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Techno-Economic Investigation of Optimal Solar Power System for LTE Cellular Base Stations

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***Abstract*— The enormous growth in the cellular communication system and omnipresent wireless services has incurred momentous energy consumption as well as the emissions of greenhouse gas (GHG) to a great extent. With the enrichment of renewable energy harvesting technology, cellular base stations (BSs) are increasingly powered by renewable energy sources (RES) to minimize functioning expenditures and carbon footprints. The remote off-grid cellular BSs are usually driven by pollution-intensive power supply solutions such as diesel generators (DG) where the utility grid is not suitable or not reliable. Exploiting available energy from renewable energy sources has been evidenced to be cost-effective and eco-friendly in comparison with DG. Accordingly, this paper explores the viability of using solar photovoltaic (SPV) panel and energy storage devices to feed the off-grid Long-Term Evolution (LTE) macro BSs in Bangladesh. The prime objective of this investigation is to minimize net present cost and GHG emissions while ensuring energy sustainability over 10 years. The simulation results demonstrate that the proposed solar PV/battery power system achieved significant enhancement of overall expenditure reduction yielding up to 54.8% compared to the diesel power system and ensure prominent energy sustainability with effective modeling of renewable energy harvesting.**

Keywords*— Green communication; Energy harvesting; Solar PV; Eco-friendly; Sustainability; LTE

I. INTRODUCTION

Due to the colossal increment of power utilization over the last few decades, carbon contamination and environmental alteration caused by fossil fuel utilization to generate power has been considered as a great crisis for the environment and got extensive attention [1]–[4]. The electricity grid power sector has generally been the biggest source of CO_2 emanations and represented around 3-4% of global greenhouse gas (GHG) emissions by Information and Communication Technology (ICT) sector [5], [6]. The denser deployment of cellular BSs increasingly pushing up mobile operators' capital expenditure and operational cost. This has propelled and accelerated to shift towards green cellular communication incorporating renewable energy sources, e.g., solar power and wind power. The integration of renewable energy has been considered to be a promising alternative to reduce CO_2 emanation as well as minimize the dependency on the traditional grid supply. Besides, as renewable energy production has been becoming more financially cost-effective and available by end-users, there have been huge endeavors to employ RE in demand-side [7], [8]. Considering this aspect, base stations (BSs) are recognized as the most energy-intensive equipment in cellular access networks that consume 60-80% energy to the entire cellular infrastructure [9]–[11]. Their power utilization is anticipated to be increased at around 140 billion kilowatt-hours every year by 2020, which approximately costs $13 billion every year in electricity bills [3], [12], [13]. Therefore, powering the radio access networks using green energy has increasingly become an ideal alternative to ensure environmental sustainability and economic well-being as well.

In order to increase energy efficiency and decrease electricity bills, enormous research has been carried out by applying renewable power green cellular base stations [14]–[16]. According to previous research [17]–[19], BSs are generally designed for peak traffic arrivals regardless of the variation in time and spatial domain. Meanwhile, base stations have been endeavoring to incorporate renewable energy sources to meet their traffic demand for ensuring sustainability. Powering radio access networks utilizing renewable energy is getting to be another pivotal objective for accomplishing sustainable operations by decreasing energy expenditure. For instance, Google purchases 100% green energy to tackle its entire annual demand to carry out its global operations as a part to achieve sustainable operations in its data centers [20]. Nowadays, installing solar PV panels directly offset grid consumption during peak hours through the highest level of energy harvesting and thereby reduces the energy cost as well as maintains environmental sustainability. Moreover, after satisfying real-time demand, additional harvested energy can be stored in storage devices to improve base station resilience.

Considering the aforementioned circumstances, exploiting the enhanced use of renewable energy has become an attractive solution and a paramount strategy for attaining energy-efficient and cost-effective BS operations. Nevertheless, the intermittent and stochastic behavior of solar energy imposes challenges to reliable operations in terms of meeting the total electricity required of cellular access sectors. This motivates many research works to adopt hybrid-powered cellular infrastructure with the co-optimization of power procurement incorporated with solar power generations and adequate storage devices [21]–[25]. The idea of deploying a diesel generator (DG) or procuring electricity from the traditional electric grid (EG) supply enables the aggregate solution to handle the limitations raised by green power sources. It is projected that the global carbon footprints of ICT circle will rise from 170 Mtons in 2014 to a massive amount of 235 Mtons by 2020 (about 51% increment) [26], [27] since the burning of fuel causes the considerable environmental pollution and damages the ozone layer. Despite some drawbacks of non-renewable energy sources, a joint solution of RE and non-RE offers an emerging solution for the envisaged cellular architecture. However, with the advancement of new technology [28]–[34] the world is moving toward renewable energy and the researchers are always trying to find out an efficient way to utilize renewable energy sources [26], [27], [35].

Nowadays, energy-efficient green communications have drawn intensive attraction owing to the rapid surge of energy demand and ensuring the desired level of energy efficiency (EE). Numerous significant researches are carried out pointing out the optimization of hybrid power supplies focusing on to evaluate EE [35], [36], throughput enhancement [37]–[39], zero outage with guaranteed network coverage [40], [41], energy cooperation mechanism [42]–[44], still the research in this context is not mature yet. Reference [45] focused on the relay selection enabled power budgeting method to curbing down power consumption of the grid. The authors developed an optimization algorithm to downsize the EG power while enhancing green power utility [46]. Alsharif et. al. [47] examined the feasibility analysis of hybrid renewable-powered based stations with OPEX performance. On the other hand, reference [48] developed a heuristic algorithm for the minimum cost method for PV incorporated LTE cellular BSs. However, these works did not account for the optimal utilization of green power. Besides, the impact of tempo-spatial variation of RE generation and EE analysis with optimal power supply is not considered. Authors [49] investigated the performance analysis of the combined solution of solar PV and biomass power envisioned LTE cellular networks taken into account of dynamic variation of RE production under optimal condition. Authors [50]–[52] studies the opportunity and challenges of RE implementation including per unit cost, operation & maintenance cost (OMC), life span, and governing the sub-station based on the internet of things. The inherent benefits of energy sharing strategy among collocated BSs in terms of energy efficiency are extensively studied in [53], [54].

Reference [55] proposed the sleeping mode mechanism of BSs according to traffic arrivals for reducing energy consumption but this method degrades the system performance because of proper coordination technique. Furthermore, a substantial investigation is done on distributed renewable energy management [56], [57] along with centralized RE generation [58], [59] aiming to minimize EG consumption. The downlink energy efficiency [60] and uplink spectral efficiency [61] performance integrating joint transmission coordinated multipoint technique (CoMP) in the context of green cellular networking. With the advancement of modern technology it is always desirable to develop a sustainable cellular network which will subsequently minimize the grid pressure and CO_2 [60-65]. A traffic-aware CoMP based simulator to investigate the network's performance under different network settings, for example, system bandwidth, transmit power, and tempo-spatial variation of RE profile is developed in [66], [67].

In this research work, we approach the feasibility to power an energy-efficient Long Term Evolution (LTE) BS consisting of PV panels and adequate energy storage devices. The dimensioning of PV powered cellular systems is based on the minimization of net system cost including capital expenditure (CAPEX) over 10 years period. In particular, we investigate the multiple key aspects of stand-alone power supply solution for LTE macro BS: i) the optimum size and technical criteria of a stand-alone solar/battery power system, ii) cost analysis, and iii) examined the implications of proposed solar power system concerning the case of DG solution. In our computations, we consider the temporal variation of solar generation and practical BS traffic load to make the system more realistic. Moreover, we focus on the global optimization of net present cost (NPC) for the stand-alone PV powering system along with the energy sustainability performance of network devices and also estimate the GHG emissions. However, the optimization of technical and economic feasibility for various sorts of BS is analyzed using a hybrid optimization model for electric renewables (HOMER) software.

The rest of the paper is organized as follows. Section II outlines the architecture of the proposed solar/battery driven LTE macro BS system, along with the solar PV model, battery model, converter design, and BS power consumption model. Optimization and cost modeling is presented in section III. Section IV demonstrates the simulation setup and the simulation results including energy yield discussion and cost analysis. Section V concludes the paper with key findings.

II. SYSTEM ARCHITECTURE

Figure 1 depicts the proposed system architecture of the BS power system. An LTE macrocell BS typically consists of transceivers (TRXs), power amplifiers (PAs), a radio-frequency (RF) unit, a baseband (BB) unit to perform signal coding as well as processing, a DC-DC power supply, and a cooling system (not shown in the proposed model). Two different BS configurations have been taken into account in the system modeling i. e 2/2/2 LTE macro BS with and without remote radio head (RRH). Modern cellular networks extensively adopted the concept of the distributed base station where the BB signal processing unit is detached from the radio frequency (RF) unit is defined as RRH. Since RF and PA components are in close proximity to the antenna and connected to the core unit of BS through an optical fiber, LTE BS with RRH has the inherent potential to eradicate feeder cable loss. The term n/n/n denotes a three-sector site with n antennas per sector.

A. PV System

Photovoltaic panels are arrays consisting of many solar cells that are interconnected in series/parallel to transform ubiquitous sunlight energy into electrical energy. The volume of solar energy generated by a PV panel greatly depends upon the geographic location, materials used in the panel, fabrication technology, and tilt of PV panels. HOMER computes the annual energy output of a solar PV (SPV) array by using the following formula [47]

$$E_{SPV} = R_{SPV} \times PSH \times \eta_{SPV} \tag{1}$$

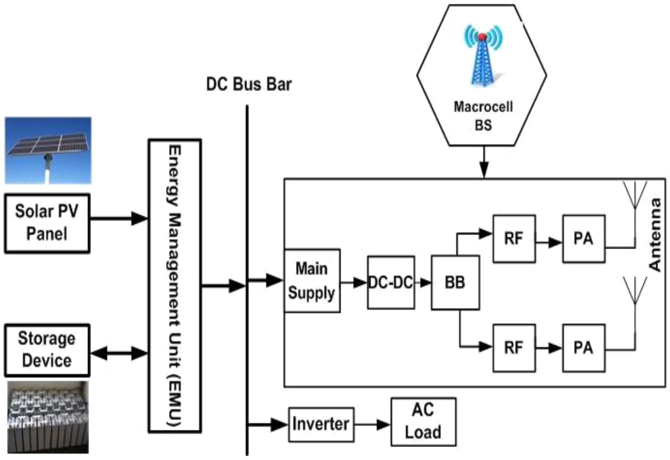

Figure 1: Solar powered LTE macrocell BS architecture.

where, R_{SPV} is the rated capacity of the used SPV array (kW), PSH is the peak solar hour which is equivalent to the average daily solar radiation and SP V is the efficiency of the η_{SPV} that is used to account the effects of dust, wire losses, temperature, and other factors which subsequently affect the generation of solar energy of a solar array.

B. Battery Model

A battery bank is used in the proposed architecture as a backup energy storage system that stores excess electrical energy reaped by the solar panel. Based on the state of charge (SOC) condition, the battery is modeled where the minimum SOC of the battery, B_{SOCmin} is the lower limit that does not discharge below the minimum state of charge. The depth of discharge (B_{DOD}) is the maximum electrical energy that can be delivered from the battery to BS and can be expressed as [47]

$$B_{DOD} = \left(1 - \frac{B_{SOC\min}}{100}\right) \tag{2}$$

It is noteworthy to mention that the battery bank autonomy (B_{aut}) is a significant parameter that gives the information of the potential number of days that the battery bank can provide the necessary energy to drive BS load provided that malfunctions of PV array have taken place. This parameter is expressed as the ratio of the battery bank size to the BS load [47]

$$B_{aut} = \frac{N_{batt} \times V_{nom} \times Q_{nom} \times B_{DOD} \times (24h/day)}{L_{BS}} \tag{3}$$

where N_{batt} is the number of batteries, V_{nom} is the nominal voltage of a single battery in V, Q_{nom} is the nominal capacity of a single battery in (Ah), and LBS is the average daily BS load in kWh.

On the other hand, battery lifecycle is another crucial factor that has a direct impact on replacement costs throughout the project duration. HOMER calculates the battery bank life (L_{batt}) using the following equation [47]

$$L_{batt} = \min\left(\frac{N_{batt} \times T_{batt}}{T_a}, R_{batt,f}\right) \tag{4}$$

where T_{batt} is the lifetime throughput of a single battery (kWh), T_a is the annual battery throughput (kWh/year), and $R_{batt,f}$ is the battery float life (year). In this paper, the Trojan L16P battery model is used due to the large capacity and high reliability.

C. Inverter

An inverter converts DC voltage into usable AC voltage having the desired frequency of the load. The inverter capacity (C_{inv}) is calculated based on the following equation [47]

$$C_{inv} = \left(\frac{L_{AC}}{\eta_{inv}}\right) \times \sigma_{sf} \tag{5}$$

where L_{AC} represents the peak AC load in kW, η_{inv} is the efficiency of the inverter in %, and σ_{sf} is the safety factor.

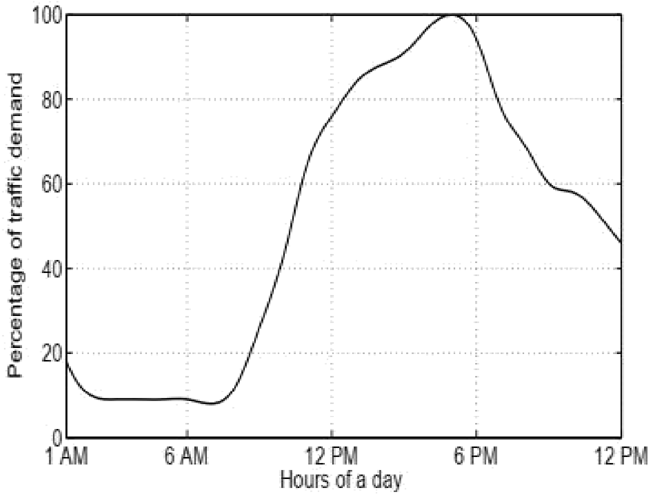

Figure 2: Daily traffic load profile.

TABLE I: BS approximate power consumption model parameters [53].

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

D. Diesel Generator

The energy produced by a DG (E_{DG} in kWh) with given rated power output (P_{DG}) is expressed as follows [53]

$$E_{DG} = P_{DG} \times \eta \times t \qquad (6)$$

where η is the efficiency of the DG and top is the operational time. However, the fuel consumption (FC) is calculated as

$$Fc = E_{DG} \times F_s \qquad (7)$$

where F_s is the specific fuel consumption (L/kWh).

E. BS Power Consumption Model

Dimensioning and modeling of the sustainable solar power system are heavily dependent on the BS load. In a practical cellular network, the incoming traffic arrival rate is time-varying and the BSs energy consumption is directly related to the traffic volumes. An approximate traffic pattern shown in Figure 2 can be estimated by using the Poisson distribution model as follows [53]

$$\rho(t,\alpha) = \frac{\alpha^t}{t!} \qquad (8)$$

where, $\rho(t,\alpha)$ is the Poisson distribution function of traffic demand, and α is the mean value where the peak number of traffic arrivals occur at 5 PM.

The total approximate BS power consumption considering the number of transceivers (N_{TRX}) and traffic load (χ) is defined as [53]

$$P_{in} = N_{TRX}(P_1 + \Delta_p P_{TX}(\chi - 1)) \text{ if } 0 < \chi \leq 1 \qquad (9)$$

where $P_1 = P_0 + \Delta_p P_{TX}$ and P_0 is the consumption at idle state. The load dependency is accounted for by the power gradient, Δp. The scaling parameter = 1 indicates that a fully loaded system, i.e. BS transmitting at full power with all of their resource blocks occupied, and = 0 indicates idle state. The dynamic power consumption is varied with the traffic loading parameter as seen from Figure 2. The parameters are summarized in Table I.

The power consumption of the air-conditioning unit depends on the internal temperature of the BS cabinet and approximately consumes 10% of total power. We have assumed that the air-conditioning unit runs 18 hours in a day with 6 hours running and 2 hours shut off, and so on. Also, an auxiliary 25 W lamp is connected to BS running from 7 PM to 6 AM. The total BS energy consumption according to (9) is listed in Table II.

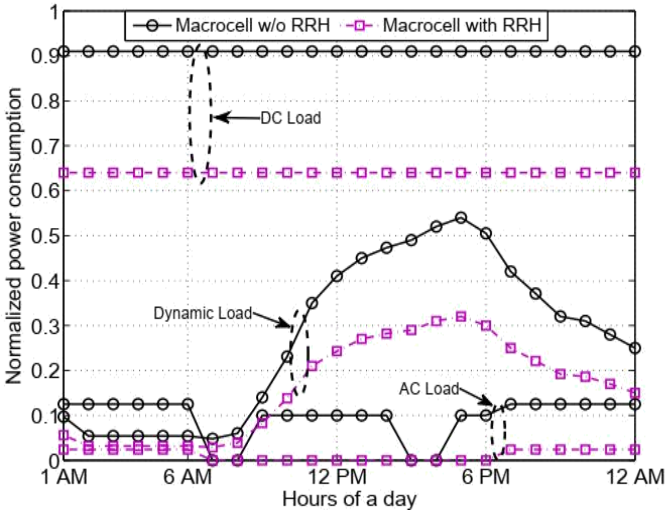

Figure 3: Hourly normalized load profile for solar-powered 2/2/2 macro BS.

TABLE II: BS load energy consumption in kWh.

BS Type	Daily consumption	Annual consumption
Macro with RRH	16.45	6,006
Macro w/o RRH	25.24	9,213

Figure 3 shows the variation of hourly normalized load profile (concerning 1,051 W which is the macro BS consumption per hour) including the DC load, AC load, and dynamic power consumption scheme. The implementation of a standalone solar power system for two different BS architecture in the HOMER simulation platform is presented in Figure 4 and Figure 5. The schematic diagram of the seasonal AC load profile for macrocell without RRH is depicted in Figure 6.

1) Macrocell without RRH: The annual DC load energy demand is 8,404 kWh (91.2%), whereas its AC load energy demand is 809 kWh (8.8%). Among the total AC power consumption, the air-conditioner unit consumes 700 kWh/year and 25 W lamp consumes 109.5 kWh/year.

2) Macrocell with RRH: The annual DC load energy demand is 5,897 kWh (98.2%) and the AC load energy demand is 109.5 kWh (1.8%) due to the only lamp. Therefore, with the incorporation of the RRH unit with 2/2/2 macrocell LTE BS inherently reduces 34.81% of total annual energy consumption.

F. Energy Efficiency Metrics

The word ’energy efficiency’ is used to measure network output, and can be defined as the number of bits transmitted per energy joule. The energy efficiency is the ratio of total network capacity and total power consumed by the network. According to Shanon’s theorem of knowledge efficiency, total achievable network throughput at a time of t can be expressed as follows [53]

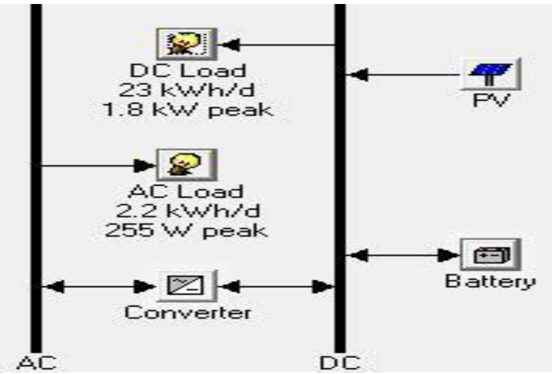

Figure 4: Schematic diagram for 2/2/2 macro BS without the RRH system in HOMER.

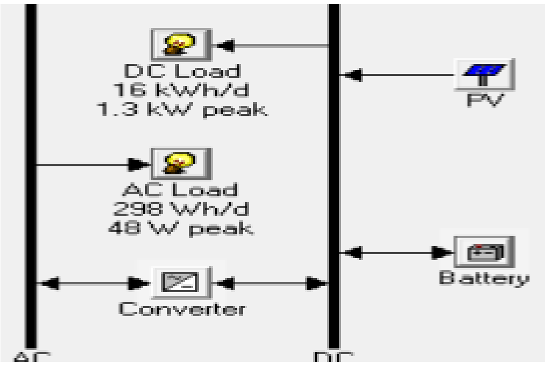

Figure 5: Schematic diagram for 2/2/2 macro BS with RRH scheme in HOMER.

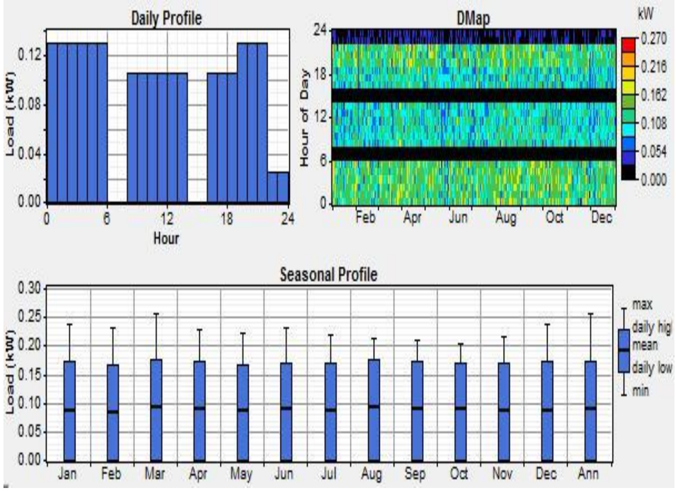

Figure 6: Seasonal AC load profile for macro BS without RRH.

$$C_{total}(t) = \sum_{k=1}^{U} \sum_{i=1}^{N} BW \log_2(1 + SINR_{i,k}) \qquad (10)$$

where N is the number of BSs transmitted, U is the total number of network UEs, BW is the system bandwidth, SINR is the signal to interference noise ratio. The energy efficiency of a network can be approximated by the following equation [53]

$$\eta_{EE} = \frac{C_{total}(t)}{P_{net}}$$

where P_{net} is the net power consumed in all the BSs at time t, which is estimated using (9).

III. COST MODELING AND OPTIMIZATION

An optimization tool namely HOMER is utilized in this rigorous study to assess the optimal solar power system required that fulfills user-defined constraints ensuring the lowest net present cost (NPC) including the capital costs (CC), replacement costs (RC), O&M costs (OMC), and salvage value (S) during the entire project period. The NPC is computed as follows [47]

$$NPC = \frac{TAC}{CRF} = CC + RC + OMC - S \qquad (12)$$

Total annualized cost (TAC) value and capital recovery factor (CRF) can be expressed as follows:

$$TAC = TAC_{CC} + TAC_{RC} + TAC_{OMC} \qquad (13)$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (14)$$

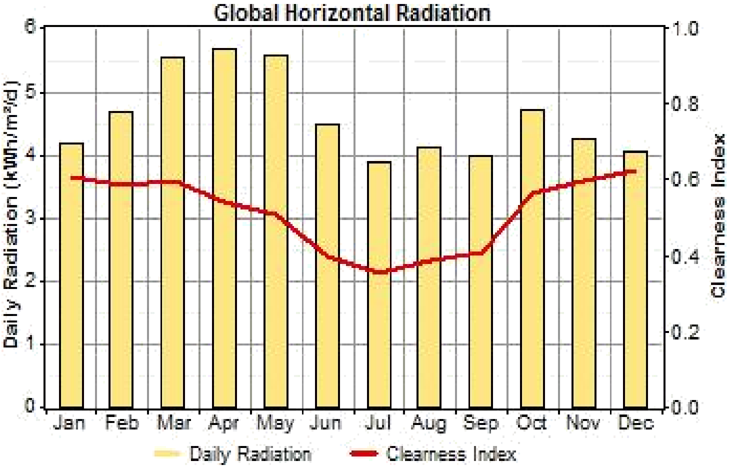

Figure 7: Average annual profile of solar irradiation in Bangladesh.

where N is the duration of the project and *i* represents the annual real interest rate.

The salvage value is typically calculated at the end of the project lifecycle and applicable to components that usually have greater lifetimes in comparison with the project lifecycle. The salvage value is calculated as follows [47]

$$S = rep\left(\frac{rem}{comp}\right) \qquad (15)$$

where rep, rem, and comp are the replacement cost of the component, the remaining lifetime, and the lifetime of the component respectively.

However, the objective function of optimization is to minimize the NPC.

Minimize NPC

Subject to

$$E_{SPV} > 0 \tag{16a}$$

$$E_{SPV} > E_{BS} \tag{16b}$$

$$E_{SPV} + E_{batt} = E_{BS} + E_{losses} \tag{16c}$$

$$E_{Excess} = E_{SPV} - E_{BS} - E_{losses} \tag{16d}$$

where E_{losses} comprises battery loss and inverter loss per year, E_{losses} is the annual BS load consumption as obtained from Table II and E_{batt} is the energy supply from the battery bank. The constraint in (16b) ensures that the annual energy production by the solar PV array carries the annual BS consumption. The total energy contribution including battery supply satisfies the total energy consumption and is pointed out in constraint (16c). The amount of excess electricity is preserved for future use or during abnormal condition is described by the constraint (16d).

IV. PERFORMANCE EVALUATION

A. Simulation Setup

The lifetime of the project is 10 years and the annual interest rate used in this study is 6.75% [53], which affects the total project cost. Moreover, dual-axis tracking mode PV panels are modeled and 10% back power is reserved to serve the BS load, even if the solar energy generation suddenly decreases. HOMER decides at each time step to meet the energy requirements at the lower net present cost, subject to the constraint from the dispatch strategy chosen in the simulation. The annual average solar irradiation is 4.59 kWh/m^2/day. Figure 7 illustrates the solar resource profile for one year. Techno-economic specifications and system constraints are presented in Table III.

B. Energy Yield Analysis

Table IV summarizes the optimal system architecture of the solar-powered BS for both macro without RRH and macro with RRH configurations.

1) Solar PV panel: The yearly energy output of the solar PV panels is calculated utilizing (1); 7 kW × 4.59 × 0.90 × 365 days/year = 10,554 kWh. A dual-axis tracker boosts the energy by one quarter which is 13,192 kWh. However, the total yearly BS energy consumption is 9,213 kWh. HOMER determines the battery and inverter losses are 870 kWh/year and 41 kWh/year respectively. So that, the yearly excess electricity can be estimated as 13,192 kWh - 9,213 kWh - 870 kWh - 41 kWh = 3,068 kWh/year (23.26%). These values are evaluated for LTE macro BS without RRH considering real traffic patterns.

TABLE III: HOMER simulation setup [53].

System Components	Parameters	Value
Resources	Solar radiation	4.59 kWh/m^2/day
	Interest rate	6.75%
SPV	Operational lifetime	25 years
	Derating factor	0.9
	System tracking	Dual-axis
	Capital cost	$1/W
	Replacement cost	$1/W
	OMC/year	$0.01/W
Battery	Round trip efficiency	85%
	B_{SOC}	30%
	V_{nom}	6 V
	Q_{nom}	360 Ah
	Capital cost	$300/unit
	Replacement cost	$300/unit
	OMC/year	$10/unit
Inverter	Efficiency	95%
	Operational lifetime	15 years
	Capital cost	$0.4/W
	Replacement cost	$0.4/W
	OMC/year	$0.01/W
DG	Efficiency	30%
	Operational lifetime	25,000h
	Capital cost	$0.66/W
	Replacement cost	$0.66/W
	OMC/year	$0.05/h

TABLE IV: Optimal system architecture from HOMER simulation.

Components	Macro with RRH	Macro w/o RRH
SPV (kW)	4	7
Battery (Units)	32	32
Inverter (kW)	0.1	0.2

On the other hand, 16 Sharp modules are required for LTE macro BS with RRH layout for the capacity of the PV array is 4 kW. Similarly, the annual energy contribution of the SPV array is 7,539 kWh, whereas the BS consume 6,006 kWh/year. The annual excess electricity is 963 kWh (12.77%); (7,539 kWh - 6,006 kWh - battery loss (565 kWh)- inverter loss (5 kWh). Figure 8 shows the monthly solar PV power production. The maximum output power occurs in March because of summer and the PV array produces minimum output power during the rainy season particularly in July.

2) Battery Bank: The total number of batteries is 32 connected 8 in series and 4 in parallel to be compatible with the 48 V DC bus bar for the LTE BS. The battery annual energy is 5,869 kWh, while the annual out energy is 4,999 kWh accounting the roundtrip efficiency is 85%, resulting in 870 kWh battery losses per year. The amount of time that the battery bank can autonomously support the BS 46 hours, which is calculated using (3); (32batteries × V_{nom} = 6V × Q_{nom} = 360Ah × B_{DOD} = 0:7 24h)/daily average BS load 25.24 kWh. Moreover, the expected battery life is 6.35 years for the annual throughput and lifetime throughput is 5,424 kWh and 34,400 kWh which is computed by (4). However, all the numerical data are calculated for 2/2/2 macrocell BS without the RRH pattern. Likewise, HOMER calculates the battery bank

autonomy is 70.8 hours, battery loss 565 kWh/year and the expected battery life is 9.65 years for the 2/2/2 macrocell BS with RRH configuration. The autonomy capacity is more enough to fix PV malfunctions or any other failures. From the energy yield analysis, BS with RRH could provide 24.8 hours more battery autonomy and enhanced battery life additional 3.3 hours than to macro BS without RRH.

C. Energy Efficiency Analysis

The word ‘throughput’ is used to calculate the transmitted bits per second. For making 4G/5G communication it is highly desirable to have a higher throughput value. Table V represents the quantitative comparison of energy efficiency output for with and without RRH configuration. Energy efficiency is directly proportional to the output of the throughput and inversely proportional to the BS power consumption. As a result, the RRH macro base station has better results in terms of energy efficiency than the one without RRH.

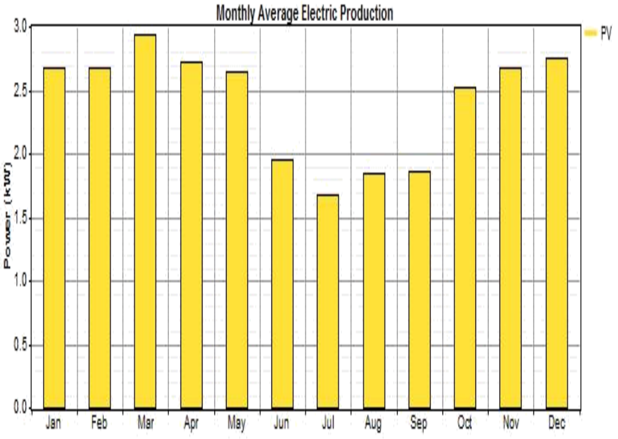

Figure 8: Monthly average of the SPV array power output for the macro BS without RRH.

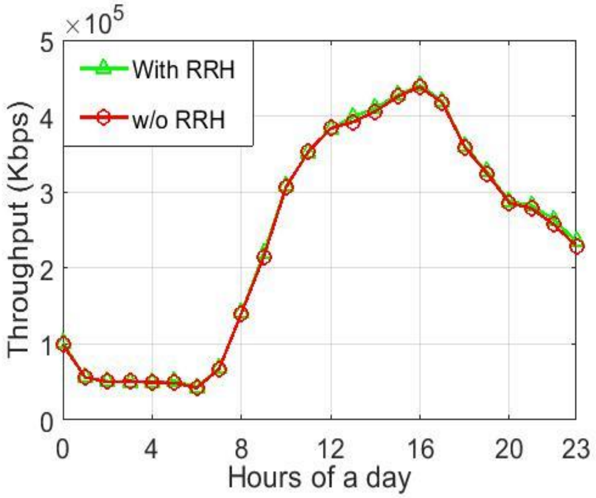

Figure 9: Throughput variation for 24 hours.

D. Economic Analysis

The breakdown for the gross capital cost (CC), operation and maintenance cost (OMC), replacement costs (RC), and the salvage value (S) incurred within the lifetime of the project are calculated using data of Table III.

From Table VI and Table VII, the net present cost (NPC) for the macro cell without RRH and macrocell with RRH LTE-BS is $21,496 and $15,237 respectively, which is calculated using (12). Figure 10 represents the annual cash flows for the 2/2/2 macro BS without RRH while Figure 11 depicts the annual cash flows for the 2/2/2 macro BS with the RRH system. On the other hand, Figure 12 demonstrates the comparison of summarized cost analysis for the entire cellular system to take into consideration of both solar power and DG power system. A profound impact on the savings of operational expenses using the proposed solar-powered cellular system has been found in Figure 12. Despite the higher initial cost for stand-alone solar power systems, over time the proposed system achieved superior NPC savings. It has been found that the incorporation of RRH with macrocells could achieve 29% NPC savings over traditional macro BS configuration. Furthermore, the PV/battery power system for LTE BS performs a lot better than the DG power system as clearly evident from Figure 12.

E. Economic Feasibility Analysis of the Proposed Solar Power System incorporated with a Diesel Generator

1) Macrocell without RRH: The DG required is around 4 kW that is calculated as (maximum BS load 1.05 kW) divided by (η_{DG} = 30% X η_{inv} = 95%).

a) Capital Cost (CC): The capital cost is 2,640 (size 4kW cost660/kW).

b) O&M Costs (OMC): Annual maintenance cost is $438, which is calculated as ($0.05/h yearly DG functioning duration 8760 h). The DG consumes 0.388 L/kWh [53] and according to (6) the yearly energy production of the DG is 10,512 kWh. The total diesel consumption is 4079 L per year as computed using (7). Hence, the overall fuel cost is $3,263 (diesel price $0:80/L 4 079L× year). Therefore, the annual O&M cost is $3,701 (excluding fuel transport expenditure and future up trending fuel price) and the total O&M costs over the project lifetime is $37,010.

TABLE V: Throughput and energy efficiency performance of the system.

BS Type	Average throughput (Kbps)	Energy efficiency (Kbps/W)
Macro with RRH	2,40,235	347.3
Macro w/o RRH	2,38,136	228.4

TABLE VI: Cost analysis breakdown for macrocell with RRH.

Components	CC($)	RC($)	OMC($)	S($)	NPC($)
SPV	4,000	0	284	1,249	15,274
Battery	9,600	5,122	2,274	4,798	
Converter	40	0	7	7	
Total cost	13,640	5,122	2,565	6,053	

TABLE VII: Cost analysis breakdown for macrocell w/o RRH.

Components	CC($)	RC($)	OMC($)	S($)	NPC($)
SPV	7,000	0	497	2,186	21,496
Battery	9,600	6,334	2,274	2,114	
Converter	80	0	21	14	
Total cost	16,680	6,334	2,785	4,313	

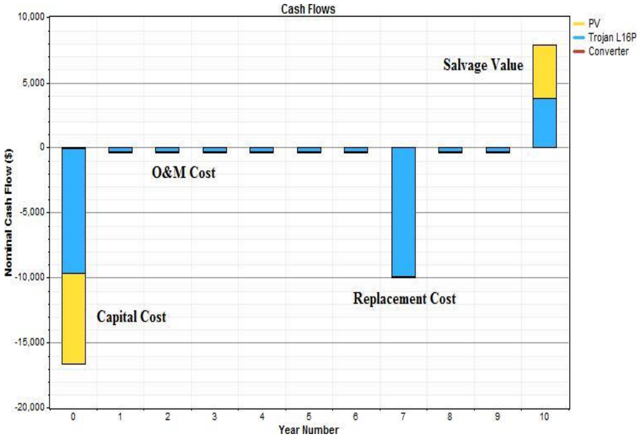

Figure 10: Cash flow for the solar-powered macrocell without RRH.

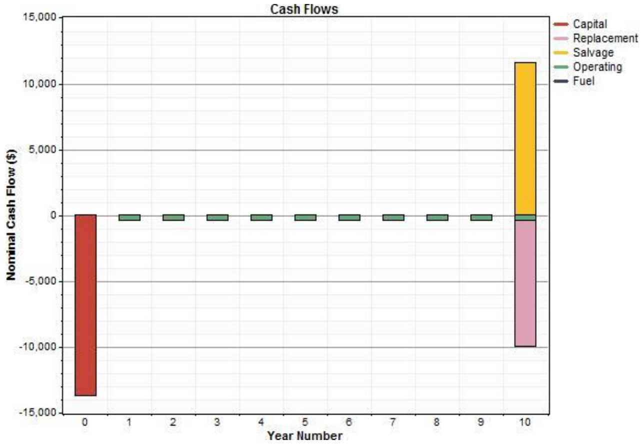

Figure 11: Cash flow for the solar powered macrocell with RRH.

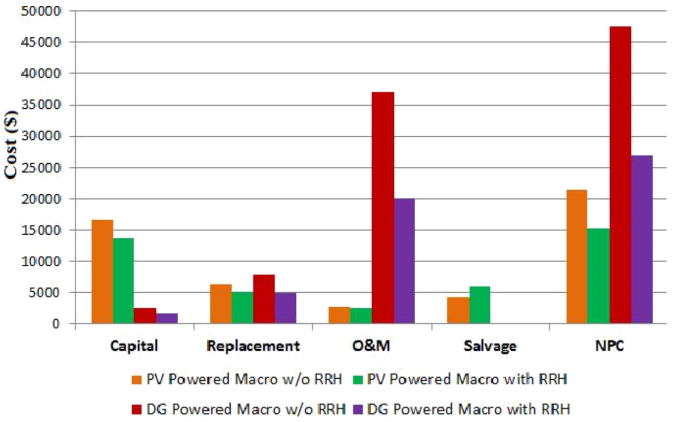

Figure 12: Comparison of cost analysis between solar power and DG power system for macro BS.

c) Replacement Costs (RC): The DG may need to be replaced every three years by telecom operators and thus, the DG will be replaced at least three times during the project lifetime. Accordingly, the total replacement cost is 3 × (size $4kW × cost $660=kW), totaling at least $7,920.

d) Net Present Cost (NPC): The NPC is $47,570 ($2,640 + $37,010 + $7,920) overestimated project lifecycle.

2) Macrocell with RRH: The DG needed is approximately 2.5 kW (BS peak load 0.685 kW) divided by (DG = 30% × η_{inv} = 95%). The yearly energy production is 6,570 kWh.

a) CC: The capital cost is $1,650.

b) OMC: The diesel consumption per year is 2,549 L. Annual maintenance cost is $438, whereas the total fuel cost per year is $2,039. Therefore, the total OMC is $24,770 over the estimated project lifetime.

c) RC: The total replacement cost is at least three times of capital cost (i.e. $4,950).

d) NPC: The NPC is the sum of CC, OMC, and RC and the total amount is about $31,370 over a 10-year project lifecycle. To the end, Table VI and Table VII summarize the comparison of operating cost and net present saving between stand-alone PV power and DG power scheme for the LTE cellular networks.

TABLE VIII: Percentage of cost savings for macrocell with RRH.

Cost type	Solar system	DG system	Savings (%)
OMC	$2,565	$24,770	89.65
NPC	$15,237	$31,370	51.43

TABLE IX: Percentage of cost savings for macrocell w/o RRH.

Cost type	Solar system	DG system	Savings (%)
OMC	$2,785	$37,010	92.5
NPC	$21,496	$47,570	54.8

F. Carbon Footprints

It is mentioned in [53] that a diesel generator emits 2.68 kg/L of CO2. According to [6] the annual diesel consumption of DG powered macrocell without RRH is 4,079 L and produces 10,932 kg carbon emissions per year. On the other hand, the DG powered macro BS with the RRH feature generates a comparatively lower amount of greenhouse gas emissions is about 6,831 kg/year.

CONCLUSION

This paper reports the viability of two different LTE macro base stations located at off-grid remote sites in Bangladesh which is capable of undergoing its operation by the stand-alone solar power system. The optimal system architecture including the technical and economic feasibility parameters has been extensively appraised using the HOMER software package. The numerical findings demonstrate that the amount of annual excess electricity produced by solar PV array is 3,068 kWh for the macro cell without RRH and 963 kWh for the macrocell with RRH. This implies a stand-alone SPV array meets the required energy demand of the LTE macro BS independently. In addition to this, the backup battery bank can supply the LTE macro BS without RRH for 46 hours and macro BS with RRH for 70.8 hours autonomously in case of the failure of the solar array to harvest the required amount of energy to fulfill the BS energy demand. Furthermore, the solar-powered BS without RRH and BS with RRH has achieved NPC cost savings 54.8% and 51.43% to the DG system respectively. Besides, the integration of RRH with 2/2/2 macro BS significantly saves 29% overall net present cost and also achieves a substantial enhancement in network energy savings yielding up to 34.8%. These findings show that the solar power system with RRH is an excellent alternative for cellular communication to lessen both the operational costs and carbon emissions. The extension of this work will focus on the energy-efficient performance of the hybrid power cellular system via energy sharing.

Conflicts of Interest: The authors declare no conflicts of interest.

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