Long-Term Techno-Economic Analysis of Sustainable and Zero Grid Cellular Base Station

MOHAMMED H. ALSHARIF 1, RAJU KANNADASAN 2, ABU JAHID 3, (Graduate Student Member, IEEE), MAHMOUD A. ALBREEM 4, (Senior Member, IEEE), JAMEL NEBHEN 5, AND BONG JUN CHOI 6,7, (Senior Member, IEEE)

1Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, Seoul 05006, South Korea
2Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Chennai 602117, India
3School of Electrical and Computer Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada
4Department of Electronics and Communication Engineering, A’Sharqiyah University, Ibra 400, Oman
5College of Computer Engineering and Sciences, Prince Sattam Bin Abdulaziz University, Alkharj 11942, Saudi Arabia
6School of Computer Science and Engineering, Soongsil University, Seoul 06978, South Korea
7School of Electronic Engineering, Soongsil University, Seoul 06978, South Korea

Corresponding authors: Jamel Nebhen (j.nebhen@psau.edu.sa) and Bong Jun Choi (davidchoi@soongsil.ac.kr)

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ABSTRACT Green wireless networking has attracted considerable research attention, especially in academics and industry from economic and ecological perspectives. Promoting wireless infrastructures by exploiting green power sources has the potential to enhance sustainability and address the adverse impact of conventional power sources. A sustainable optimal standalone solar-powered model for green cellular base stations in urban locations of South Korea is proposed in this work to extend 24-hour uninterrupted power supply support to LTE cellular base stations (BSs) and take advantage of integrated storage devices. The optimal system architecture, energy management, and economic analysis are examined using the hybrid optimization model for electric renewable optimization software based on actual prevailing conditions of regions and their technical feasibility. Results showed that the proposed solar photovoltaic system can achieve significant operational expenditure savings of up to 43% and 43.58% in on- and off-grid sites, respectively, and reduce greenhouse gas emissions in the telecommunications sector. Moreover, the results of this study can provide a stronger platform for a sustainable green wireless network paradigm that can ensure energy sustainability compared with conventional technology.

INDEX TERMS Green wireless networks, energy-efficiency, eco-friendly, photovoltaic (PV), sustainability.

I. INTRODUCTION Rapid technological advancement has remarkably increased mobile devices/subscribers and data/multimedia applications in the last few decades. Consequently, wireless applications have progressed rapidly and significantly. Telecommunications operators have increased the number of base stations (BSs), which are considered key energy consumption sources in cellular networks and account for 57% of the total energy used, to satisfy high data demand [1], [2]. Energy consumption and operational expenditure (OPEX) have increased significantly due to the substantial growth of installed BSs to meet subscriber demands [3], [4]. Therefore, network operators have applied economic energy consumption schemes to reduce the OPEX and increase profit while mitigating adverse environmental issues [5]. However, meeting the energy demand while considering both ecological issues and OPEX savings to attain energy-efficient cellular networks is a challenging task for researchers, academics, vendors, and network operators due to its anticipated financial and environmental impact in the coming years. Accordingly, a new initiative of green communication was created to shift toward energy-efficient cellular networks [1], [2]. The green communication initiative primarily focuses on increasing energy efficiency, curtailing the OPEX, and eradicating greenhouse gas (GHG) emissions.
Available renewable energy sources (RESs), specifically solar energy, can be adopted for long-term, cost-effective, and reliable power supply to BSs because sunlight is free, available everywhere, and an effective alternative energy option for remote areas. However, creating a photovoltaic (PV) scheme requires a viability assessment to avoid poor power supply, particularly in BSs. Therefore, cellular operators need to consider both technical and economic factors before the implementation of solar-powered BSs.

### A. RELATED WORK

A combination of various RESs or non-RESs with RESs have been proposed to overcome the limitations of a single technology. For instance, the combination of an electric grid with RESs or a single RES with adequate battery storage devices is put forward to power access networks in wireless infrastructures. Table 1 summarizes the different investigations on renewable energy-powered BSs.

| Site       | Ref. | Year | Technique                                                                 |
|------------|------|------|---------------------------------------------------------------------------|
| On-grid    |      |      | Discussed the energy management problem among BSs, battery charging and     |
|            | [10] | 2019 | discharging rate, and energy purchased from the grid.                     |
|            | [11] | 2019 | Energy is saved by cutting down on grid energy and sharing surplus green   |
|            |      |      | energy among BSs.                                                         |
|            | [12] | 2018 | Proposed to switch off unneeded BSs besides energy management depending on  |
|            |      |      | the smart grid.                                                           |
|            | [13] | 2017 | A hybrid energy sharing framework that utilizes a combination of physical  |
|            |      |      | power lines and energy trading with other BSs using a smart grid is       |
|            |      |      | proposed.                                                                 |
|            | [14] | 2016 | Investigated the green energy provisioning problem, which aims to         |
|            |      |      | minimize the OPEX by satisfying quality-of-service requirements.          |
|            | [15] | 2015 | Considered hybrid energy sources and limited energy storages and used a    |
|            |      |      | joint power allocation and battery management scheme to cut down on        |
|            |      |      | electricity cost.                                                         |
|            | [16] | 2015 | Considered heterogeneous networks with BSs powered from both RESs and      |
|            |      |      | grid power.                                                              |
|            | [17] | 2015 | Specified the renewable power inventory policy, that is, the power storage  |
|            |      |      | level for BSs powered by a combination of RES and the conventional electric|
|            |      |      | grid.                                                                    |
|            | [18] | 2015 | Proposed a new design methodology of hybrid energy supply for green        |
|            |      |      | cellular networks with the help of Lyapunov optimization techniques.       |
|            | [19] | 2014 | Proposed a model for energy cooperation between BSs with individual hybrid  |
|            |      |      | power supplies (including both the conventional grid and RESs).           |
| Off-grid   |      |      | Investigated the feasibility of PV and biomass resource-based hybrid       |
|            | [20] | 2020 | supply systems for powering off-grid BSs.                                 |
|            | [21] | 2019 | Considered BSs powered by the smart grid and local RESs.                   |
|            | [22] | 2019 | Focused on an essential energy management approach for enhancing energy     |
|            |      |      | efficiency and reducing fuel consumption of off-grid BSs that are         |
|            |      |      | supplied with hybrid power sources, including PV and DG.                 |
|            | [23] | 2018 | Discussed the choice of parameter quantization for time, weather, and      |
|            |      |      | energy storage to derive guidelines for the development of accurate and    |
|            |      |      | credible models that can support the power system design.                 |
|            | [24] | 2016 | Considered a cluster of BSs powered with PV and equipped with energy storage|
|            |      |      | units. Implemented resource on-demand strategies to reduce the cluster     |
|            |      |      | energy consumption and adapt to energy availability.                      |
|            | [25] | 2014 | Investigated the sustainable performance of a wireless mesh network       |
|            |      |      | powered by RES and proposed adaptive resource management and admission     |
|            |      |      | control schemes to address the intermittently available capacity of the    |
|            |      |      | energy supply.                                                           |

### Challenges

| Site       | Challenges                                                                 |
|------------|---------------------------------------------------------------------------|
| On-grid    | Utilization of power from the electric grid, i.e., conventional power     |
|            | production, such as burning fossil fuels, extensively generates GHGs and   |
|            | increases global warming.                                                 |
| Off-grid   | Economic, environmental, and technical issues.                            |

While hybrid utilization of RES with on-grid is presented to warrant a reliable power supply to the BSs. Optimal conditions, key challenges, and viable solutions are suggested to extract the maximum power from RESs to reduce the grid pressure. However, utilization of power from the electric grid, that is, conventional power production, such as burning fossil fuels, extensively generates GHGs and increases global warming. Therefore, the hybridization of various RESs is proposed. The commissioning of RES-powered BSs is based on the availability of wind profile/solar irradiation that relies on latitude, seasonal disparities, and ecological circumstances.

The desired zone for PV-powered BSs is located in the midlatitude between 30° N and 30° S. Notably, low latitudes are highly profitable regions for PV-based BSs. On the one hand, preferred locations for PV-based cellular networks in the world are the western coast of the USA, northern coast of South America, Mediterranean littoral, southern part of Africa, northwestern part of India, and eastern coast of Australia. On the other hand, wind energy-based BSs are commonly installed in mountainous and coastal parts. Considering these factors, wind energy-based BSs can be positioned in the northeastern coast of North America, southern area of South America, England, northern area of Europe, northwestern part of India, southern coast of China, and coastal area of Japan [6].

### B. CONTRIBUTIONS

This work investigates the plausibility of using the solar PV system as the principle power source to meet the energy needs of BSs.
demand of macro LTE-BS 2/2/2 in metropolitan cities of South Korea.

South Korea is positioned at a latitude between 34° N and 38° N. The geographical report of these locations showed excellent potential for solar energy production with an average daily solar irradiation ranging from 2.474 kWh/m² to 5.622 kWh/m² between December and May [7]. Wind turbines are excluded from this study because South Korea demonstrates low wind potential at an average of 4 m/s [7], [8]. Moreover, a standalone solar PV system together with adequate storage devices is preferable for low-rated energy demand applications, such as cellular BSs.

Studies on solar PV systems remain unclear due to their uncertain parameters and diverse design options. Furthermore, the high complexity of solar irradiation is due to its intermittent, seasonal, and uncertain nature. The application of the HOMER model mitigates these challenges by creating the energy balance scheme for every one hour of 8,760 hours per year [9]. HOMER relates the actual electric demand of the load for every one hour with energy generation, computes energy transactions between each component of the scheme, and governs charging and discharging characteristics of batteries. Furthermore, this model determines the feasibility of the configuration on the basis of energy balance under definite conditions and installation and operating costs of the system throughout the lifespan of the entire scheme. Therefore, HOMER is used in this work to examine the techno-economic viability of the solar-powered macro LTE-BS 2/2/2.

Significant contributions of this study are summarized as follows:

- Proposes and determines technical benchmarks of an optimal standalone PV system that guarantees energy autonomy.
- Obtains long-tenure energy balance for cellular networks on the basis of available solar irradiation in metropolitan cities of South Korea that warrant sustainable green wireless networks
- Examines, analyzes, and evaluates the viability of a standalone PV system for maximum energy yield and economic savings that require both sustainability and cost effectiveness
- Assesses the influence of adopting a standalone PV system over existing works while considering OPEX savings

C. PAPER ORGANIZATION

The remainder of this work is prepared as follows. Section II describes the proposed system. Section III presents the cost model and optimization formulation. Section IV presents the methodology and simulation configuration. Subsequently, the results and discussion are presented in Section V. Further, the economic feasibility of the proposed system is given in Section VI. Lastly, Section VII concludes the work.

II. SYSTEM ARCHITECTURE AND MODELING

Fig. 1 illustrates the two subsystems of the proposed architecture: (i) the cellular macro LTE-BS 2/2/2, and (ii) the solar power subsystem (PV array, battery bank, inverter). A set of standalone solar PV panels arranged in series and parallel connections based on voltage and current ratings functions as an energy source of the proposed system. A battery bank comprising a number of small cells organized in a series/parallel fashion and accompanied by an intelligent energy management system forms the storage device for preserving surplus electricity from the PV array. Notably, the use of a storage device guarantees the desired system reliability and power quality of the generated source. Hence, excess energy stored in a battery energy storage system (BESS) can be utilized during non-sunny periods, especially at night (load shedding hours).

DC bus maintains the constant voltage (e.g., 48 V for the proposed model) and supplies power to the cellular macro LTE-BS 2/2/2. A DC/AC converter is used to power to AC for the AC load (Air Conditioner). The following subsections demonstrate the architecture of the solar-powered macro LTE-BS 2/2/2 in detail.

A. MACRO LTE-BS 2/2/2 SUBSYSTEM

The cellular BS consists of various equipment, namely, (i) multiple transceivers (TRXs), (ii) power amplifiers (PAs), (iii) radio frequency (RF) units, (iv) baseband (BB), (v) DC–DC power supply, and (vi) cooling systems. TRXs comprise of PAs that augment the signal power coming from the BB unit, which is adopted for internal processing and coding. The detailed block diagram of macro LTE-BS 2/2/2 hardware elements is shown in Fig. 1. A detailed discussion of BS components are referred to in [26], [27].

The power consumption of the BS is expressed as follows [26], [27]:

\[
P_{BS} = N_{TRX} \left( p_{PA}^{DC} + p_{RF}^{DC} + p_{BB}^{DC} \right) \frac{1}{1 - \sigma_{DC}} \frac{1}{(1 - \sigma_{cool})},
\]

where \( N_{TRX} \) represents the number of transmitting/receiving antennas for individual sites, that is, transceivers, and \( p_{PA}^{DC} \), \( p_{RF}^{DC} \), and \( p_{BB}^{DC} \) represent the power amplifier, radiofrequency, and BB power, respectively. Power loss factors are approximately \( \sigma_{DC} = 6\% \) and \( \sigma_{cool} = 10\% \) for converters and air conditioners, respectively.

Typically, the most efficient PA operating point is close to the maximum output power \( P_{PA}^{max} \) (near saturation). Unfortunately, nonlinear effects and OFDM modulation with non-constant envelope signals force the power amplifier to operate in a more linear region (6–12 dB below saturation). This prevents adjacent channel interference due to nonlinear distortions, and therefore avoids performance degradation at the receiver. However, this high operating back-off gives rise to poor power efficiency \( \eta_{PA} \), which translates to an increased PA power consumption \( P_{PA}^{max} / \eta_{PA} \). The output power of the BS is normally influenced by the range of coverage radii \( R_{0} \) and signal propagation fading. The macro-BS
transmission power is normalized to \( P_o = 40 \) W with a coverage \( R_o \) of 1 km to establish a simple derivation model. Furthermore, the BS output power considering coverage radii is computed using the relation \( P_{\text{tx}}^{\text{max}} = P_o \times (R/R_o)^{\alpha} \), where \( \alpha \) defines the loss coefficient of the path. Finally, the operating power of the BS with coverage radii \( R \) is reformulated as

\[
P_{BS} = \frac{N_{\text{TRX}} \cdot \frac{BW}{10\text{Mz}} \left( \frac{P_o}{\eta_{\text{PA}}} \right)^{\alpha} + P_{\text{DC}}^{\text{RF}} + P_{\text{DC}}^{\text{BB}}}{(1 - \sigma_{\text{DC}})(1 - \sigma_{\text{cool}})}. \tag{2}
\]

The power utilization scale of various parts of the macro LTE-BS 2/2/2 system with 2 × 2 multi-input and multi-output (MIMO) antenna arrangement with three sectors is presented in Table 2.

### B. SOLAR PV SUBSYSTEM

The solar PV subsystem comprises several types of equipment that generate green energy effectively for the entire system, achieves energy savings, and allows ease of dismantling for recycling.

1) **PV ARRAY**

The PV array consists of numerous solar cells connected in series and parallel and generates DC electric power via absorption of shortwave irradiance [28], [29]. The total annual energy of the PV array \( (E_{PV}) \) is calculated as [9]

\[
E_{PV} = PC_{PV} \times PSH \times DF_{PV} \times 365 \text{ days/year}. \tag{3}
\]

where \( PC_{PV} \) represents the peak capacity of the PV array (kW); \( PSH \) represents the peak sun hours or peak solar hours and is calculated on the basis of the equivalent average daily solar irradiation; and \( DF_{PV} \) is the derating factor of the PV array that represents the influence of dust, losses, temperature variations, and added potential issues that can reduce the output power of the panel.

**TABLE 2. Power consumption scale of different hardware elements [26], [27].**

| Elements | Parameters | Unit | LTE-BS 2/2/2 |
|----------|------------|------|--------------|
| PA       | Maximum transmitting power (RMS) | dBm | 46.0         |
|         | PAPR       | dB   | 8.0          |
|         | Output power (Peak value) | dBm | 54.0         |
|         | Efficiency (\( \mu \)) | %   | 38.8         |
| Total    | power (\( P_{\text{DC}}^{\text{RF}} \)) | Watts | 102.6 |
| TRX      | \( P_{\text{RF}} \) | Watts | 5.7         |
|          | \( P_{\text{RF}} \) | Watts | 5.2         |
| Total    | RF (\( P_{\text{DC}}^{\text{RF}} \)) | Watts | 10.9       |
| BB       | Radio (inner Rx/Tx) | Watts | 5.4         |
|          | Turbo code (outer Rx/Tx) | Watts | 4.4         |
|          | Processor | Watts | 5.0         |
|          | Total power (\( P_{\text{DC}}^{\text{BB}} \)) | Watts | 14.8       |
| Loss factor (\( \sigma_{\text{DC}} \)) | % | 6.0 |
| Loss factor (\( \sigma_{\text{cool}} \)) | % | 10.0 |
| Total power/\( N_{\text{TRX}} \) | Watts | 151.65 |

2) **BATTERY BANK**

A battery bank or BESS stores the excess power generated by PV arrays during the day for use at night or during bad weather conditions to prevent outages. The BESS capacity of the BS merely depends on the depth of discharge (DOD), which must be evaluated before the commissioning. The DOD can be expressed as

\[
DOD = 1 - \frac{SOC_{\text{min}}}{100}. \tag{4}
\]
where $SOC_{\text{min}}$ represents the minimum state of charge. The Trojan L16P battery model considered in this study demonstrates a DOD of 70%, which indicates that 70% of the energy can be shared and 30% can be used for the critical condition.

Days of autonomy ($A_{\text{batt}}$) must be computed to determine the performance of fully charged batteries, that is, the number of days fully charged batteries can supply power to the load without any influence of supplementary power sources. $A_{\text{batt}}$ is derived using HOMER as follows [9]:

$$A_{\text{batt}} = \frac{N_{\text{batt}} \times V_{\text{nom}} \times Q_{\text{nom}} \left(1 - \frac{SOC_{\text{min}}}{100}\right) (24h/d)}{L_{\text{prim-ave}} \times (1000\text{Wh/kWh})},$$

where $N_{\text{batt}}$ and $V_{\text{nom}}$ are the total quantity of battery units BESS and the nominal voltage of a single battery unit (V), respectively; $Q_{\text{nom}}$ represents the nominal rating of a single battery (Ah); and $L_{\text{prim-ave}}$ refers to the nominal rating of the average daily load of macro LTE-BS 2/2/2 load (kWh).

The total cost of solar-powered BS highly depends on the cost of batteries. Therefore, the lifetime of the battery plays a crucial role. The lifetime of a battery can be predicted on the basis of its operational settings. Specifically, the DOD during every diurnal charge–discharge cycle demonstrates an important part of the battery lifetime. $R_{\text{batt}}$ can be computed using HOMER as follows [9]:

$$R_{\text{batt}} = \min \left(\frac{N_{\text{batt}} \times Q_{\text{lifetime}}}{Q_{\text{thrp}}}, R_{\text{batt,f}}\right),$$

where $Q_{\text{lifetime}}$ represents the lifespan throughput of an individual battery in kWh, $Q_{\text{thrp}}$ represents the annual battery throughput in kWh per year, and $R_{\text{batt,f}}$ represents the battery float life in years.

The number of series-connected batteries is computed by the ratio of DC busbar voltage ($V_{b-b}$) and voltage rating ($B_V$) of a single battery that can be expressed as

$$N_{\text{batt}} = \frac{V_{b-b}}{B_V}.$$  \hspace{1cm} (7)

The total number of parallel paths can be determined by the ratio of the total number of batteries adopted and the total number of series-connected batteries.

3) INVERTER

The output power from the PV system is the DC, which can be converted into usuable 220 V AC voltage with nominal frequency using an inverter that feeds the power to the AC load, such as the cooling system of the BS. The total capacity of the inverter ($C_{\text{inv}}$) is calculated as follows [30]:

$$C_{\text{inv}} = \frac{L_{\text{AC}}}{\eta_{\text{inv}}} \times \sigma_{sf},$$

where $L_{\text{AC}}$ represents the available maximum AC load, $\eta_{\text{inv}}$ represents the inverter efficacy, and $\sigma_{sf}$ represents the safety factor.

### III. COST MODEL AND OPTIMIZATION FORMULA

The configuration of the solar-powered BS is based on the following considerations:

- What are essential components involved in the complete design?
- How many components need to be used?
- Size of each element

Selecting energy resources from various sources is difficult due to the many technology options. The HOMER software is an effective platform established by the U.S. National Renewable Energy Laboratory to simplify the modeling process of solar-powered systems and evaluate the maximum number of possible system configurations [9]. Furthermore, the HOMER micropower optimization tool aids in obtaining the optimal PV system with lower present cost (NPC). The NPC term contains all incurred expenses and income throughout the project lifetime [9].

The total accumulated cost ($C_{\text{TAC}}$) demonstrates the annual price of the complete scheme in $/year that contains the initial capital ($C_{\text{TAC}}^{\text{cap}}$), replacement ($C_{\text{TAC}}^{\text{rep}}$), and operation and maintenance (O & M) ($C_{\text{TAC}}^{\text{O&M}}$) costs. The complete description of the cost can be expressed as

$$C_{\text{TAC}} = C_{\text{TAC}}^{\text{cap}} + C_{\text{TAC}}^{\text{rep}} + C_{\text{TAC}}^{\text{O&M}}.$$  \hspace{1cm} (9)

The net present cost ($C_{\text{NPC}}$) can also be described for the annualized value as

$$C_{\text{TAC}} = C_{\text{NPC}} + CRF(i, N),$$

where $C_{\text{NPC}}$ represents all prices that incur within the scheme lifespan but with impending cash flows cut-rate to the current discount ratio. The NPC comprises the initial capital (IC), replacement, and O & M costs. However, the total NPC value is reduced due to the salvage value, particularly at the end of the venture lifespan. Capital recovery factor (CRF) denotes the recovery factor that converts $C_{\text{NPC}}$ into the flow of equal annual costs over a definite period and can be calculated on the basis of the annual interest rate ($i$) and project lifespan ($N$) as follows:

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

where $N$ is equal to 10 years and $i$ is 0.5%. The salvage value ($S$) is calculated as

$$S = C_{\text{rep}} \frac{R_{\text{rem}}}{R_{\text{comp}}},$$

where $R_{\text{comp}}$ represents the lifespan of the component in years, $R_{\text{rem}}$ represents the remaining lifespan of the component in years, and $C_{\text{rep}}$ represents the replacement rate of the component in $.

This study aims to decrease the total cost of NPC because the optimal scheme of a standalone PV system depends on various constraints. The objective function of NPC is defined as

$$\min_{E_{PV}, E_{Battery}, E_{Lestor}, E_{BS}} C_{\text{TAC}} = \frac{C_{\text{TAC}}}{CRF(i, N)},$$

where $E_{PV}$, $E_{Battery}$, $E_{Lestor}$, and $E_{BS}$ represent the energy provided by the PV system, battery, and other components, respectively.
where $E_{BS}$ is the annual BS load consumption and $E_{PV}$ is the total annual energy of the PV array subjected to the (i) number of PV panels; (ii) derating factor, which represents the influence of dust, losses, temperature variations, and added potential issues that can distress the output power of the panel; and (iii) peak sun hours, as presented in Eq. (3).

$E_{Battery}$ is the energy afforded by the battery bank. The Trojan L16P battery model is used in this study because

**FIGURE 2.** Flowchart of the proposed system.
its DOD is 70%. Hence, this battery can deliver 70% of its energy effectively with 30% of its energy reserved for use in the critical condition. If $E_{PV}$ is higher than the required BS load with losses, then the excess energy will be stored in the battery bank. If $E_{PV}$ is lower than the required BS load with losses, then the battery bank will compensate for the shortage in energy and the maximum energy allowed for sharing is 70% of the total energy of the battery bank.

Power shortages must be prevented in the cellular network sector. The output power of the PV system must not constantly be larger than zero because of the absence of generation at night. Thus, the constraint (13.1) guarantees that the energy generated by the PV and battery must be higher than zero. In addition, the supply, which (energy output of PV [$E_{PV}$] and battery bank [$E_{battery}$]) must be larger or equal to the demand (load [$E_{BS}$] and losses [$E_{losses}$]), is represented in the second constraint equation (13.2).

### IV. METHODOLOGY AND SIMULATION CONFIGURATION

The algorithm of the proposed system is simplified in the flowchart depicted in Fig. 2. The standalone solar-powered cellular system is defined as the optimization problem with an objective function of the minimum NPC subjected to different design conditions. The operation of the methodology can be categorized into the following steps. First, if the green energy ($E_{PV}$) harvested from the on-site installed solar panel can sufficiently handle the BS demand and associated losses, then energy will not be stored in the battery bank and without deficit. Second, the additional solar energy can be accumulated when $E_{PV}$ is higher than the required BS load. Note that total losses include battery and converter losses because devices are non-ideal. The energy conversion from the DC power to feed the AC load incurs some conversion losses and the battery charging–discharging phenomenon causes the battery loss. By comparison, the storage device supplies backup electricity when the harvested solar energy is insufficient due to abnormal conditions. Moreover, the surplus electricity should not exceed the maximum battery storage capacity and the excess electricity becomes equal to zero when energy

| Components | Parameters | Range |
|------------|------------|-------|
| Control factors [31, 32] | Interest rate-Annual | 0.5% |
| | Project lifespan (N) | 10 years |
| | Dispatch scheme | cyclic charging |
| | Apply set point SOC | 80% |
| | Percentage of load and hourly load | 10% |
| PV [33] | Sizes considered | 5, 5.5, 6, 6.5, 7, 7.5 kW |
| | Operational lifetime | 25 years |
| | Efficiency | 85% |
| | System tracking | Two-axis |
| | IC | $1/Watt |
| | Replacement rate | $1/Watt |
| | O & M price/year | $0.01/Watt |
| Inverter [34] | Sizes considered | 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 kW |
| | Efficiency | 95% |
| | Operational lifespan | 15 years |
| | IC | $0.4/Watt |
| | Replacement rate | $0.4/Watt |
| | O & M price/year | $0.01/Watt |
| Trojan L16P Battery [35] | Number of batteries | 24, 32, 40, 48, 56, 64, 72 |
| | Round trip efficacy | 85% |
| | Minimum SOC | 30% |
| | Nominal voltage | 6 Volt |
| | Nominal current | 360 Ah at 20 h |
| | Nominal capacity | 6 Volt $\times$ 360 Ah = 2.16 kWh |
| | Lifetime throughput | 1075 kWh |
| | Maximum charge rate | 1 A/Ah |
| | Maximum charge current | 18 A |
| | Self-discharge ratio | 0.1% per hour |
| | Minimum operational lifespan | 5 years |
| | IC | $300 |
| | Replacement rate | $300 |
| | O & M price/year | $10 |
TABLE 4. Comparative analysis of the proposed solar powered macro LTE-BS 2/2/2 for main metropolitan cities of Korea.

| Resources          | Seoul    | Incheon | Daegu | Daejeon | Busan | Gwangju |
|--------------------|----------|---------|-------|---------|-------|---------|
| Average solar irradiance (kWh/m²/day) | 4.65     | 4.69    | 4.83  | 4.98    | 5.06  | 5.19    |
| PV                 |          |         |       |         |       |         |
| Size (kW)          | 6.0      | 6.0     | 5.5   | 5.5     | 5.0   | 5.0     |
| Energy (kWh/Year)  | 10,993   | 10,738  | 10,220| 10,452  | 9655  | 9983    |
| IC cost ($)        | 6000     | 6000    | 5500  | 5500    | 5000  | 5000    |
| Discounted O&M cost ($) | 584   | 584     | 535   | 535     | 487   | 487     |
| Discounted Salvage value ($) | 3425  | 3425    | 3139  | 3139    | 2854  | 2854    |
| Batteries          |          |         |       |         |       |         |
| Units              | 64       | 64      | 64    | 64      | 64    | 64      |
| Energy in (kWh/Year) | 5245  | 5224    | 5241  | 5200    | 5220  | 5177    |
| Energy out (kWh/Year) | 4458  | 4440    | 4455  | 4420    | 4437  | 4401    |
| Expected life (Year) | 10    | 10      | 10    | 10      | 10    | 10      |
| Autonomy (h)       | 106      | 106     | 106   | 106     | 106   | 106     |
| IC cost ($)        | 19,200   | 19,200  | 19,200| 19,200  | 19,200| 19,200  |
| Discounted O & M cost ($) | 6227 | 6227    | 6227  | 6227    | 6227  | 6227    |
| Inverter           |          |         |       |         |       |         |
| Size (kW)          | 0.10     | 0.10    | 0.10  | 0.10    | 0.10  | 0.10    |
| Energy in (kWh/Year) | 837   | 837     | 837   | 837     | 837   | 837     |
| Energy out (kWh/Year) | 795   | 795     | 795   | 795     | 795   | 795     |
| Losses (kWh/Year)  | 42       | 42      | 42    | 42      | 42    | 42      |
| Operation hours (h/Year) | 8759 | 8759    | 8759  | 8759    | 8759  | 8759    |
| IC cost ($)        | 40       | 40      | 40    | 40      | 40    | 40      |
| Discounted O & M cost ($) | 10    | 10      | 10    | 10      | 10    | 10      |
| Discounted Salvage value ($) | 13   | 13      | 13    | 13      | 13    | 13      |
| Discounted project cost |        |         |       |         |       |         |
| IC cost ($)        | 25,240   | 25,240  | 24,740| 24,740  | 24,260| 24,260  |
| O & M cost ($)     | 6821     | 6821    | 6772  | 6772    | 6724  | 6724    |
| Salvage value ($)  | 3438     | 3438    | 3152  | 3152    | 2867  | 2867    |
| NPC ($)            | 28,623   | 28,623  | 28,360| 28,360  | 28,147| 28,147  |
| OPEX saving        |          |         |       |         |       |         |
| On-grid            | $21,584  | (43%)   | $21,847| (43.51%)| $21,847| (43.51%)| $22,090| (44%)| $22,090| (44%)|
| Off-grid           | $22,11   | (43.58%)| $22,376| (44.10%)| $22,376| (44.10%)| $22,619| (44.58%)| $22,619| (44.58%)|

FIGURE 4. Average PV output power (month wise).

production balances the energy consumption. By contrast, the deficit energy can be computed when the cumulative contribution of $E_{PV}$ and storage discharging ($E_{disch}$) are lower than the required BS demand that includes losses. However, energy deficiency is zero under the balance condition, that is, $E_{PV} + E_{disch}$ can handle the total load demand for specified
FIGURE 5. Average PV, BESS, and excess electricity output (hourly).

network settings. Note that HOMER determines every hour whether to cater to the BS load demand, including losses, by calculating excess and deficit energy values throughout the duration of one year. Hence, HOMER computes the minimum component combinations to meet the load demand and ensure zero energy shortage under each iteration. Finally, the minimum NPC is calculated on the basis of the total annualized cost and capital recovery factor among a number of iterations.

HOMER typically consists of three major parts, namely, inputs, optimization, and outputs [9].

1) Inputs:
- Load data, as provided in Table 2.
- Monthly average solar irradiation values (Fig. 3).

2) Definitions of economic value, system value, project lifespan, and interest rate, as provided in Table 3.
- Configuration of the range and sizes of components, such as PV, battery, and inverter.
- Application of the cost information for individual components, such as IC, replacement, O&M.
- Other technical restraints, such as lifetime and efficiency, as listed in Table 3.

3) Optimization:
The HOMER software performs an hourly simulation for all potential arrangements by calculating the accessible energy from the PV arrangement ($E_{PV}$), matching it with the available electric demand ($E_{BS}$) and losses ($E_{losses}$), and managing the surplus PV power during excess generation (battery charging) or producing extra energy during deficit (battery discharging). Finally, HOMER sorts all possible combinations to increase the NPC, which characterizes the lifecycle cost of the scheme.

4) Outputs:
The investing, maintenance, and auxiliary (replacement) costs and the salvage value of each component are used to calculate TAC by adding annualized costs and the economic index of individual components. TAC is used to calculate the total NPC value.

V. RESULTS AND DISCUSSION
A brief comparative study of the proposed solar-powered macro LTE-BS 2/2/2 for main metropolitan cities of South Korea is presented in Table 4. Optimal size measures, energy harvest, and economic investigation for Seoul City is discussed thoroughly in the following subsections as the case study in this work. Seoul is the capital and largest city in the country with a high population. This investigation can be extended to include other metropolitan cities with small variances in daily peak sun hours (solar irradiation).
A. ENERGY YIELD ANALYSIS

The total NPC cost of the solar-driven macro LTE-BS 2/2/2 comprising 6.0 kW-rated PV panels and 64 numbers of batteries is economical at $28,623. Batteries are connected to eight parallel strings along with a 0.1 kW inverter.

The yearly energy output of the PV array is calculated using Eq. (3). The total energy output of the PV arrangement is calculated at 8,656 kWh ($6 \text{ kW} \times 4.65 \text{ h} \times 0.85 \times 365 \text{ days/year}$). The generating energy may increase to a maximum of 27%, that is, 10,993 kWh more annually due to the use of a dual-axis tracking system. This energy yield also means losses incurred in the system, including BESS and inverter losses of approximately 787 and 42 kWh, respectively, and supplies the power to load (7,972 kWh) the BS with an annual excess energy of up to 2,192 kWh, which is 19.93% of the total energy generation. The monthly average energy generation by the PV system is illustrated in Fig. 4. The maximum and minimum energy generation occurred in February and August, respectively. Monthly disparities occur largely due to the elevation angle shift of the sun. In addition, the extended spell of rainy meteorological conditions in early summer remarkably reduces the global horizontal irradiance in August. The average hourly energy generation of the PV, BESS, and excess electricity for 12 months is presented in Fig. 5. The initial phase of August shows a low rate of energy contribution in the PV system. Therefore, the energy stored in the BESS condensed into the minimum scale, and the SOC stretched to 44%, as shown in Fig. 6. Seasonal statistics of the maximum and minimum SOC are illustrated in Fig. 7. The maximum energy influence of the BESS occurred in August due to the minimal energy contribution of the PV array.

The annual energy output and input of BESS are 4,458 and 5,245 kWh, respectively, with a battery roundtrip efficiency of 85%. Moreover, the BESS supplies power to the load for approximately 106 h during the malfunction of the PV system.

The net capacity of the inverter unit is 0.1 kW, and its efficiency is computed between the input (837 kWh) and output (795 kWh) energy annually at 95%. The total operating hours are 8,759 hours/year (24 hours $\times$ 365 days/year).

B. ECONOMIC ANALYSIS

The cash flow summary for Seoul City throughout the project lifespan is presented in Fig. 8. The breakdown of the cash flow summary is presented as follows.
The size of the system is directly proportional to the IC cost. The total IC cost of the proposed scheme of $25,240 is composed of the following:

- **a)** 23.77% for the PV array ($6,000 = 23.77\% \times 6.0 \text{ kW} \times \$1,000/\text{kW} = 23.77\% \times 6,000)$
- **b)** 76.07% for the BESS ($19,200 = 76.07\% \times 64 \times \$300/\text{unit} = 76.07\% \times 64 \times 300)$
- **c)** 0.16% for the inverter ($40 = 0.16\% \times 0.1 \text{ kW} \times \$400/\text{kW} = 0.16\% \times 40)$

The O&M cost of the system of $6,821 is composed of the following:

- **a)** $584 (8.56\%) for the PV array
- **b)** $6,227 (91.29\%) for the BESS
- **c)** $10 (0.15\%) for the inverter

The BESS demonstrates a higher ratio from the capital cost compared with other components but depends on the sum of individual batteries used for the arrangement. HOMER computed the optimal number of batteries at 64 in this configuration. Reducing the total number of batteries is possible, but it reduces the load autonomy, which is a serious concern.

Replacement costs are excluded due to the short operational lifespan of the project (10 years) and the long lifespan of the BESS, PV arrays, and inverter of 10, 25, and 15 years, respectively.

The salvage value of each component at the end of the project lifespan must be considered. Eq. (12) is used to compute the salvage value of the PV array at $3,425, which is the highest value among all components. The salvage value of the inverter is estimated at $13. The total salvage value at the end of the venture lifespan is $3,438.

The net NPC is $28,623, that is, $25,240 (IC) + $6,821 (O&M)–$3,425 (salvage). This investigation can be extended to other schemes with system costs dependent on individual component sizes.

### C. IMPLEMENTATION OF THE PROPOSED SOLAR-DRIVEN MACRO LTE-BS 2/2/2

Fig. 9 presents the implementation of the solar-powered macro LTE-BS 2/2/2.

The array of PV panels rated 6.0 kW is considered using 24 Sharp ND-250QCs modules (polycrystalline) [36]. The voltage ($V_{pm}$), current ($I_{pm}$), and power ($P_{pm}$) of the system are 29.80 V dc, 8.40 A, and 250 W, respectively. Four series and six parallel modules (24 Sharp ND-250QCs) are connected to achieve compatibility with solar control regulator (Solarcon SPT-4830) specifications [37]. The open-circuit voltage of the SCR ($V_{oc}^{SPT-4830}$) is 192 V dc, which is greater than that of the PV panel (153.2 V dc with four PV modules in series $\times V_{oc}^{ND-250QCs} = 38.3$ V dc). The voltage rating and capacity of the single Trojan L16P battery are approximately 6 V dc and 360 Ah, respectively [35]. Sixty-four batteries are arranged in eight series and eight parallel to obtain the required ratings.
The inverter rating must be capable of handling 0.1 kW. An LS Drive/M100 model with a capacity of 0.1 kW, 12/24/48 Vdc input voltage, and output voltage (220/110 Vac) is considered in this study. An AC output power with a frequency of 50/60 Hz with pure sine waves is obtained.

VI. ECONOMIC FEASIBILITY OF THE PROPOSED SOLAR POWERED MACRO LTE-BS 2/2/2

Mobile operators primarily aim to increase their profit with reduced OPEX in cellular networks. The economic viability of the PV system with conventional energy resources is as follows:

- The net energy cost spent for the macro LTE-BS 2/2/2 due to the utilization of the electrical grid for 10 years is approximately KRW 56.328 million (the annual energy consumption of the macro LTE-BS 2/2/2 is 7,972 kWh × 706.57 KRW/kWh [energy price] × 10 years [project lifespan]. The value of 56.328 million KRW is equal to $50,207 (USD 1 = KRW 1,121.90 as of November 08, 2020).

- DGs are commonly used to power the macro LTE-BS 2/2/2 in remote areas, such as off-grid stations. The DG rating should be around 3.5 kW, which can be obtained between the ratio of the maximum macro LTE-BS 2/2/2 and 30% of DG efficiency [39] × converter efficiency of 95%. The net NPC is computed and recorded at $50,736 ($2,310 [IC] + $41,496 [O&M costs] + $6,930 [replacement costs]). The detailed description of these costs are as follows:
  - IC costs are computed by multiplying the system size of 3.5 kW with its cost of around $660/kW.
  - The O & M cost (annual) of the DG is approximately $4,150 (excluding the fuel transportation cost), which includes the following:
    - The net maintenance cost of DG is $438/year, which is estimated using the product of DG maintenance cost ($0.05/h) with annual operational hours (8,760 h).
    - The total fuel cost of $3,712 is computed using the product of the diesel price ($1.04/liter) with the total diesel consumption (3,569 liter/year). This calculation is based on specific fuel consumption (0.388 liter/kWh) × annual electricity generation by the DG (9,198 kWh/year, that is, the product of DG size [3.5 kW] and its efficiency [0.3 × 24 hours × 365 days per year]). Therefore, the net O&M cost for the complete plan lifespan is estimated at $41,496.
A cellular operator must replace the DG every three years, that is, a minimum of three DG replacements during the lifespan of the scheme. Therefore, the net replacement rate is equal to $6,930 (3 \times 3.5 \text{ kW} \times \$660/\text{kW})$.

The net NPC of the solar-powered macro LTE-BS 2/2/2 is approximately $28,623. Compared with conventional power sources, the total OPEX savings of 43% and 43.58% can be achieved in on- and off-grid areas, respectively, by applying the proposed solar-powered macro LTE-BS 2/2/2 scheme.

VII. CONCLUSION

A comparative analysis of the proposed solar-powered macro LTE-BS 2/2/2 for main metropolitan cities of South Korea is performed in this study to minimize the OPEX. The following key aspects are highlighted in this study: (i) optimum system architecture, (ii) energy yield analysis, (iii) implementation and technical criterion, and (iv) economic analysis. The simulation results revealed that the proposed PV-based system can meet the total demand of macro LTE-BS 2/2/2. Moreover, the BESS can supply essential power to the macro LTE-BS 2/2/2 load autonomy for 106 h, which is considered sufficient time to fix the solar array in case of malfunctions. The simulation results showed that the proposed solar-powered system can significantly reduce the OPEX. These outcomes demonstrate that the PV-based energy system can be a superior alternative for telecommunication providers.

APPENDIX

A list of abbreviations used in this paper have been shown in Table 5.

A list of symbols used in this paper have been shown in Table 6.

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MOHAMMED H. ALSHARIF received the B.Eng. degree from the Islamic University of Gaza, Palestine, in 2008, and the M.Sc.Eng. and Ph.D. degrees from the National University of Malaysia, Malaysia, in 2012 and 2015, respectively, all in electrical engineering (wireless communication and networking). In 2016, he joined the Sejong University, South Korea, where he is currently an Assistant Professor with the Department of Electrical Engineering. His current research interests include wireless communications and networks, including wireless communications, network information theory, the Internet of Things (IoT), green communication, energy-efficient wireless transmission techniques, wireless power transfer, and wireless energy harvesting.

RAJU KANNADASAN graduated from the Vel Tech Engineering College, Chennai, and received the M.E. and Ph.D. degrees from the College of Engineering Guindy, Anna University, Chennai, India. He is currently working as an Assistant Professor with the Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Chennai, India. He has published articles in international journals, and international and national conferences. His research interests include the design of metal oxide arresters for very fast transients, insulation coordination, synthesis of metal oxide nanoparticles, material processing, flexible AC transmission systems, smart waste management systems, and electric vehicles. He is an Editorial Member of the American Journal of Electrical Power and Energy Systems.

ABU JAHID (Graduate Student Member, IEEE) received the bachelor’s and M.Sc. degree in electrical engineering from MIST, Dhaka, Bangladesh. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Ottawa, Canada. From 2010 to 2012, he worked as a BSS engineer at Huawei Technologies, where he researches on radio network planning and optimization. From 2016 to 2019, he was an Assistant Professor with the Department of EEIE, Bangladesh University of Business and Technology, Dhaka. His research interests include green cellular networking, photonic integrated circuit, and microwave photonics. He has been serving as a TPC member and reviewer in many reputed international journals and conferences.

MAHMOUD A. ALBREEM (Senior Member, IEEE) received the B.Eng. degree in electrical engineering from the Islamic University of Gaza, Palestine, in 2008, and the M.Sc.(EE) and Ph.D.(EE) degrees from the University Sains Malaysia (USM), Malaysia, in 2010 and 2013, respectively. From 2014 to 2016, he was a Senior Lecturer with the Universiti Malaysia Perlis. Since February 2016, he has been an Assistant Professor of communications engineering with the Department of Electronics and Communications Engineering, A’Sharqiyyah University, Oman, where he currently chairs the department. In 2019, he was a Visiting Scholar with the Centre for Wireless Communications (CWC), University of Oulu, Finland. His research interests include the MIMO detection and precoding techniques, machine learning applications for wireless communication systems, and green communications. He received several scholarships and grants, such as the Nokia Foundation Centennial Grant in 2018, the USM Fellowship for the term 2011–2013, and the Best Master's Thesis Award of the School of Electrical and Electronics Engineering, USM, in 2010.

JAMEL NEBHEN received the M.Sc. degree in microelectronics from the National Engineering School of Sfax, Tunisia, in 2007, and the Ph.D. degree from the Aix-Marseille University, France, in 2012, all in microelectronics. From 2012 to 2018, he worked as a Postdoctoral Researcher in France with LIRMM-Lab Montpellier, IM2NP-Lab Marseille, ISEP Paris, LE2I-Lab Dijon, Lab-Sticc Telecom Bretagne Brest, and IEMN-Lab Lille. In 2019, he joined as an Assistant Professor with Prince Sattam Bin Abdulaziz University, Alkhair, Saudi Arabia. His research interests include the design of analog and RF integrated circuits, the IoT, biomedical circuit, and sensors.

BONG JUN CHOI (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from Yonsei University, South Korea, both in electrical and electronics engineering, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Canada. He was an Assistant Professor with the Department of Computer Science, State University of New York Korea, South Korea, and a Research Assistant Professor with the Department of Computer Science, Stony Brook University, USA. He is currently an Associate Professor with the School of Computer Science and Engineering and jointly with the School of Electronic Engineering, Soongsil University, Seoul, South Korea. His research interests include energy-efficient networks, distributed mobile wireless networks, smart grid communications, and network security. He is a member of the ACM.