	PV=1 kW, WT=1 kW, Conv.=0.1 kW, N_{batt}=64
Hybrid PV/BG	PV=3.5 kW, BG=1 kW, Conv.=0.1 kW, N_{batt}=64	PV=4 kW, BG=1 kW, Conv.=0.1 kW, N_{batt}=64

Table 10. Optimal criteria comparison among the different supply scheme under P_{TX}=20 W and BW=10 MHz.

Supply scheme	B_{aut} (hours)		B_{life} (yeasrs)		NPC ($)		COE ($)		GHG (kg/kg)		EE (kbps/W)	
	with RRH	with RRH	w/o RRH	with RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH	with RRH	w/o RRH
Stand-alone PV	162	140	10	10	39,852	40,379	0.719	0.634	0	0	404.78	349.07
Stand-alone DG	162	140	10	10	61,425	64,685	0.995	0.802	5,695	6,440	404.78	349.07
Hybrid PV/DG	162	140	10	10	40,864	41,752	0.732	0.640	51	62	404.78	349.07
Hybrid PV/WT	162	140	10	10	39,271	39,271	0.694	0.610	0	0	404.78	349.07
Hybrid PV/BG	162	140	10	10	40,624	41,212	0.723	0.638	0.47	0.57	404.78	349.07

Table 10 outlines the comparison of the optimal criteria with different power providing schemes. It is found that though the stand-alone PV and hybrid PV/WT scheme provide better performance for both with and without RRH configuration, the first system is not so reliable due to its dependence on the single source of renewable energy and the latter is not a feasible solution due to the poor wind profile in the selected location. In line with our expectation, the stand-alone DG and hybrid PV/DG have poor performance because of burning huge amounts of fossil fuel and high fuel transportation costs in the remote areas. Despite emitting a very negligible amount of carbon contents, a hybrid solar PV/BG system is an attractive solution for the remote off-grid areas where biomass energy potential is sufficient. Moreover, the proposed system indirectly reduces GHG emissions by reducing the burning of biomass in cooking purposes.

7. Conclusion

This paper addresses the key challenges of installing a hybrid solar PV and biomass energy-assisted green cellular network considering the average solar radiation and biomass profile of Bangladesh. The optimal sizing, technical criteria, economic, and clearness aspects are extensively analyzed through the HOMER simulation. Simulation results reveal that the proposed renewable energy-focused supply system is technically feasible and sustainable in the long run if sufficient energy storage devices are provided. The battery bank can support the macro BS autonomously for 162 hours, which is enough time to fix the system. In addition, the hybrid supply system has around 2,094 kWh excess electricity that ensures the zero percent energy outage. Moreover, the total NPC and GHG emissions can be saved respectively up to 33.86 % and 99.9 %, if the stand-alone DG system is replaced by the hybrid solar PV/BG system. Moreover, the proposed system exhibits a greater level of wireless performance that is identified by the performance metrics. Finally, macro with RRH enabled hybrid solar PV/BG system is a good choice for developing a green mobile communication.

Conflicts of Interest: The authors declare no conflict of interest

Summary of the notations and symbols.

BB	Battery Bank
BG	Biomass Generator
BM	Biomass
BS	Base Station
BW	Bandwidth
COE	Cost of Electricity
DG	Diesel Generator
EE	Energy Efficiency
E_{Excess}	Excess Electricity
GHG	Greenhouse Gas
NPC	Net Present Cost
N_{batt}	Number of Batteries
PA	Power Amplifier
P_{TX}	BS Transmit Power
PV	Photovoltaic
QoS	Quality of Service
RRH	Remote Radio Head
R_{PV}	Rated Capacity of the Solar PV
TRX	Transceiver
WT	Wind Turbine
χ	BS traffic load

References

[1] M. H. Alsharif, "Techno-economic evaluation of a stand-alone power system based on solar power/batteries for global system for mobile communications base stations," *Energies*, vol. 10, no. 3, pp. 1-20, Mar. 2017.

[2] A. Jahid, M. K. I. Monju, M. S. Hossain and M. F. Hossain, "Hybrid power supply solutions for off-grid green wireless networks," *Int. J. of Green Energy*, vol. 16, no. 1, pp. 12-33, Sep. 2018.

[3] A. Jahid and M. S. Hossain, "Dimensioning of zero grid electricity cellular networking with solar powered off-grid BS," *IEEE Int. Conf. on Elec. & Elect. Engg. (ICEEE)*, Rajshahi, Bangladesh, 2017, pp. 1-4

[4] A. Aris and B. Shabani, "Sustainable power supply solutions for off-grid base stations," *Energies*, vol. 8, no. 10, pp. 10904–10941, Sep. 2015.

[5] E. Oh, K. Son and B. Krishnamachari, "Dynamic base station switching-on/off strategies for green cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2126–2136, May 2013.

[6] H. Soonmin, A. Lomi, E. C. Okoroigwe and L. R. Urrego," Investigation of solar energy: The case study in Malaysia, Indonesia, Colombia and Nigeria" *Int. J. Renew Energy Res.*, vol. 9, no. 1, pp. 86-95, Mar. 2019.

[7] M. S. Hossain, B. K. Raha, D. Paul, and M. E. Haque, "Optimization and generation of electrical energy using wind flow in rural area of Bangladesh," *Res. J. of Applied Sciences, Engg. and Tech.*, vol.10, no. 8, pp. 895-902, Jul. 2015.

[8] K. D. Mercado, J. Jiménez and M. C. G. Quintero, "Hybrid renewable energy system based on intelligent optimization techniques," *IEEE Int. Conf. on Renew. Energy Res. and Applic. (ICRERA*), Birmingham, 2016, pp. 661-666.

[9] NASA. Surface meteorology and solar energy: a renewable energy resource. Available online: https://eosweb.larc.nasa.gov/sse/. (Accessed on: Jan. 20, 2020).

[10] A. Jahid, M. S. Hossain, M. K. H. Monju, M. F. Rahman and M. F. Hossain, "Techno-economic and energy efficiency analysis of optimal power supply solutions for green cellular base stations*," IEEE Access*, , vol. 8, pp. 43776-43795, Feb 2020.

[11] A. S. N. Huda, S. Mekhilef and A. Ahsan, "Biomass energy in Bangladesh: current status and prospects," *Renew. and Sustainable Energy Reviews*, vol. 30, no. 1, pp. 504-517, Feb. 2014.

[12] M. Ahiduzzaman and A. Sadrul Islam, "Energy utilization and environmental aspects of rice processing industries in Bangladesh," *Energies*, vol. 2, no. 1, pp. 134–149, Mar. 2009.

[13] E-plus, Nokia Siemens networks build Germany first off-grid base station. Available online: http://www.nokiasiemensnetworks.com, 2011. (Accessed on: 15.01.2020).

[14] Sustainable energy use in mobile communications, Ericsson Inc., White Paper, 2007. (Accessed on: 15.01.2020).

[15] Huawei. Mobile networks go green. Available online:http://www.huawei.com/en/abouthuawei/publications/co 082734.htm. (Accessed on: 15.01.2020).

[16] P. Nema, S. Rangnekar and R. K. Nema, "Pre-feasibility study of PV-solar/wind hybrid energy system for GSM type mobile telephony base station in central India," *IEEE Int. Conf. on Com. and Aut. Engg. (ICCAE)*, Singapore, Feb. 2010, pp. 152-156.

[17] V. Chamola and B. Sikdar, "Solar powered cellular base stations: current scenario, issues and proposed solutions," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 108–114, May 2016.

[18] V. Ani and E. A. Nnene, "Simulation and optimization of hybrid diesel power generation system for GSM base station site in Nigeria," *Electron. J. Energy & Environ.* vol. 1, no. 1, pp. 37-56, May 2013.

[19] M. M. Diaz, R. Villafafila, D. M. miracle and A.S. Andru, "Study of optimization design criteria for stand-alone hybrid renewable power systems," *Int. Conf. on Renew. Energies and Power Quality (ICREPQ)*, Bilbao, Spain, Mar. 2013, pp. 1266-1270.

[20] S. Paudela, M. S. Dahala, M. Adhikarib and J. N. Shresthaa, "Technical and economic assessment of renewable energy sources for telecom application: A case study of Nepal telecom," *Int. Conf. on Power and Energy Systems (ICPS)*, Kathmandu, Nepal, Oct. 2013, pp. 1-11.

[21] K. Kusakana and H. J. Vermaak, "Hybrid renewable power systems for mobile telephony base stations in developing countries," *Renew. En*ergy, vol. 51, no. 1, pp. 419-425, Mar. 2013.

[22] P. Bajpai, N. P. Prakshan and N. K. Kishore, "Renewable hybrid stand-alone telecom power system modeling and analysis," *IEEE Region 10 Conf. (TENCON)*, Singapore, Jan. 2009, pp. 1-6.

[23] V. Ani and N.A. Ndubueze, "Potentials of optimized hybrid system in powering off-grid macro base transmitter station site," *Int. J. Renew. Energy Res.*, vol. 3, no.3, pp. 861-871, Dec. 2013.

[24] M. Alsharif, J. Kim, and J. H. Kim, "Energy optimization strategies for eco-friendly cellular base stations," *Energies*, vol. 11, no. 6, pp. 1500, Jun. 2018.

[25] M. H. Alsharif, R. Nordin and M. Ismail, "Green wireless network optimisation strategies within smart grid environments for long term evolution (LTE) cellular networks in Malaysia," *Renewable Energy*, vol. 85, no. 1, pp. 157-170, Jan. 2016.

[26] M. H. Alsharif, R. Nordin, and M. Ismail, "Energy optimisation of hybrid off-grid system for remote telecommunication base station deployment in Malaysia," *EURASIP J. Wireless Commun. Netw.*, vol. 2015, no. 1, p. 64, Dec. 2015.

[27] W. A. Imtiaz, K. Hafeez, "Stand alone PV system for remote cell site in Swat Valley," *Abasyn Int. Conf. on Tech. and Bus. Manag.*, Pakistan, Dec. 2013, pp 1-5.

[28] A. Jahid, M. S. Islam, M. S. Hossain, M. E. Hossain, M. K. H. Monju and M. F. Hossain," Toward energy efficiency aware renewable energy management in green cellular network with joint coordination," *IEEE Access*, vol. 7, pp. 75782-75797, Jun. 2019.

[29] M. S. Hossain, A. Jahid and M. F. Rahman,"Quantifying potential of hybrid PV/WT power supplies for off-grid LTE base station," *IEEE Int. Conf. on Comp., Commu., Chemical, Material and Electronic Engg. (IC4ME2)*, Rajshahi, Bangladesh, 2018, pp. 1-5.

[30] O. T. Winarno, Y. Alwendra and S. Mujiyanto," Policies and strategies for renewable energy development in Indonesia," *IEEE Int. Conf. on Renew. Energy Res. and Applic. (ICRERA)*, Birmingham, 2016, pp. 270-272.

[31] A. Jahid, M. K. H. Monju, M. E. Hossain and M. F. Hossain, "Renewable energy assisted cost aware sustainable off-grid base stations with energy cooperation," *IEEE Access*, vol. 6, pp. 60900-60920, Oct. 2018.

[32] A. B. Shams, A. Jahid and M. F. Hossain, "A CoMP based LTE-A simulator for green communications," *IEEE Int. Conf. on Wireless Commun., Signal Process. and Netw. (WiSPNET)*, Chennai, India, 2017, pp. 1751-1756.