Green and Sustainable Cellular Base Stations: An Overview and Future Research Directions

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Energy efficiency and renewable energy are the main pillars of sustainability and environmental compatibility. This study presents an overview of sustainable and green cellular base stations (BSs), which account for most of the energy consumed in cellular networks. We review the architecture of the BS and the power consumption model, and then summarize the trends in green cellular network research over the past decade. As its major contribution, this study highlights the uses of renewable energy in cellular communication by: (i) investigating the system model and the potential of renewable energy solutions for cellular BSs; (ii) identifying the potential geographical locations for renewable-energy-powered BSs; (iii) performing case studies on renewable-energy-powered cellular BSs and suggesting future research directions based on our findings; (iv) examining the present deployment of sustainable and green BSs; and (v) studying the barriers that prevent the widespread use of renewable-energy-powered BSs and providing recommendations for future work.

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Review

Green and Sustainable Cellular Base Stations: An Overview and Future Research Directions

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Keywords: cellular BSs; renewable-energy-powered BSs; sustainable BSs; green BSs; cost effectiveness

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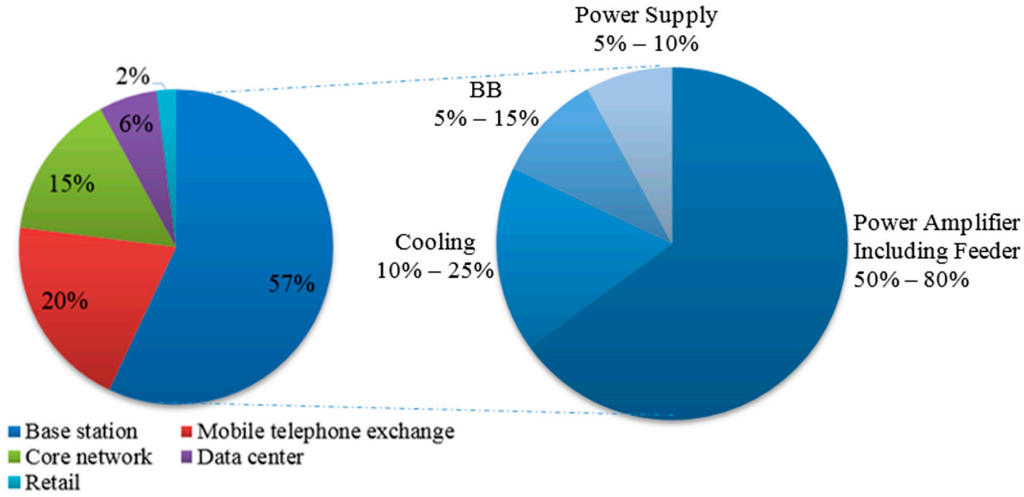
1. Introduction

Mobile communication is among the most successful technological innovations in modern history. Cellular networks have developed significantly over the last five years and now offer data-oriented services that include, but are not limited to, multimedia communication, online gaming, and high-quality video streaming [1]. The data traffic and the number of mobile subscribers have also increased exponentially [2], thereby prompting cellular network operators to install additional cellular base stations (BSs) to meet the increasing demand [3]. The number of BSs worldwide has doubled between 2007 and 2012 [4] and exceeded more than four million today [2]. The increasing number of BSs has significantly increased energy consumption because these stations account for around 57% of the total consumed energy in cellular networks [2,3] as shown in Figure 1a; these BSs also increase the operational expenditures (OPEX) of cellular networks that are mostly spent on electricity bills [1,5]. In 2014, more than $22 billion of the OPEX of cellular networks globally have been allocated to electricity consumption [6]. Cellular network operators also actively expand their network coverage, open new markets, and provide services to a billion potential customers in rural areas around the globe [7]. Unfortunately, the low electrification progress in rural areas (Figure 2), which can be attributed to their geographical limitations and economic challenges, has prompted cellular network operators to use diesel generator (DG) in powering their BSs, which increases their OPEX by 10 times [3,8]. However, using DG to power BSs does not present a viable option for those network companies that aim to expand and deliver their services to new customers [8,9].



(a) Power consumption of a wireless cellular network (b) Power consumption distribution in a BS

Figure 1. Breakdown of power consumption in a cellular network and BS [2,3].

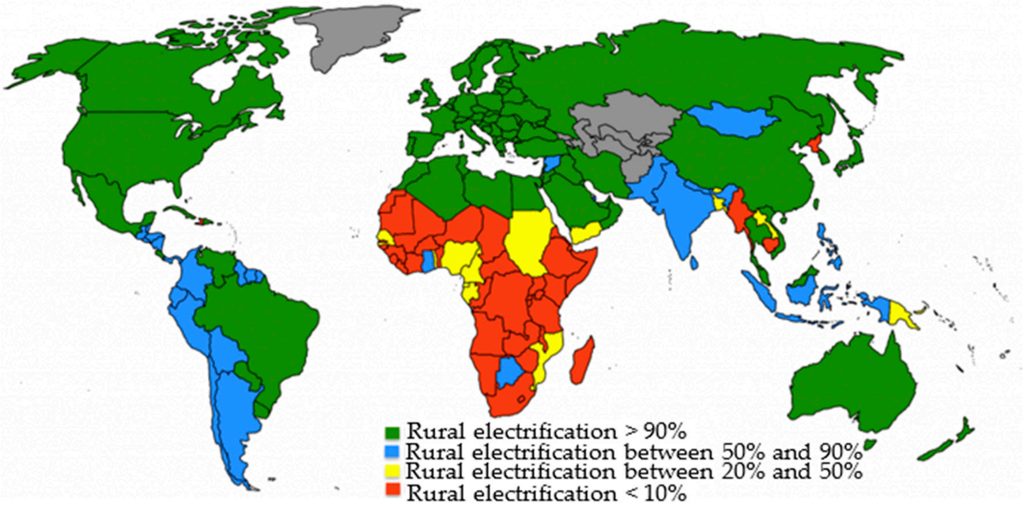


Figure 2. Electrification progress in rural areas around the world [10].

Cellular network operators endeavor to improve the energy efficiency of cellular networks not only to maintain their profitability but also to reduce the negative environmental effects of their operations. The cellular networks sector has become a major emitter of greenhouse gases (GHG). According to [11], the amount of carbon dioxide (CO_2) emitted by the mobile sector will reach 179 $MtCO_2$ by 2020 and account for 51% of the total carbon footprint of the information and communication technologies sector. Therefore, cellular network operators are pressured to meet the demands in environmental conservation and OPEX reduction. Improving the energy efficiency of cellular networks also poses a challenge to researchers, vendors, and mobile operators because of its anticipated economic and ecologic influence in the coming years. Consequently, the relatively new research discipline of "green communication" was recently introduced [2,3].

The green communication initiative primarily aims to improve the energy efficiency, reduce the OPEX, and eliminate the GHG emissions of BSs to guarantee their future evolution [2,3]. Cellular network operators attempt to shift toward green practices using two main approaches. The first approach uses energy-efficient hardware to reduce the energy consumption of BSs at the equipment level and adopts economic power sources to feed these stations. However, the inefficient utilization of network resources can waste a large amount of energy. Therefore, the second approach promotes the intelligent management of network elements based on traffic load variations [12]. Section 3 presents additional details about these approaches.

Most studies on green cellular networks have adopted ideal models. As its name implies, the green communication initiative aims to make cellular networks "greener" by reducing their power consumption using the aforementioned approaches. Additional survey information on the use of green technologies in wireless communication networks can be found in [1–3,12–16].

This study examines renewable-energy-powered cellular BSs as a long-term solution to the problems in the mobile cellular network industry [17]. Apart from offering recommendations for future research, this study comprehensively analyzes the related literature, the potential renewable energy solutions for cellular BSs, the potential geographical locations for renewable-energy-powered BSs, the case studies on the use of renewable energy in cellular networks, the open issues on solar panel systems, wind turbines, and fuel cells, the current deployment of renewable-energy-powered BSs, and the barriers that prevent the spread of green BSs. In addition to its advantages and limitations, this study briefly reviews the current research trends in improving the energy efficiency of cellular networks.

The rest of this paper is organized as follows: Section 2 discusses the architecture of BSs, analyzes the power consumption of their parts, and establishes a generic power consumption model to devise energy-efficient solutions for these stations. Section 3 comprehensively analyzes the recent trends, challenges, and barriers in green communication research. Section 4 discusses the renewable energy option. Section 5 concludes the paper.

2. Modelling the Power Consumption of Cellular BSs

To understand the power consumption problems in cellular BSs, one must explore the architecture of these systems and the power consumption of their parts. BSs act as access links that connect mobile stations to a core network. These stations cover a cell that is divided into several sectors, with each sector being covered by a sector antennas [18] as shown in Figure 3. Cellular BSs are classified into macro-, micro-, femto- (indoor), and pico-BSs according to their coverage area, and each cell has a unique size, output power, and data rate [19,20]. Small BSs generally consume less power because of their small coverage range and low radiation power demand [21,22].

A macro-BS site typically comprises several pieces of power-consuming equipment as shown in Figure 3. The macro-BS operating power can be mathematically expressed as follows [23,24]:

$$P_{macro-BS} = (N_{Sect} \times N_{TX}) \frac{P_{PA} + P_{BB} + P_{RF}}{(1 - \sigma_{MS})(1 - \sigma_{DC})(1 - \sigma_{cool})} + P_{mw} + P_{au} \quad (1)$$

where P_{PA}, P_{BB}, and P_{RF} denote the power amplifier (PA), digital signal processing or baseband unit (BB), and transceiver (RF) power, respectively. The output of PA is a linear function of BS transmission power (P_{tx}) and is expressed as P_{tx}/η_{PA}, where η_{PA} denotes PA efficiency. σ_{MS}, σ_{DC}, and σ_{cool} denote the losses incurred by the rectifier, regulator, and active cooling, respectively, which are scaled linearly with the power consumption of the other components [23,24]. P_{mw} denotes the microwave backhaul link [25], while P_{au} represents the auxiliary equipment (P_{au}), such as lighting and closed-circuit television cameras [26]. Given the multiple sectors and antennas in a BS, the power consumption of these components must be multiplied by the number of sectors (N_{Sect}), and the power consumption of the BS must be multiplied by the number of transmitting antennas (N_{TX}) for one sector [18].

Air conditioning (σ_{cool}) is usually omitted in small BSs (micro- and pico-BSs [23,24], fiber links are used instead of microwave links (P_{mw}) to communicate with the backhaul network [25], and all sectors are equipped with a rectifier (σ_{MS}) and regulator (σ_{DC}) [21]. Figure 4 shows the power consumption of the components of BSs per antenna and sector.

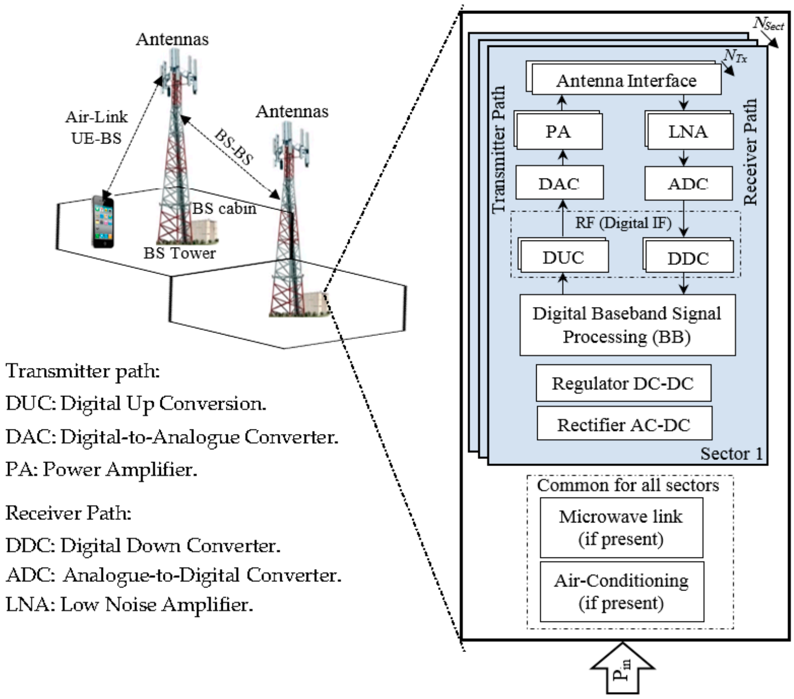


Figure 3. Block diagram of macro-BS hardware elements [21–23].

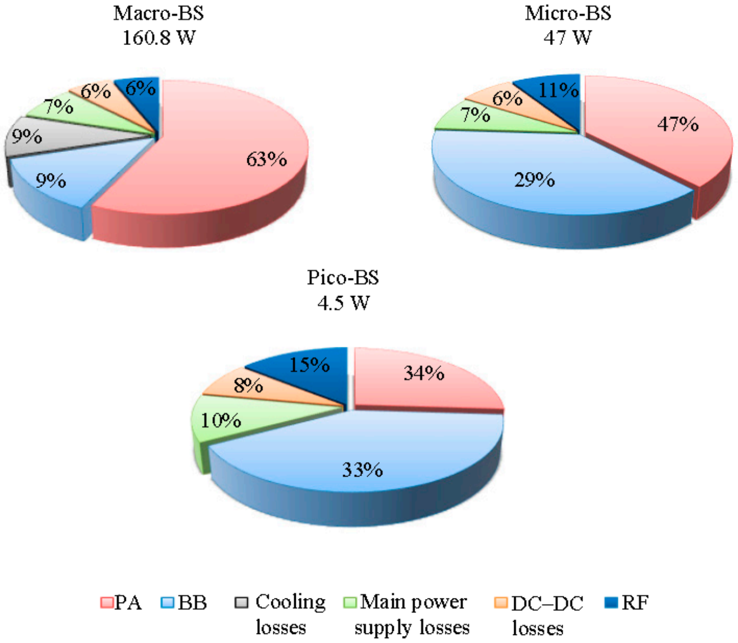


Figure 4. Power consumption of the components of BSs per antenna and sector [23,24].

The power consumption of a BS differs from one cellular generation to another [27]. Several cellular communication systems have been adopted to date, including the global system for mobile communication (GSM) or "second generation (2G)", the universal mobile telecommunications system (UMTS) or "third generation (3G)", and the long-term evolution (LTE) or "fourth generation (4G)" [28]. Table 1 summarizes the power consumption of common cellular BSs for the different cellular generations being used today. The nomenclature $n/n/n$ denotes a three-sector site with n antennas per sector. For example, 2/2/2 means that a BS comprises three sectors with each sector having two antennas.

Table 1. Total power consumption of a typical macro-BS for different cellular generations.

Site	Site Power Range (Watt)	Peak Power Draw (Watt)	Reference
GSM BS 2/2/2	600–1800	1800	[27,29]
GSM BS 4/4/4	900–2300	2300	[27,29]
GSM BS 6/6/6	2500–3700	3700	[30,31]
UMTS Node B 2/2/2	750–1000	1000	[27,29]
UMTS Node B 4/4/4	1300–1700	1700	[27,29]
LTE eNode B 2/2/2	965	965	[24]

The fifth generation (5G) technology is rapidly coming into the limelight, and commercial 5G mobile wireless networks are expected to be deployed by 2020 [28]. Energy efficiency presents a key issue in the next generation of cellular networks, and 5G is expected to be more energy efficient than the previous generations [32].

3. Green Communication Research Trends in the Last Decade

Various research projects have been launched in the last decade, such as *EARTH*, *eWIN*, *OPERA-Net*, and *Green Radio*. The successful project *EARTH* attempted to develop a new generation of energy-efficient equipment, deployment strategies, and network management solutions [1,12]. Many studies in the last decade have covered a wide range of topics to address the energy efficiency problems of cellular networks. The environmental effects and costs of BSs may be reduced in two ways. First, energy-efficient hardware can: (i) improve the energy consumption of BSs at the equipment level and (ii) facilitate the adoption of renewable energy systems (RESs) as main power sources for BSs. Second, the intelligent management of network elements can be adopted in (i) network operation and management and (ii) network planning deployment based on traffic load variations.

3.1. Energy-Efficient Hardware

3.1.1. Improving the Energy Efficiency of the Hardware Components of a BS

Most components of the current cellular network architecture have an unsatisfactory energy efficiency [2]. Most of the input energy is dissipated as heat in PA, which consumes the largest amount of energy in a typical BS as shown in Figure 1b [2,33]. Figure 5 describes the PA efficiency of various cellular communication generations.

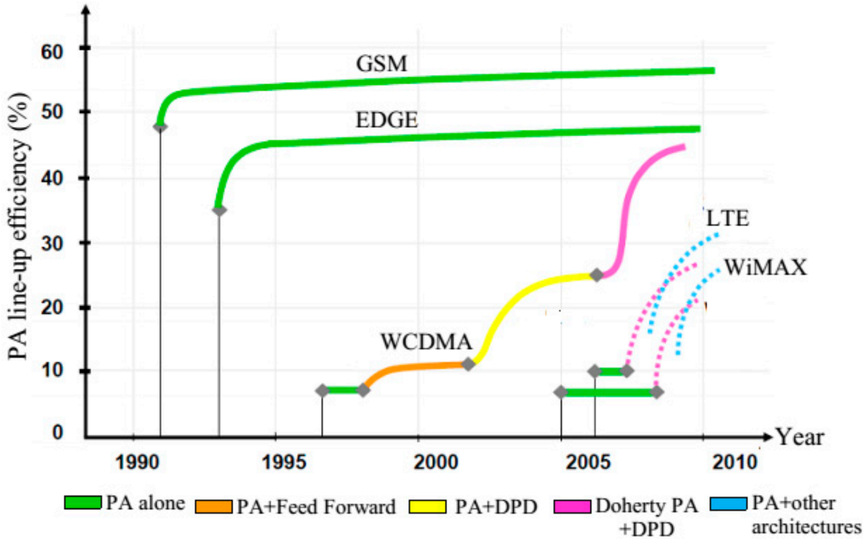


Figure 5. PA efficiency of different cellular communication generations [34].

PA efficiency decreases in each generation as the peak to average power ratio (PAPR) increases to 6.5 dB in UMTS and 8.5 dB in LTE [34]. Accordingly, many studies aim to improve the energy efficiency of PA [33,35–38] while maintaining the linearity and increasing the operating bandwidth of BSs.

Previous studies show that the potentially optimized ratio of output power to input power for PA (power efficiency) may reach as high as 60% to 85% [12,33,35,39,40]. Table 2 summarizes the advantages and limitations of the proposed techniques for improving amplifier efficiency. Although necessary for macro- and micro-BSs, these techniques are not employed in small BSs because of the increased PAPR; the PA power consumption for small BSs also accounts for a small percentage of power breakdowns, thereby allowing for a high operating back-off [24]. High-efficiency PA techniques and their classifications are further described in [19,41].

Table 2. Proposed techniques for improving PA efficiency.

Techniques		Enhancements	Limitations
Digital pre-distorted Doherty-architectures and GaN [24]		Up to 50%	Requires extra feedback for pre-distortion and signal processing.
Envelope tracking designs [39]		Up to 60%	Requires a very fast and high-bandwidth power supply as well as an accurate envelope signal for power supply.
Switched mode PA (SMPA) [35]	Class-AB	60%–70%	Overlap between voltage and current, which reduces efficiency.
	Class-D	70%	High peak voltage and limited operation between 1 GHz and 2 GHz.
	Class-F	75%	Realizing harmonic terminations at high frequencies presents a main challenge. Practical designs are typically limited to terminating the third harmonic.
	Class-E	85%	Can be supported by a transistor with slow switching characteristics and is better suited to high-frequency operations.

A substantial amount of energy can be saved if additional energy-efficient components are included in the network. However, the aforementioned approaches have a high implementation cost. Network operators must carefully consider both the operational and economical aspects of these approaches before replacing their hardware [2,3].

As for the other elements of BSs, the power consumed by air conditioning in a macro-BS can be reduced by minimizing the operational temperature of BS models or using additional elements, such as heat exchangers, membrane filters, smart fans, or heater modules [8]. The power consumed by signal processing can be reduced using DSP or the field-programmable gate array architectures of integrated circuits, which are often combined to improve efficiency. The AC/DC conversion and efficiency of BSs in high traffic load conditions can be improved using highly efficient converters [42].

3.1.2. Adopting Renewable Energy Resources

The economic, environmental, and social sustainability of power sources present main challenges because power shortages and service outages are strictly prohibited in the cellular mobile sector. The power supply requirements for BSs, including cost-effectiveness, efficiency, sustainability, and reliability, can be satisfied using the technological advancements in renewable energy [8,43]. Renewable-energy-powered cellular BSs offer an ideal long-term solution for the mobile cellular network industry in off-the-grid areas without a mature electric network and in developed countries that suffer from continuous power cuts [17]. Section 4 presents further details on these BSs.

3.2. Intelligent Management of Network Elements

3.2.1. Network Operation and Management

BSs consume the highest amount of energy in cellular networks. The deployment of dense BSs has resulted in small coverage areas and highly random traffic patterns for each BS, thereby making sleep mode operations desirable for these stations. These approaches conserve energy by monitoring the traffic load in the network and deciding whether to switch *off*/*on* certain elements of the network. Several studies [44–50] switch certain elements, including, but not limited to, PAs, signal processing units, cooling equipment, the entire BS, or the whole network, back and forth between the sleep and active modes [51]. However, a minimum number of BSs must always stay *on* to support the basic operations of the network. Given that sleep mode techniques are based on the current architecture of BSs, they can be easily tested and implemented because they do not require the replacement of any hardware. While switching these elements *on*/*off* can conserve energy, this approach may negatively affect the radio service (coverage) and quality of service (QoS) of the network unless specific remedial solutions are adopted [19]. Under an intense traffic demand, few BSs can be switched off and render the sleep-mode-based algorithm ineffective.

Several other techniques have attracted research attention. For instance, [52] investigates the multi-radio access technology with the switching *on*/*off* approach, while other studies examine the energy-aware management of individual cellular networks. The cooperation among mobile network providers in the same geographical area can effectively reduce OPEX as stated in [53,54]. In this cooperation, one or more BSs are switched *off* under low traffic load conditions to manage the coverage with a subset of active BSs through either the same or another operator, with both networks covering the same geographical area.

3.2.2. Network Planning and Deployment

Reducing the distance between the user equipment (UE) and BS can increase the data rate and reduce the transmit power, thereby improving the energy efficiency of both uplink and downlink communication. Small cells deployment [55], relay technique (fixed and user-cooperative relay systems) [56–59], and heterogeneous network (HetNet) deployment increase energy efficiency by decreasing the propagation distance between UE and BS [20]. However, previous studies have mostly focused on HetNet deployments (multilayer network) [60–64]. In HetNet, a macro BS provides connectivity and service for high mobility users, while small cells, such as micro- and pico-BSs, serve low mobility users at high data rates. Each BS type in this architecture has a unique capability, transmit power, range, power consumption, access, backhaul, and operating functionality [19,20].

Given the short distance between the transmitter and mobile station, low transmit power requirement, high data rate, and low BS power consumption, small cell BSs offer an attractive option for increasing network capacity and energy efficiency [20]. More than 40,000 small cells were deployed in 2015 [65], and this number is expected to increase in the future upon the deployment of 5G technology [66]. As shown in [67], the number of 5G small cells is anticipated to become four times larger than the number of existing macro sites to cover the same service area. The deployment of additional small cells in the future is expected to consume around 4.4 TWh of power by 2020, which will increase both the OPEX and energy consumption of conventional macro cell networks by 5% [2].

Determining the number and location of BSs to be deployed can improve spectral efficiency by reducing the radio interference of neighboring cells and increase energy efficiency by reducing the number of small cell BSs [20]. Accordingly, previous studies have addressed the following issues relating to this aspect: (i) optimizing the layouts of small cells that overlay the conventional cell (macro-cell); and (ii) creating power models for macro- and small cell BSs. Optimizing the layouts of small cells that overlay the conventional cell (macro-cell) by improving energy efficiency has been investigated in [33,63,68–72]. Optimizing BS size, location, and density has been investigated in [73–77]. The power model adapts to the traffic load variations in micro BSs to improve energy efficiency under high user density conditions. The power models for macro and micro BSs at the component level are examined in [78]. A significant amount of energy and traffic capacity can be saved by deploying micro BSs in consideration of other network design parameters. Optimizing the cell structure of the network has been discussed in [69], which examines the role of average micro sites per macro cell, average macro cell size, and changes in number of micro and macro sites in achieving a similar system performance under full load conditions. Integrating the deployment of small cell BSs using sleep mode schemes can save a large amount of energy [2,79]. Ensuring energy efficiency under uniformly distributed traffic has been investigated in [72], which shows that turning the transceivers on and off to match the variations in traffic demand can reduce energy consumption. The type of BSs (micro or macro) to be added or switched off to achieve an optimal BS density subject to a QoS has been examined in [80].

Many practical challenges must be addressed in future research to realize the benefits of integrating small cell BSs deployment with sleep mode schemes, including high backhaul bandwidth to support increasing traffic, inter-tier interference, resource management, and handover process. Given that the 5G technology aims to enhance or support, rather than replace, the existing technologies, the design issues relating to the application of the switch-off mechanism for 5G small cells may also be of interest to researchers, vendors, and mobile operators in the future, specifically after the introduction of millimeter wave (mmWave) frequencies in 5G systems.

Several other techniques have also attracted research attention. For instance, [81] shows that cooperating transmission can effectively reduce the number of deployed BSs while maintaining a low transmission power. Given that PA consumes the largest amount of energy in the entire BS, the performance of different distributed antenna system (DAS) configurations has been investigated in [82–84] to improve the spectral efficiency, uniform coverage, and energy efficiency of cellular networks.

In sum, achieving a high energy efficiency requires a fundamental change in the design principles and implementation practices in the mobile telecommunications industry. Using BS sleep mode techniques to reduce the total energy consumption in cellular networks is generally preferred because these techniques do not require upgrade of equipment and have a low implementation cost. These approaches exploit the traffic load variations to turn off certain elements, including, but not limited to, PAs, signal processing units, cooling equipment, the entire BS, or the whole network. In other words, these elements shall "only be activated and transmitted when needed".

BS sleep mode techniques are particularly effective in cellular networks with low traffic demand. By contrast, only few BSs can be switched off under an intense traffic demand, thereby rendering the sleep-mode-based algorithm ineffective. Given that renewable energy sources are free, clean, widely available, and can meet the energy demands of cellular networks during peak hours, renewable energy systems have been proposed for powering BSs. However, these resources are unpredictable, intermittent, and dynamic. Therefore, renewable energy systems must be integrated with other sources of non-renewable energy (with DG or grid as a backup power source) and/or means of energy storage (batteries) to secure energy supplies, improve system reliability, and prevent mobile service outages.

4. Overview of the Renewable-Energy-Powered Cellular BSs

Using renewable energy in the telecommunication sector is not new. Since the 1970s, renewable energy has been used for powering microwave repeaters in remote areas and for connecting remote towns and homesteads to telecommunication grids, thereby granting them access to radio, telephone, and television services. Telecommunication satellite stations, rural telephony, and telephone exchanges can also be powered by solar energy [85]. Therefore, the use of renewable energy for powering cellular BSs, reducing OPEX, and diminishing GHG has been highlighted. RESs are very practical and easy to install, disassemble, and separate, thereby facilitating the expansion of renewable systems. This section examines the following topics:

(i) the potential use of renewable energy solutions for cellular BSs and the system model;
(ii) the potential geographical locations for deploying renewable-energy-powered BSs and for widely deploying green cellular BSs;
(iii) conducting case studies on the establishment of renewable-energy-powered cellular BSs and recommending future research directions based on the outcome of these studies;
(iv) the current deployment of sustainable and green BSs, which can reflect the practical results of a green communication initiative; and
(v) the barriers that hinder the spread of renewable-energy-powered BSs and recommendations for future research.

4.1. Potential of Renewable Energy Solutions for Cellular BSs and the System Model

Renewable energy is collected from renewable resources (i.e., sunlight, wind, rain, tides, and waves) that are widely available across different geographical areas and offer important opportunities for guaranteeing energy efficiency [86]. Unlike other energy sources that are available in a limited number of countries, solar and wind energies are widely used in the cellular communication sector because of their wide availability [4,12,29]. The use of solar and wind energy in cellular communication may proliferate over the next few decades because they are well-suited to rural and remote areas as well as developing countries [17,87].

The cellular BS is fed directly from the RES, which may have either an autonomous or hybrid design with other means of renewable or non-renewable energy. Renewable energy resources, such as solar radiation and wind speed, have key roles in selecting the optimal RES design. However, these resources are unpredictable, intermittent, and dynamic. Therefore, renewable energy systems must be integrated with other sources of non-renewable energy (with DG or grid as a backup power source) and/or means of energy storage (batteries) to secure energy supplies, improve system reliability, and prevent mobile service outages [8,88]. The backup DG feeds the cellular BS when the RES malfunctions, when the BS demand exceeds the RES power output, and when the batteries reach their maximum depth of discharge (DOD) [43,88]. However, cellular BS are rarely fed from DG because the reachability of RES may increase up to 99.99% with an optimal design [89]. Without any auxiliary power sources, the battery bank can power the BS for at least three days, which is long enough to fix the malfunctions.

4.1.1. System Model of Solar-Powered BS

A solar-powered BS typically comprises photovoltaic (PV) panels, batteries, an integrated power unit, and the load as shown in Figure 6. Connected via an open switch, the DG acts as a backup power source in the case of malfunctions as discussed in the second paragraph of Section 4.1.

(a) PV panels absorb and convert shortwave irradiance into direct current (DC) electricity, which provides power for running BSs and for charging batteries. A 1 kW PV panel typically has a 5 m^2 area, and the lifetime of a typical PV panel may exceed 25 years [90]. The power generated by a PV panel may be affected by several factors, including the DC rating of the PV panel, geographic location or solar irradiation profile of the site, tilt of the PV panel, and DC–AC loss factor [43]. PV cells based on mono and poly-crystalline silicon are commonly used in large-scale applications with an efficiency of 14% to 19%. PV panels with a DC rating of 1 kW currently cost around $1000 USD [43]. The efficiency of next-generation high concentration solar cells, which are based on germanium, gallium arsenide, and gallium indium phosphide, can reach 40%.
(b) Solar regulator charger: Given that the highest power demand in a typical BS is based on 48 V_{dc} voltage, DC/DC solar regulator converters that directly convert the unregulated DC output voltage and current from a solar panel into a regulated output voltage for the BS equipment must be used to protect the battery bank [88].

(c) Battery banks store excess electricity for the future consumption of BSs at night, during load-shedding hours, or when the available solar energy cannot sufficiently feed the BS load. A charge controller must be included to protect the battery. A charge controller or battery regulator limits the rate at which the electric current is added to or drawn from the electric batteries, thereby preventing overcharging and overvoltage, which in turn may reduce the performance or lifespan of batteries and pose a safety risk. A charge controller also prevents the battery from completely draining ("deep discharging") or from releasing controlled discharges, thereby extending battery life depending on the battery technology [88]. Table 3 summarizes the key features of the battery models that are used with cellular BSs.

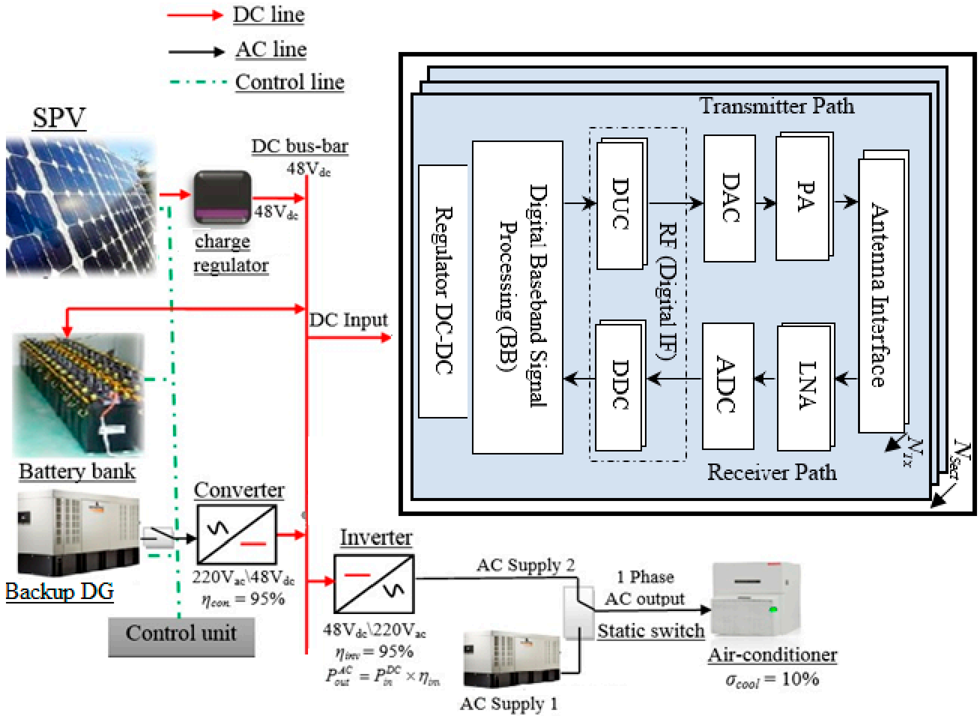


Figure 6. Scheme of the solar-powered BS.

Table 3. Key features of the battery models that are used with cellular BSs [91].

Battery type	Cost ($/kWh)	Efficiency (%)	Max. DOD (%)	No. of Cycles (at Max. DOD)	Self-Discharge (%/Month)
Lead–acid (conventional)	110–140	75–85	70	500–1000	1.5–5
Lead–acid (SLA–VRLA)	140–340	80–90	80	1200–1800	1.5–5
Nickel–cadmium	400–900	70–80	100	1500–3000	5–20
Nickel metal hydride	800–1200	65–70	100	600–900	10–25
Lithium–polymer	950–1650	90–100	80	600	2–5
Lithium–ion	1000–1700	95–100	80	1500–3000	1–5

(a) Inverters convert a low DC-voltage into usable 220 V AC voltage, thereby making these items a main element of the system. Inverters vary according to their output wave format, output power, and installation type. Inverters have also been called as power conditioners that change the form of electric power. The output wave format can be classified into modified sine-wave (MSW) and pure sine-wave. MSW inverters are economical and efficient, while sine wave inverters are usually more sophisticated than MSW, demonstrate a high-end performance, and operate any type of load [88].

(b) The control system serves as the brain of a complex control, regulation, and communication system. Wireless modems or network solutions are the most common communication units in the remote interface [88]. Apart from its control functions, the data logger and alarm memory capabilities of the control system are very important. Those power sources that work in parallel are managed by a sophisticated control system and share the load to prevent power shortages, which are not admissible in the cellular telephony sector.

4.1.2. System Model of Wind-Powered BS

In wind-powered BSs, the wind turbine (WT) acts as the main power source, the DG acts as a backup power source, and the other components serve the similar functions as those of the solar-powered BS as shown in Figure 7. The WT can be connected to the DC-power bus and convert wind energy into a regulated power. Vertical windmills have a 15-year lifetime and show special benefits for a small power load, such as BSs [88]. Given that WTs are installed above tall trees to gain open access to the wind, lightning may prevent the use of WTs in rural areas [92].

Fuel cells (FCs) are clean and highly efficient alternatives to generators and batteries for generating prime and backup power, respectively, that have attracted wide usage in cool areas [93,94]. FCs can be used in cellular BS sites as (i) back-up power; (ii) temporary main power supply; and (iii) emergency power supply. The emergency power supply feed the main elements in the BS site to guarantee the availability of radio services.

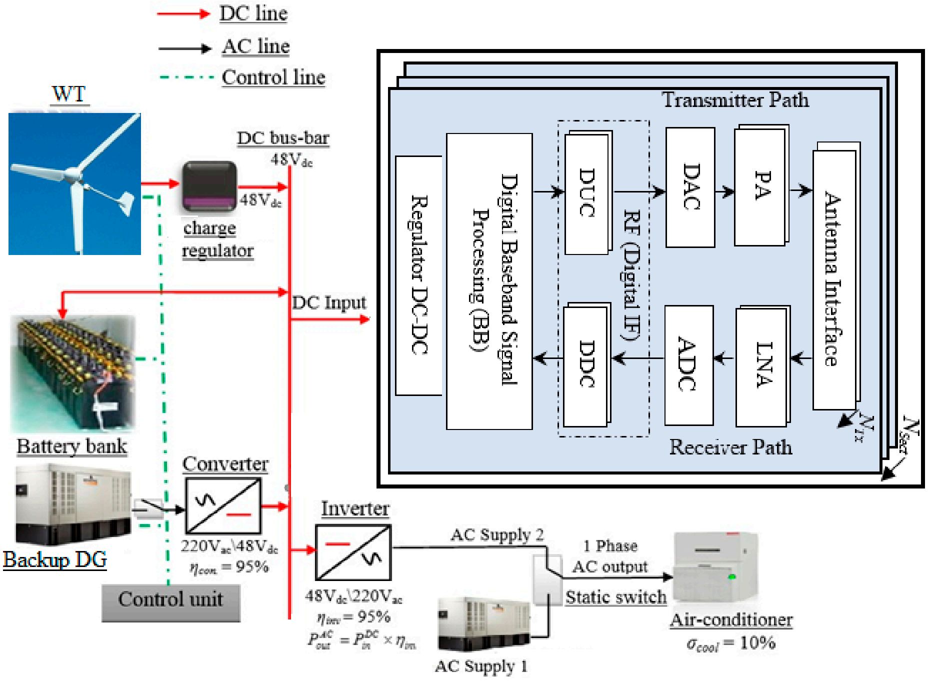


Figure 7. Scheme of the wind-powered BS.

4.2. *Potential Geographic Locations for Deploying Renewable-Energy-Powered BSs*

4.2.1. Potential Locations of Solar-Powered BSs

The solar radiation at the Earth's surface is largely determined by latitude, seasonal variations, and geographical/climatic conditions. Figure 8 shows the global distribution of horizontal irradiation rated by averaged effective hours when the irradiance power of 1 kW/m^2 falls on a plane that has the same orientation as the PV generator. The region at mid-latitude between latitude 30° North and South is a preferred region for a solar-powered BS when only solar radiation is considered. The averaged irradiance at this region, except for the inland of China, ranges from 4.5 kWh/m^2 to 7.5 kWh/m^2.

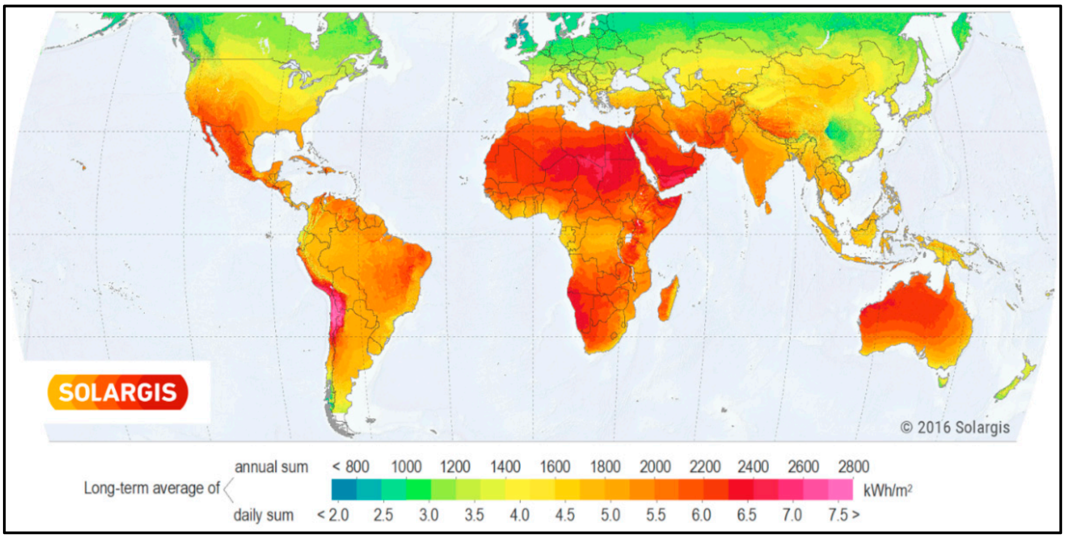


Figure 8. Global solar irradiation map [95].

As another practical requirement, the electrical energy must be consumed at the neighborhood of the PV system or the PV system must be connected to the electrical grid. Despite the high averaged irradiance, the desert is an unsuitable location for solar-powered BSs because only few residents in this area are using a cellular phone. The same condition is observed in the jungle area at the middle regions of South America.

If the above requirements (i.e., solar irradiation and electrical power consumption) are considered, then the suburbs around the town at low latitudes are identified as the most profitable locations for solar-powered BSs. The western coast of the USA, the northern coast of South America, the Mediterranean littoral, the southern part of Africa, the northwestern part of India, and the eastern coast of Australia all satisfy the requirements for installing these BSs. Those regions with relatively low solar irradiance and favorable economic efficiency are also preferred.

4.2.2. Potential Locations of Wind-Powered BSs

Installing wind- and solar-powered BSs must fulfill the same requirements (i.e., the amount of wind/solar energy and electrical power consumption). To generate electricity from wind energy, the wind speed must exceed the cut-in speed (around 3.5 m/s) or the minimum speed for safely operating the WT. However, unlike solar energy, an extremely high wind speed can damage the wind power generation system. In this case, the wind speed must be maintained below the cut-out speed (around 14 m/s to 20 m/s) or the maximum wind speed at which the WT can be safely operated.

Figure 9 shows the global wind speed as recorded in a 10-year numerical weather prediction model run. The maximum power output, which varies along with wind power, may be obtained at a wind speed of about 10 m/s. The potential locations for wind-powered BSs are largely distributed in mountainous regions and coastal areas. However, the number of these locations may be reduced further by considering the desolate circumstances of mountainous regions. Following these requirements, wind-powered BSs may be located in the northeastern coast of North America, the southern area of South America, England, the northern area of Europe, the northwestern part of India, the southern coast of China, and the coastal area of Japan.

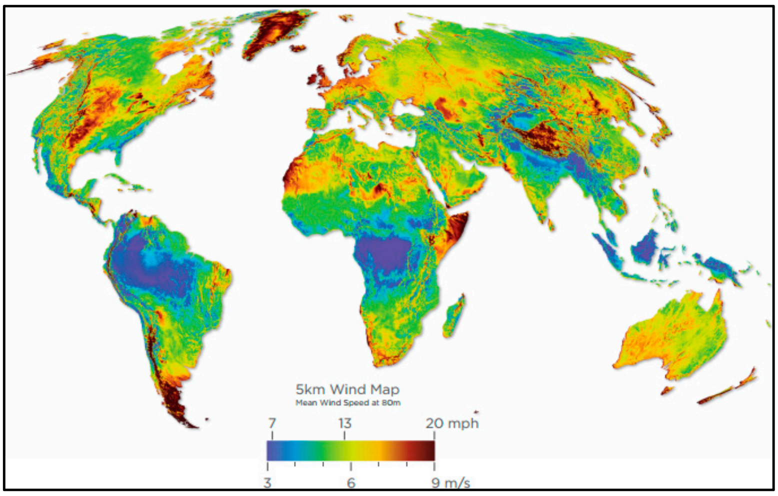


Figure 9. Global wind speed map [96].

4.3. Case Studies for Enabling Green Cellular BSs

Numerous studies have been conducted in various regions worldwide to help cellular network operators establish a green cellular network. This section presents existing studies on cellular BSs powered by renewable energy sources, investigates the motives behind the use of renewable energy, and proposes directions for future research.

4.3.1. South Korea

Cellular networks in South Korea have developed significantly over the last five years, particularly its LTE cellular network, which offers data-oriented services. The LTE cellular network of South Korea leads in terms of technology, reliability, and global coverage (i.e., cellular phone users in South Korea use LTE 97% of the time). South Korea had 35,255 LTE BSs in 2013; this number increased 4.7-fold and reached 165,193 BSs in 2015 [97]. Such increase intensified both the energy consumption and OPEX of these BSs because of the high prices of energy and fossil fuels.

The average daily solar radiation in South Korea is approximately 4.01 kWh/m^2, which is relatively higher than the figures in other countries located at similar latitudes [43]. The performance of solar-powered LTE BSs was analyzed in [43], which found that these stations could save up to 48.6% OPEX compared with that of a DG system. A PV/WT hybrid power system for LTE BSs was examined in [98]; the findings of this study indicated that this hybrid system could save up to 48.52% OPEX compared with that of a DG system. Therefore, the use of solar-powered BSs is a cost-effective option for cellular network operators.

In June 2016, the LG Uplus operator tested a solar-powered LTE BS with an energy storage system (batteries) that could operate between 24 h and 48 h even on cloudy days. The proposed system satisfies the energy requirements of LTE BSs [99], thereby motivating other operators to adopt green energy technologies. However, the adoption of renewable energy sources remains limited in the Korean telecommunications industry because numerous issues on the most cost-effective optimal hybrid power systems, such as integrated PV/FC and PV/WT/FC, are yet to be examined. The supply of renewable energy to 2G and 3G BSs also warrants further study.

4.3.2. Malaysia

The tropical climate of Malaysia provides considerable potential for the use of renewable energy resources, particularly solar energy, because of the high amount of solar radiation (2–6 kWh/m^2/day) that the country receives throughout the year. The use of a solar panel measuring 1 m^2 can reduce CO$_2$ emissions by 40 kg annually [92]. Thus, several researchers have studied the use of solar energy in telecommunications applications [7,100,101]. The integration of RESs into an electricity grid to supply energy to LTE BSs in on-grid sites was investigated in [100]. Meanwhile, the use of a PV/DG hybrid system for rural LTE BSs was examined in [7]. These studies underscored the benefits of solar energy to cellular network operators in terms of limiting their environmental effects and reducing their OPEX. The Solar Energy Research Institute (SERI) at the University Kebangsaan Malaysia launched a solar-powered BS project in 2015. On the basis of the results of this project, SERI recommended that cellular network operators should install solar-powered BSs and shift toward greener networks. In 2016, Digi operator tested the potential of a hybrid hydrogen FC system to power BSs [102]. However, the application of renewable energy to the Malaysian telecommunications industry remains limited. In addition, several issues, such as using PV/WT/FC and supplying RESs to UMTS BSs, should be examined further.

4.3.3. Turkey

The GSM BS of a Turkish telecommunications operator was used in [103] to test a commercial FC backup power unit under actual operating conditions; the FC backup power unit successfully supplied power to the BS in 256 (out of 260) instances of electric power outages. At the system level, the FC backup power unit achieved 98.5% reliability. However, approximately 90% of the energy consumption of Turkish cellular networks is obtained from purchased electricity, which resulted in the emission of 172,812.3 tons of CO_2 in 2015 [104]. Turkey has four seasons and experiences a high solar radiation rate during summer [105,106]. The country had at least 12 solar-powered BSs in 2014 [107]. The potential use of PV/WT, PV/FC, and PV/WT/FC hybrid systems in Turkey and the supply of RESs to UMTS and LTE BSs must be investigated further.

4.3.4. India

Approximately 400,000 BSs in India (over 70% of the total BSs) experience power outages more than 8 h a day. This situation prompts cellular network operators to use DG to power their BSs and prevent cellular service interruptions. The penetration rate of cellular networks in rural India reaches 30% to 40%. These figures indicate that 200 million people are yet to be connected to these networks. Many regions in India have poor grid connectivity, thereby encouraging the use of DG. Cellular network operators also consume over 2 billion L of diesel, spend approximately 1.4 billion USD, and produce more than 5 metric tons of CO_2 emissions annually [107,108]. Therefore, operators must adopt economical, clean, reliable, and sustainable power sources to address the aforementioned issues.

Several studies [107,109–113] have examined the potential of hybrid renewable energy to supply power to cellular BSs. Amutha et al. [109] investigated the optimization of hybrid RESs that use DG as a backup power source. PV/DG, PV/WT/DG, PV/WT/DG/FC, PV/WT/FC, and PV/WT hybrid power systems have also been examined in previous studies. The HOMER simulation results show that the hybrid PV/WT/battery/FC/DG is the most economically feasible configuration for GSM BSs with a net present cost (NPC) of $75,515. In the same context, the authors of [110] explored the hybrid PV/WT system for UMTS BSs. Although India has over 3360 solar-powered BSs [107], cellular network operators must still shift toward green cellular networks. Moreover, supplying UMTS and LTE BSs with the required energy based on various hybrid RESs should still be addressed.

4.3.5. Bangladesh

Bangladesh has over 36,679 GSM BSs; among which, 14% lack access to grid electricity. The DG–battery hybrid system feeds 81% of all off-grid sites in the country [114]. Literature [114] also indicates that cellular networks in Bangladesh are likely to consume as much as 642 million kWh of energy. In the same context, GSMA estimates that implementing green technology solutions can save up to 90 million USD.

The potential of using renewable energy was explored in [115], which found that solar power is the most suitable alternative power source for off-grid telecommunications systems and for grid areas that frequently experience power failure. A feasibility study conducted on a solar PV system in grid-connected BS sites was presented in [116]. To achieve the most economically feasible configuration, BSs in Bangladesh must have 2.5 kW PV and sixteen batteries in two parallel strings, as well as two 4 kW DGs with an energy cost of $1.657/kWh. Over 521 solar-powered BSs have been installed in Bangladesh [107], and cellular network operators must further increase this number. The PV/WT hybrid power system also warrants further investigation because the annual average wind speed along the coastal area of Bangladesh exceeds 5 m/s at a height of 30 m [115]. Both UMTS and LTE BSs must also be considered.

4.3.6. Pakistan

Pakistan exhibits considerable potential in using solar energy due to its average daily insulation that ranges from 4 kWh/m^2 to 5.3 kWh/m^2. Such insulation is particularly high in southwestern provinces with highly suitable conditions for accumulating solar energy. Pakistan experiences 8 h to 8.5 h of sunlight daily or approximately 3000 h annually [117], and wind speed may exceed 7 m/s to 8 m/s [87,118]. However, the green initiatives of the Pakistani telecommunications sector require further development; this sector also depends largely on DG to supply power to its off-grid BSs, and fossil fuel costs account for 64% and 56% of the OPEX in off- and on-grid sites, respectively [87]. Imtiaz et al. [118] proposed a hybrid PV/DG system design for a GSM BS. The HOMER simulation results show that 6 kW PV, 2 kW DG, and eight 200Ah batteries comprise the optimal combination of energy system components. However, Asif et al. [119] identified 5 kW PV, 3 kW DG, and sixteen 225Ah batteries as the optimal combination for PV/DG system components; 1 kW WT, 3 kW DG, and twenty-four 225Ah batteries for WT/DG system components; and 5 kW PV, 5 kW WT, and 5 kW DG for PV/WT/DG system components.

Despite the aforementioned initiatives and continuous support from the government for a shift toward renewable energy use, the number of solar-powered BSs in Pakistan remains below the 602 GSM BSs recorded in 2014 [107]. However, many cellular network operators continuously attempt to increase the number of green BSs [87]. Both UMTS and LTE BSs must also be considered in their future plans.

4.3.7. Nigeria

The electric power infrastructure in Nigeria negatively affects the expansion of cellular network coverage and significantly influences the OPEX of cellular telecommunications systems because of the unavailability of grid power supply. Approximately 11,692 mobile sites in Nigeria are connected to the national grid, and 9%, 10% and 81% of these sites experience up to 6, 6–12, and over 12 h grid outage/day; by contrast, 12,560 sites in the country are completely off-grid [120]. The uncertain availability of power has driven network operators to use DG, which consumes over 500 million L of diesel and emit 1.3 million metric tons of CO_2 annually [120]. Nigeria has an average monthly solar radiation of 5.8 kWh/m^2 per day and an average daily sunshine of 6 h [121]. The country has an annual average wind speed of approximately 2 m/s in the coastal region and 4 m/s in the far northern region [122].

Several studies [120,123–127] have attempted to encourage a shift toward renewable technologies. Wa et al. [120] studied the optimization of various hybrid RESs, including PV/DG and PV/WT/DG hybrid systems. The HOMER simulation results indicate that the most economically feasible configuration is the PV/DG system with an NPC of 69,811 USD and an electricity cost of 0.409 USD per unit. However, considering that most African countries have a high solar radiation rate (Section 4.2.1), these countries are encouraged to use solar power in other industrial sectors aside from telecommunications.

Vodacom, a cellular operator in the Democratic Republic of Congo, spends over 5 million USD annually for its 157 diesel-powered BSs (approximately 32,000 USD per BS annually) [128]. Kusakana et al. [9] examined the potential of PV, WT, and PV/WT as primary energy sources for remote GSM BSs in Congo. The NPC of a PV system may reach as low as $8336 annually, whereas that of wind and diesel systems may reach as high as $11,420 and $29,773 annually, respectively. The optimization of various RESs (PV/DG/battery, PV/WT/battery, PV/battery, and PV/FC/electrolyzer/battery) for UMTS BSs in the urban and rural areas of Nepal was explored in [89,129], and the hybrid PV/DG/battery and PV/FC/electrolyzer/battery present the most feasible solutions for these two areas, respectively. Martínez-Díaz et al. [130] examined the potential of RESs, PV/DG, WT/DG, and PV/WT/DG in providing power to GSM BSs in Spain. They identified PV/DG as the most economically feasible solution with an energy cost of €0.436/kWh.

Salih et al. [131] studied the potential of RESs (stand-alone PV, PV/DG, and PV/WT/DG) to power remote GSM BSs in Sudan, and identified PV/DG as the most economically feasible configuration with an energy cost of1.157 USD/kWh. Hossam et al. [132] designed four hybrid RESs for GSM BSs in Cairo, Egypt and proposed the use of a PV/electrical grid in urban areas; PV, PV/DG, and PV/DG in remote areas; and DG on cloudy days. The energy costs of PV/electrical grid, PV/DG (on cloudy days), PV, and PV/DG reach as low as $0.1, $0.21, $0.29 and $0.31/kWh, respectively. Therefore, the use of PV/DG on cloudy days is the most economically feasible configuration, and the optimal system architecture comprises 18 kW PV array, 10 kW DG, and 1400Ah battery with a nominal voltage of 6 V.

Belkhiri et al. [133] studied an optimized PV/WT hybrid power system for UMTS BSs in Algiers, Constantine, Ghardaia, and Adrar, and recorded energy costs of $0.417, $0.371, $0.325 and $0.285/kWh, respectively in these areas. The power system for Ardrar with 3 kW PV array, 1 kW WT, and 16 T-105 batteries achieves the lowest energy cost. Kaldellis et al. [134] designed a solar-powered system with DG as a backup power source for a GSM cellular network in Greece. The proposed system can effectively address the lack of energy in remote BSs in Greece given its high reliability and low maintenance requirements in considering the tilt angle of optimum PV panels. Giuseppe et al. [135] proposed two discrete-time Markov chain models for achieving the dimension of the solar power (PV panel size and battery capacity) supply of an LTE macro BS in southern and northern Italy, and found that seasonal behavior significantly influences the dimensioning process. Therefore, both irradiance and battery charge must be carefully selected.

In [136,137], a hybrid solar-grid (or solar–diesel) power system achieved higher energy savings than a purely solar-powered system or a traditional power-grid system over a 10-year period in south European cities (e.g., Torino in Italy) and in locations close to the tropics (e.g., Aswan in Egypt). A framework for estimating the probability of power outage in solar-powered cellular BSs in San Diego, USA and Jaipur, India was proposed in [138], which presented the harvested solar energy, BS load, and battery levels as discrete-time Markov processes. To demonstrate its effectiveness, the proposed model was then compared with the simulation results using empirical traces of solar energy and load data. A framework for avoiding power outages and improving the QoS of a network of off-grid solar-powered BSs was proposed in [139]. Actual BS deployment data and solar energy traces were used in the evaluation, which demonstrated that the proposed framework outperformed existing benchmarks in terms of reducing power outages and ensuring good delay performance.

The application of FC-based hybrid renewable energy systems to off-grid telecommunications stations was evaluated in [94,140] using data collected from 6 of the 13 sites tested during the deployment of an EU-funded project. A hybrid solar–hydrogen system (hybridized with batteries) was tested in [93] to determine its remote telecommunications application potential in Eureka, Canada, which typically experiences extremely cold climate. A case study of 2 kW polymer electrolyte membrane FCs was then conducted to test whether the proposed model could fulfill the load requirements of a telecommunications BS. Off-grid hybrid systems based on the integration of hydrogen technologies into battery and wind/solar power technologies were proposed in [141] to meet the energy requirements of remote telecommunications BSs in the UK. A hybrid configuration of hydrogen and battery technologies can continuously transfer power from an off-grid PV or wind power source to a telecommunications BS. Despite the use of FC-based technology and the integration of various components, the models proposed in the literature have only exhibited acceptable stability and reliability levels. Table 4 summarizes issues that should be considered in future research.

Table 4. Case studies of enabling green cellular BS and open issues.

Case Study	Storage and Support System	Renewable Energy System				Results	Open Issues
		PV	WT	PV/WT	PV/FC		
South Korea [43,98]	Batteries DG	√		√		The PV system is the most economically feasible configuration for LTE BSs with 7.5 kW PV, 64 units of batteries (Trojan L16P), and annual OPEX savings of up to 48.6%.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 2G and 3G BSs
Malaysia [7,100]	Batteries Electric grid	√	√	√		The PV/WT system is the most economically feasible configuration for LTE BSs in urban areas with 2 kW PV, 1 kW WT, 3 units of batteries (Trojan L16P), 1 kW electric grid, and annual OPEX savings of up to 39%. The PV system for LTE BSs in remote areas has annual OPEX savings of up to 43%, 2 kW PV, 4 units of batteries (Trojan L16P), and 1 kW DG.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 2G and 3G BSs
India [109]	Batteries DG	√	√	√	√	The PV/WT/FC system is the most economically feasible configuration for GSM BSs with NPCs of $75,515, 2 kW PV, 3 kW WT, 2 kW FC, and 2 kW DG.	• Renewable-energy-powered 3G and 4G BSs
Bangladesh [116]	Batteries DG	√				2.5 kW PV, 16 batteries in 2 parallel strings, and 4 kW DG are the most economically feasible configurations for GSM BSs with an energy cost of $1.657/kWh.	• Hybrid PV/WT • Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Pakistan [119]	Batteries DG	√	√	√		The PV/WT system is the most economically feasible configuration for GSM BSs with an energy cost of $0.839/kWh, 5 kW PV, 1 kW WT, 16 units of batteries, and 3 kW DG.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Nigeria [120]	Batteries DG	√		√		The PV system is the most economically feasible configuration for GSM BSs with an energy cost of $0.409/kWh, 10 kW PV, 64 units of batteries (Trojan L16P), and 5.5 kW DG.	• Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs

Table 4. *Cont.*

Case Study	**Storage and Support System**	**Renewable Energy System**				**Results**	**Open Issues**
		PV	**WT**	**PV/WT**	**PV/FC**		
Egypt [132]	Batteries DG	√				The PV/electrical grid system is the most economically feasible configuration for GSM BSs in urban areas with an energy cost of \$0.1/kWh, 18 kW PV, and 1400Ah batteries, while the PV/DG system with a DG running at cloudy days is the most economically feasible configuration for GSM BSs in rural areas with an energy cost of \$0.12/kWh.	• Hybrid PV/WT • Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Sudan [131]	Batteries DG	√		√		The PV system is the most economically feasible configuration for GSM BSs with an energy cost of \$1.157/kWh, 5.7 kW PV, 72 units of batteries, and 5.6 kW DG.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Algeria [133]	Batteries DG			√		3 kW PV, 1 kW WT, and 16 batteries (T-105) are the most economically feasible configurations for UMTS BSs with an energy cost of \$0.285/kWh.	• PV system • Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 2G and 4G BSs
Democratic Republic of Congo [9]	Batteries DG	√	√	√		The PV system is the most economically feasible configuration for GSM BSs with an annual NPC of \$8336, 18 kW PV, and 131 units of batteries.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Nepal [129]	Batteries DG	√	√	√	√	The PV and PV/FC systems are the most economically feasible configurations for the GSM BSs in urban and remote areas, respectively.	• Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs
Spain [130]	Batteries DG	√	√	√		The PV system is the most economically feasible configuration for GSM BSs with an energy cost of €0.436/kWh, 2.5 kW PV, 12 units of batteries, and 2 kW DG.	• Hybrid PV/FC • Hybrid PV/WT/FC • Renewable-energy-powered 3G and 4G BSs

4.4. Current Status for Deploying Green Cellular BSs

Figure 10 shows the deployment and locations of green cellular BSs around the world. GSMA predicted that the number of green BSs would increase to 389,800 by 2020 [8], which reflects the growing awareness of cellular network operators about the significant economic and ecological influence of their networks in the coming years.

Figure 10. Worldwide deployment of green cellular BSs [107].

Figure 10 reveals that many cellular network operators in the world have still not shifted toward green cellular BS. Most of these operators are located in developing countries with limited electricity supply and unreliable electric grids. The financial issues in these countries must be investigated further.

4.5. Barriers that Hinder the Spread of Green Cellular BSs and Potential Solutions

Table 5 summarizes the technical and non-technical challenges that hinder the widespread deployment of renewable-energy-powered BSs as well as proposes some potential solutions to these barriers.

Table 5. Barriers that hinder the spread of green BSs and potential solutions.

Barrier	Description	Recommendations
CAPEX and OPEX	RESs have a higher CAPEX than traditional power systems. These systems have many expensive components, especially the PV panels. However, the CAPEX for PV panels decreased by around 40% between 2009 and 2013 because of technical advancements, and these expenditures are expected to decrease continuously in the future [107]. The long-term OPEX for RESs throughout the 10-year lifetime of BSs [43] is lower than that of traditional power systems because of the low operation, maintenance, and replacement costs of the former. Each component of RESs has a salvage value at the end of the project lifetime and typically applies to those components which lifetimes are longer than the project lifecycle, such as PV, WT, inverter, and converter.	The successful deployment of RESs requires meticulous planning to determine the appropriate geographic locations on which the solar, wind, or hybrid power system will be deployed. The optimal sizes of their components must be carefully selected. The PV system must be installed in locations with an abundant supply of solar radiation as shown in Section 4.2.1. The WT system is ideally installed in areas with high wind speeds as shown in Section 4.2.2, while the PV/WT hybrid system is ideally installed in locations with high wind speeds and an abundant supply of solar radiation.

Table 5. *Cont.*

Barrier	Description	Recommendations
Renewable energy resources	RESs heavily depend on natural resources that can be unpredictable, intermittent, and dynamic. Therefore, these systems must be integrated with other sources of renewable/non-renewable energy and/or energy storage solutions to ensure a continuous supply of energy to BSs.	(1) Use a battery bank that can feed BSs for a sufficient number of days without relying on auxiliary power sources. (2) Use a backup DG that feeds the BS during malfunctions, when the BS demand exceeds the RES power output, and when the maximum DOD of the batteries is reached.
Environment surrounding	The PV panels are installed in open areas and high locations to maximize their access to sunlight. However, the dirt, dust, tree debris, moss, sap, water spots, and mold on solar panels significantly affect the performance of PV systems. Cleaning these panels also poses a problem. Lightning strikes may damage their electronic components. The bypass diodes, which are mounted on the termination box under each panel, may either crack or short circuit under high humidity and heat conditions.	(1) The dual-axis tracking system for the PV array allows wind, rain, and gravity to remove most debris and dust. This system can also increase the total amount of energy produced by a PV system by approximately 20% to 30%. (2) Recruit trained and educated personnel to operate, maintain, and manage RESs. These systems must also be subjected to continuous maintenance.

5. Conclusions

This paper investigates the sustainability of power resources and the ideal environmental conditions for cellular communication systems. These two key issues may help cellular network operators reduce not only their OPEX but also the negative effects of their operations on the environment. Table 6 compares the approaches presented in this article. This paper specifically focuses on renewable-energy-powered BSs.

Table 6. Brief comparison of the approaches presented in this article.

Approach	Energy Savings/Enhancements	Advantages	Considerations
Improved PA design	The energy savings depend on a special design and may reach up to 85%.	1. Huge savings, which may reach * up to 50% with a Doherty architecture and GaN-based PA; and * up to 85% with SMPA	• High replacement cost • Linearity and PAPR
Network operation and management	The energy savings depend on the number of and how long the equipment or BSs have been turned off. Up to 50% of energy may be saved.	• Easy implementation • Inexpensive testing and implementation	• Coverage • Mobile battery life • Inter-cell interference • QoS
Network planning and deployment	The energy savings may reach up to 60%.	• Low implementation cost • Large potential savings	• Inter-cell interference • Resource management • QoS • Compatibility • Complexity
RESs	The energy savings depend on the insolation/wind speed rate and location of the BSs.	• Long-term solution, especially for off-grid BSs	• Natural energy resources • Locations of BSs • Costs

Exploiting the available energy from renewable resources presents these operators with an ideal long-term solution to their problems. These resources are particularly useful for those countries without mature or reliable electrical grids. A feasibility assessment must also be conducted to identify those renewable-energy-powered systems that cannot provide sufficient amount of power to BSs. Network operators must carefully consider both the operational and economical aspects of these systems before making decisions regarding their implementation. The location of renewable-energy-powered BSs must also be carefully considered because several locational factors, such as dirt, dust, tree debris, moss, sap, water spots, and mold, can significantly affect the performance of PV systems. Cleaning these panels also presents a challenge to these network operators. Energy-efficient or "green" cellular networks are broad research topics facing several issues that are yet to be addressed. Cellular network operators must shift toward green cellular networks to reduce their expenditures and minimize the environmental effects of their operations.

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