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Techno-Economic Evaluation of a Stand-Alone Power System Based on Solar/Battery for a Base Station of Global System Mobile Communication

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Abstract: Energy consumption in cellular networks is receiving significant attention from academia and the industry due to its significant potential economic and ecological influence. Energy efficiency and renewable energy are the main pillars of sustainability and environmental compatibility. Technological advancements and cost reduction for photovoltaics are making cellular base stations (BSs; a key source of energy consumption in cellular networks) powered by solar energy sources a long-term promising solution for the mobile cellular network industry. This paper addresses issues of deployment and operation of two solar-powered global system for mobile communications (GSM) BSs that are being deployed at present (GSM BS 2/2/2 and GSM BS 4/4/4). The study is based on the characteristics of South Korean solar radiation exposure. The optimum criteria as well as economic and technical feasibility for various BSs are analyzed using a hybrid optimization model for electric renewables. In addition, initial capital, replacement, operations, maintenance, and total net present costs for various solar-powered BSs are discussed. Furthermore, the economic feasibility of the proposed solar system is compared with conventional energy sources in urban and remote areas.

Keywords: power; energy; base station; cellular network; solar-powered GSM BS; green network

1. Introduction

According to [1], the global annual electricity consumption for the telecommunication sector has increased from 219 TWh in 2007 to 354 TWh in 2012. The consumption is expected to escalate at an annual additional rate of 10% from 2013 to 2018 [2]. As a result, operational expenditure (OPEX) has significantly increased because a significant portion of the OPEX is used to pay for electricity bills [3,4].

Cellular networks are the main contributors to the significant increase in energy consumption in the telecommunications sector [5]. Given the significant increase in their number, base stations (BSs) [6–9] have been the primary consumer of energy, accounting for 57% of the total consumed energy [7,8,10]. In 2014, more than US$22 billion of the OPEX of cellular networks globally have been allocated to electricity consumption [11]. Moreover, cellular network operators actively increase their network coverage areas, open new markets, and provide services to potential customers in rural areas around the globe [12]. Unfortunately, low electrification progress in rural areas, which can be attributed to geographical limitations and economic issues in these locations, has prompted cellular network operators to use diesel generators (DGs) in powering their BSs. Consequently, the OPEX increases by 10 times [1,7]. In addition, the cellular network sector has become a major emitter of greenhouse gases (GHGs). According to [5], the amount of carbon dioxide (CO_2) emitted by the mobile sector will rise to 179 MtCO_2 by 2020, which accounts for 51% of the total carbon footprint of the information and communication technology sector. Thus, the energy efficiency issue in cellular networks is increasingly important because of its significant potential economic and ecological influence.

The key features of power sources, including economic, environmental, and sustainability aspects, present a critical issue because power shortages and service outages are strictly prohibited in the cellular mobile sector. Therefore, specific power supply requirements for BSs, including cost effectiveness, efficiency, sustainability, and reliability, can be satisfied by utilizing the technological advancements in renewable energy [1,13–15]. Renewable energy resources remain abundant and free in most locations throughout the year and are green instruments because of their use in eliminating GHG emissions. Renewable-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 continued power cuts [8,16], especially since the reliability of the renewable energy system (RES) can reach up to 99.99% with an optimal design [17].

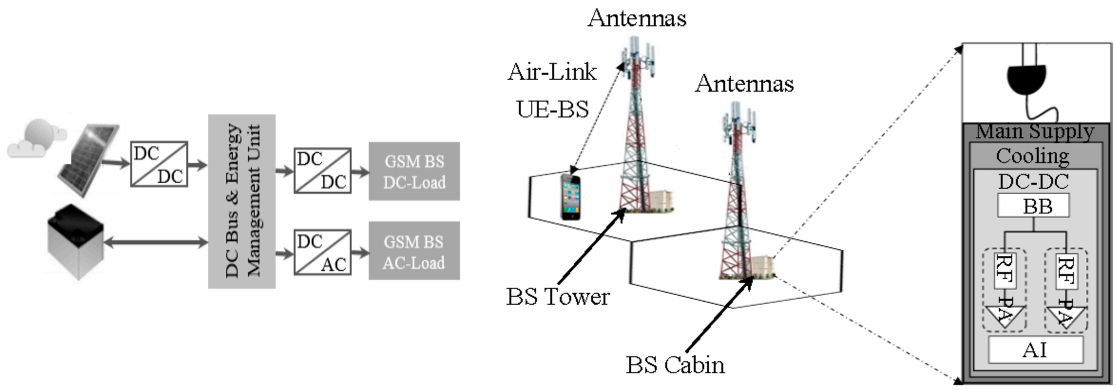
Authors of [1] comprehensively reviewed several studies conducted in different regions around the world to assist cellular network operators in building a green cellular network. In addition, studies [1,18] have estimated that up to 389,800 off-grid BSs will be operating on renewable power in remote parts of the developing world by 2020. The present study focuses on the economic feasibility for a solar-powered global system for mobile communications (GSM) BS based on the characteristics of South Korean solar radiation exposure. In addition, the study discusses optimal cost allocation of each individual component present in the solar system, and compares the proposed solar power system with conventional sources in terms of economic benefits. South Korea has an excellent potential to use solar energy. The average daily solar radiation in South Korea is estimated at 4.01 kWh/m^2, which is relatively higher than that in other countries located at similar latitudes [19,20]. Given that wind speed does not exceed 4 m/s, which is considered low [6,21], wind turbines are excluded from this study. Moreover, a stand-alone solar system is useful for low direct current (DC)-power demand applications, such as BS. The key contributions of this study are summarized as follows: (1) the optimum size and technical criteria of a stand-alone solar/battery power system that ensures 100% energy autonomy and long-term energy balance for solar-powered global system for mobile communication (GSM) BSs are determined; (2) the economic feasibility of a stand-alone solar/battery power system for ensuring 100% cost effectiveness is analyzed and evaluated; and (3) the implications of such a choice (a stand-alone solar/battery power system) with respect to a conventional powered solution is examined.

The analysis and design of RESs are difficult because of the large number of design options and uncertainty in key parameters. Renewable energy sources add further complexity because their power output may be intermittent, seasonal, and non-dispatchable; thus, availability of renewable resources may also be uncertain [22,23]. Hybrid optimization model for electric renewables (HOMER) was designed to overcome these challenges [24]. Thus, the optimum criteria for the lifetime of the solar-powered GSM BS, including economic, technical, and environmental feasibility parameters, have been analyzed using HOMER.

The rest of the paper is organized as follows. Section 2 discusses site description and modeling of system components. Section 3 presents the mathematical model of costs. Section 4 describes the HOMER configurations. Section 5 presents the optimization and simulation results for solar-powered GSM BSs. Section 6 presents the economic feasibility analysis of the solar-powered GSM BSs. Section 7 elaborates the conclusions of the study.

2. Site Description and Modelling of System Components

The architecture of solar-powered GSM BS in Figure 1 combines two subsystems: (1) the solar power system architecture and (2) site architecture of the GSM BS. The photovoltaic (PV) array directly feeds the required energy to the DC load of the GSM BS, and alternating current (AC) load (cooling and lamps) is fed via a DC/AC inverter. Excess energy is stored in the battery bank and is used in case of malfunction of the PV array or at night during load-shedding hours.



(a) Solar system (b) Site architecture of the GSM BS

Figure 1. Schematic of an electricity supply based on PV primary energy with battery to meet GSM BS requirements.

2.1. GSM BS Subsystem

The BS acts as the access link that connects the mobile stations to the core network. The BS covers an area called a cell that is divided into several sectors, and each sector is covered by a sector antenna [25] (Figure 1b). A BS site typically comprises considerable power-consuming equipment. Each sector of a BS site includes a digital signal processing or baseband unit (BB) that is responsible for system processing and coding, a power amplifier (PA) that is responsible for amplifying the transmitted signal, and a transceiver (RF) that is responsible for receiving and sending signals to the mobile stations. Each sector has a main power supply, DC–DC regulator, and air conditioning, all of which are scaled linearly with the power consumption of the other components [25–27]. Most BS sites use a microwave link to connect the BS to the core network [25,28,29]. The BS site includes auxiliary equipment, such as lighting [28].

The common GSM BSs that are being deployed at present are GSM BS 2/2/2 and GSM BS 4/4/4 [30,31]. The nomenclature $n/n/n$ represents 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. The power consumptions of a typical GSM BS 2/2/2 and GSM BS 4/4/4 are 1.8 and 2.3 kW, respectively [30,31].

2.2. Key Components of Solar-Powered GSM BSs

The solar power subsystem comprises various elements that contribute to energy savings and allow for easy disassembly and component separation for recycling.

2.2.1. PV Panels

Several solar cells are combined to form a solar module that is interconnected in series/parallel to form a PV array. These cells absorb shortwave irradiance and convert it to DC electricity [32,33]. The mathematical modelling in HOMER to compute the total annual energy contribution of the solar array (E_{PV}) is based on the following equation [24]:

$$E_{PV} = Y_{PV} \times PSH \times f_{PV} \times 365 \text{ day/year}, \tag{1}$$

where Y_{PV} is the peak capacity of the PV array in kW. PSH is the peak solar hour in hour, which is the equivalent average daily solar radiation. f_{PV} is the PV derating factor, which expresses the impact of dust, wire losses, temperature, and other factors that can affect output energy of the solar array. The derating factor refers to the relationship between the actual and target yield, and this factor is called the efficiency of the PV.

The most important factors that affect the energy produced by a PV panel include geographic location or solar irradiation profile of the site and tilt of the PV panel. The current cost of PV panels is around US$1000 for a PV panel with DC rating of 1 kW. Currently, PV cells based on mono- and poly-crystalline silicon are common in large-scale applications [34]. The Sharp solar model is considered in the present study. The applied Sharp model is highly efficient and affordable. Moreover, the Sharp solar module incorporates an advanced surface to increase light absorption and improve efficiency [35].

2.2.2. Battery

The solar-powered GSM BS is equipped with batteries that are charged during the day with the excess energy produced by the PV panels; these batteries are used to power the GSM BS during periods without sufficient solar power, such as at night and during bad weather. Thus, the depth of discharge (DOD) is an important feature that must be considered in deciding the battery bank capacity of the GSM BS. The *DOD* is used to describe how deeply the battery is discharged and is expressed in the following equation [24]:

$$DOD = 1 - \frac{SOC_{\min}}{100} \tag{2}$$

where $SOC_{\min}$ is the lower limit that does not discharge below the minimum state of charge (SOC). The Trojan L16P battery model is considered in the present study. The DOD for the Trojan L16P battery is 70%, which means that the battery has delivered 70% of its energy and has 30% of its energy reserved. The number of days fully charged batteries can feed the load without any contribution of auxiliary power sources is represented by days of autonomy and is computed in HOMER using the following equation [24]:

$$A_{batt} = \frac{N_{batt} \times V_{nom} \times Q_{nom} \left(1 - \frac{SOC_{\min}}{100}\right)(24\mathrm{h/d})}{L_{prim-avg}(1000\mathrm{Wh/kWh})} \tag{3}$$

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

The cost of batteries is a significant part of the overall cost of a solar powered BS, and thus, battery lifetime is of critical importance. The lifetime of a battery depends on the operating conditions, and the DOD during each diurnal charge-discharge cycle plays a dominant role. DOD refers to the percentage of battery capacity that has been discharged, expressed as a percentage of maximum capacity. HOMER computes the battery lifetime using the following equation [24]:

$$R_{batt} = \min\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \tag{4}$$

where $Q_{lifetime}$ is the lifetime throughput of a single battery (kWh), Q_{thrpt} is the annual battery throughput (kWh/year), and $R_{batt,f}$ is battery float life (year).

2.2.3. Inverter

An inverter is a device that changes a low DC voltage into usable 220 V AC voltage, with the desired frequency of the load (air-conditioning). An inverter is one of the main elements of the system. Inverters differ in terms of output wave format, output power, and installation type. The inverter capacity (C_{inv}) is computed using the following equation [36]:

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

where L_{AC} is the maximum AC load, η_{inv} is the inverter efficiency, and σ_{sf} is the factor of safety.

3. Mathematical Model of Costs

HOMER [24] is an optimization software package used to simulate various renewable energy source system configurations and scale them based on the net present cost (NPC). The NPC represents the lifecycle cost of the system. The calculation assesses all costs that will emerge within the project lifetime, including initial cost, component replacements within the project lifetime, and operations and maintenance (O&M) cost. Figure 2 summarizes the NPC model.

$$NPC = \frac{TAC}{CRF} \tag{6}$$

where *TAC* is the total annualized cost (US$). The capital recovery factor (CRF) is given by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

where n is the project lifetime, and i is the annual real interest rate. HOMER assumes that all prices escalate at the same rate and applies an annual real interest rate rather than a nominal interest rate.

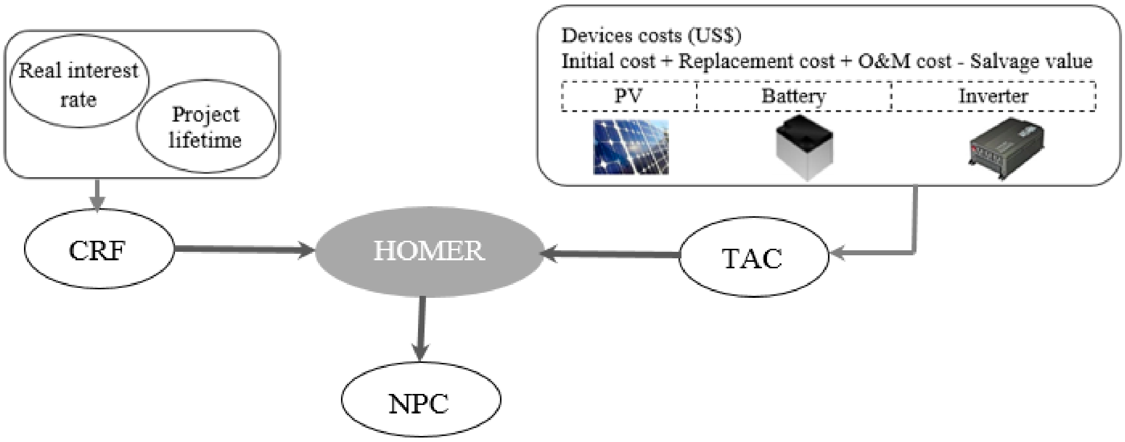


Figure 2. Model of the NPC.

Discount factor (f_d) is a ratio used to calculate the present value of a cash flow that occurs in any year of the project lifetime. HOMER calculates the discount factor using the following equation:

$$f_d = \frac{1}{(1+i)^n} \tag{8}$$

NPC estimation in HOMER also considers the salvage cost, which is the residual value of the power system components at the end of the project lifetime. The equation used to calculate the salvage value (S) is:

$$S = rep(\frac{rem}{comp}) \tag{9}$$

where *rep* is the replacement cost of the component, *rem* is the remaining lifetime of the component, and *comp* is the lifetime of the component.

4. HOMER Configurations

HOMER makes a decision in each time step to meet the power needs at the lowest cost, subject to the constraints of the dispatch strategy chosen in the simulation and a set point of 80%. The system must supply electricity to the load (GSM BS) and the backup power system each hour. Several values for the system components, such as operational lifetime, component efficiency, and costs, are considered for an efficient performance of the optimization process to develop the optimal solar power system. The configurations of the technical specifications and costs for each component to simulate the proposed solar system in HOMER are given below.

4.1. GSM BS Load

Sizing and modeling the solar power system depend on the GSM BS load profile (24 h/7 day continuous supply). Thus, the BS load is critical for designing a reliable and efficient system. Figure 3 shows the hourly load profile for GSM BS 2/2/2 and GSM BS 4/4/4. The AC load includes an air conditioner that represents 10% of the total power and 40 W lighting that operates from 7 p.m. to 6 a.m. HOMER uses 24-h load values for 365 days to ensure accurate analysis.

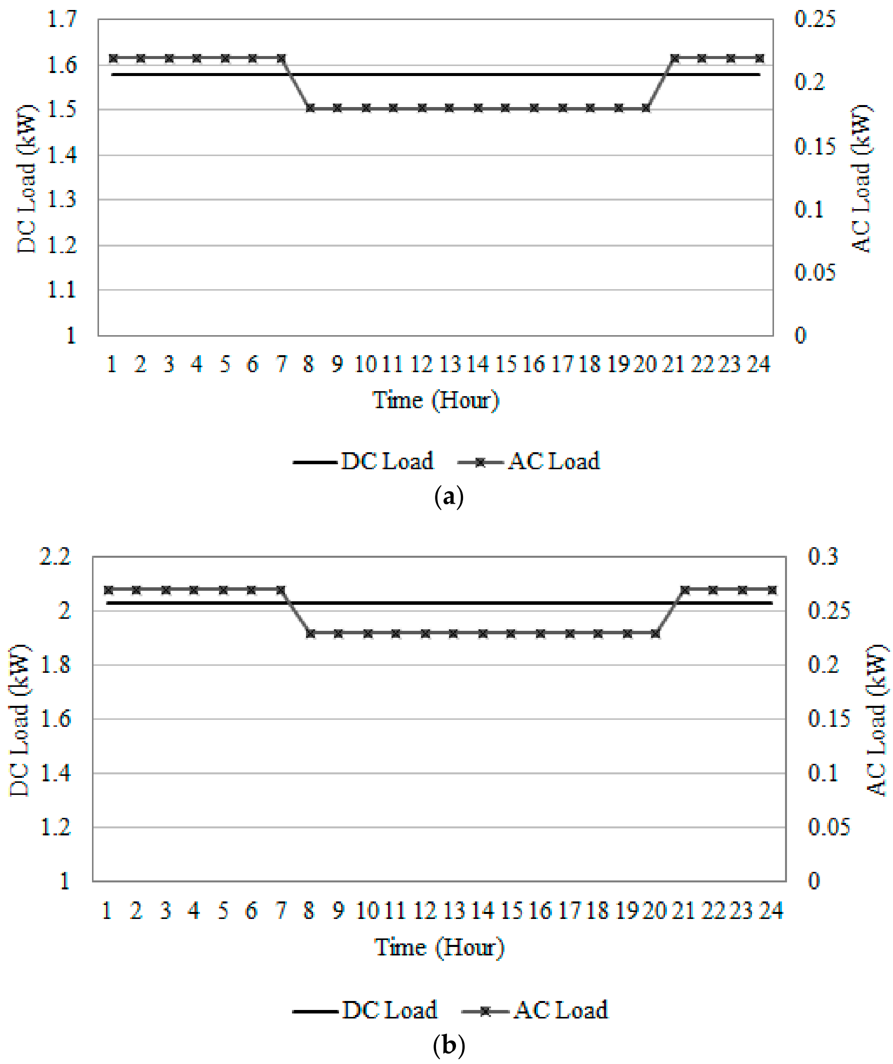


Figure 3. Hourly load profile for the GSM BS. (**a**) GSM BS 2/2/2; (**b**) GSM BS 4/4/4.

4.2. Solar Radiation

The average daily solar radiation in South Korea, which is located at a latitude between 34° and 38° north, is estimated at 4.01 kWh/m^2 and varies from 2.474 kWh/m^2 in December to 5.622 kWh/m^2 in May [19,20]. Figure 4 shows that the monthly variation is largely due to the shift in the elevation angle of the sun. In addition, the long spell of rainy weather in early summer decreases the global horizontal irradiance in June and July.

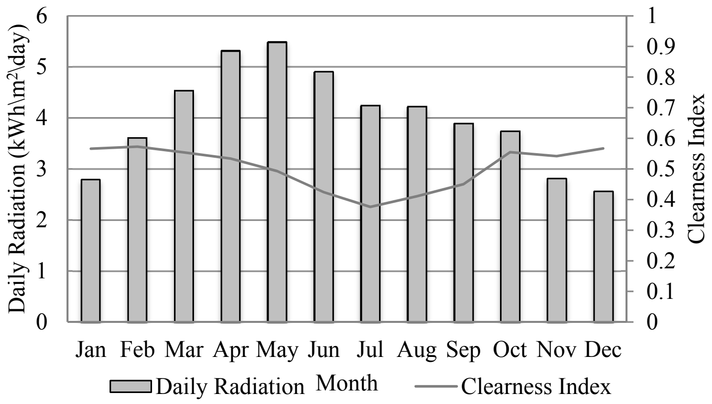


Figure 4. Average monthly daily solar resource at South Korea.

4.3. PV

The technical specifications and costs used in the HOMER simulation based on the proposed solar model are given as follows:

- Costs: initial PV installation, replacement, and annual O&M costs are US$1000/kW, US$1000/kW, and US$10/kW, respectively.
- Technical issues: lifetime of a PV array is 25 years, the derating factor is 0.85, the reflectance is 20%, and the mode is dual axis tracking [37,38].
- PV size: nine different sizes of PV (i.e., 10, 11, 12, 13, 14, 15, 16, 17 and 18 kW) are taken in the search space.

4.4. Battery

The technical specifications and costs used of Trojan L16P battery model are given as follows:

- Costs: the initial installation, replacement, and annual O&M costs are US$300/unit, US$300/unit, and US$10/unit, respectively.
- Technical issues: as shown in Figure 5.
- Battery size: The nominal voltage of the Trojan L16P battery is 6 V. Thus, eight 48-V DC bus-bar batteries will be connected in series (6 V × 8 units = 48 V). Six different sizes (i.e., 32, 40, 48, 56, 64, and 72 units) are taken in the search space.

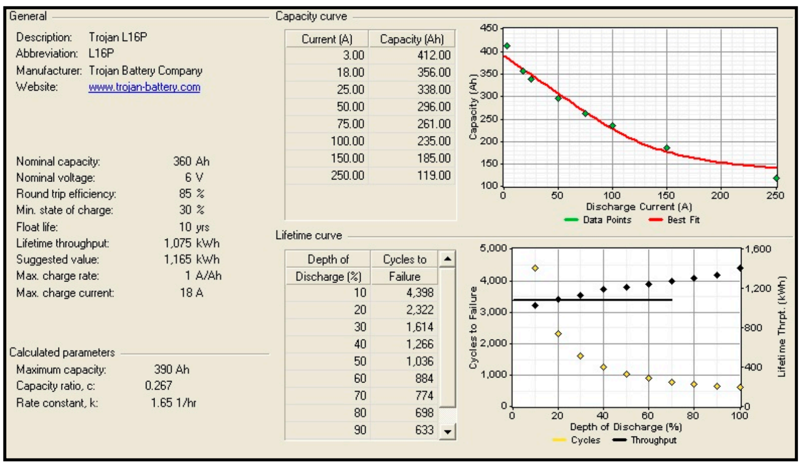


Figure 5. Technical specifications of the battery model.

4.5. Inverter

Technical specifications of and costs used by the inverter model are given as follows:

- Costs: initial, replacement, and annual O&M costs per 1 kW are US$400, US$400, and US$10, respectively.
- Technical issues: lifetime of the inverter and the efficiency are set as 15 years and 95%, respectively.
- Inverter size: five different sizes (i.e., 0.15, 0.2, 0.25, 0.3, and 0.35 kW) are taken in the search space.

4.6. Project Lifetime and Interest Rate

The project lifetime is a critical issue because it affects the total project cost, which is reflected in the economic feasibility of the project. Given a GSM BS lifetime of 10 years [39], the project lifetime is also considered to be 10 years. The annual interest rate is another critical issue because of its effect on the discount factor for each year of the project lifetime; thus, it affects the total project cost. The annual interest rate used in this study is 1.25%, which was the interest rate in South Korea in 2016 [40].

5. Optimization and Simulation Results for Solar-Powered GSM BSs

The analysis and discussion in the following sections are based on an average daily solar radiation for South Korea of 4.0 kWh/m^2 as a case study. The components, namely, optimum size, design criteria, energy output, and economic analysis of the proposed solar power system for GSM BS 2/2/2 and GSM BS 4/4/4, are discussed. A detailed comparative analysis of the criteria for unit sizing and cost optimization is summarized in Table 1.

Table 1. Comparative analysis of various solar-powered GSM BSs.

Description		Solar Powered	
		GSM BS 2/2/2	GSM BS 4/4/4
	Daily solar radiation (kWh/m^2)	4.01	
	Daily energy required (kWh)	43.2	55.2
PV	Size (kW)	13	17
	PV panels connection	4 Series × 13 Parallel	4 Series × 17 Parallel
	Energy Production (kWh/year)	20,378	26,582
	Excess energy (kWh/year)	3031 (14.87%)	4351 (16.37%)
	Initial cost (US$)	13,000	17,000
	O&M cost (US$) over project lifetime	1215	1589
	Salvage value (US$)	6887	9007
Battery	Units	64	128
	Batteries connection	8 Series × 8 Parallel	8 Series × 16 Parallel
	Energy in (kWh/year)	10,046	13,420
	Energy out (kWh/year)	8558	11,451
	Losses (kWh/Year)	1488	1969
	Expected life (Year)	10	10
	Autonomy (h)	53.76	84.14
	Initial cost (US$)	19,200	38,400
	O&M cost (US$) over project lifetime	5981	11,962
Inverter	Size (kW)	0.25	0.30
	Energy in (kWh/year)	1827	2289
	Energy out (kWh/year)	1736	2175
	Losses (kWh/year)	91	114
	Operation hours (h/year)	8759	8759
	Initial cost (US$)	100	120
	O&M cost (US$) over project lifetime	24	28
	Salvage value (US$)	29	35
Total Cost	Initial cost (US$)	32,300	55,520
	O&M cost (US$)	7220	13,579
	Salvage value (US$)	6906	9042
	NPC (US$)	32,614	60,057

5.1. GSM BS 2/2/2

The optimal sizing criteria, energy yield, and economic analysis of the proposed solar system for GSM BS comprise three sectors, with each sector having two antennas, and are provided in the following subsections.

5.1.1. PV Array

The optimal capacity of the PV array, as determined by the HOMER simulation is 13 kW. The designed PV array has 52 Sharp modules (polycrystalline), and each proposed module is rated at 250 W with nominal voltage of 29.80 V, nominal current of 8.40 A, open circuit voltage of 38.3 V, and short circuit current of 8.9 A. Furthermore, 52 modules can be connected as 4 in series and 13 in parallel to be compatible with the specifications of the solar control regulator (Solarcon SPT-4820) that is suggested in this case study.

The annual energy contribution of the PV array is computed using Equation (1); the PV peak capacity is 13 kW × 4.01 h peak solar hours × PV derating factor of 0.85 × 365 days/year = 16,173 kWh. The present simulation adopted a dual-axis tracker that increases the total amount of energy by 23% to be 20,378 kWh, whereas the total annual energy needed by the BS is 15,768 kWh. The difference between the energy production of the PV array and consumption by the BS is equal to the excess energy of 3031 kWh/year plus the battery losses of 1488 kWh/year plus inverter losses of 91 kWh/year. Figure 6 shows the time series in average hourly values of the PV array power output over a 12-month period. Figure 7 summarizes the monthly average of the PV array power output. The result is axiomatic and in times of little or no power output from PV array, the battery bank is used to compensate the amount of energy required by the BS. Figures 6 and 7 show that the minimum output power contribution of the PV array occurs in end of July. This result indicates that the maximum power contribution of the battery bank will occur by end of July, as demonstrated by the low SOC shown in Figure 8 (details in Section 5.1.2).

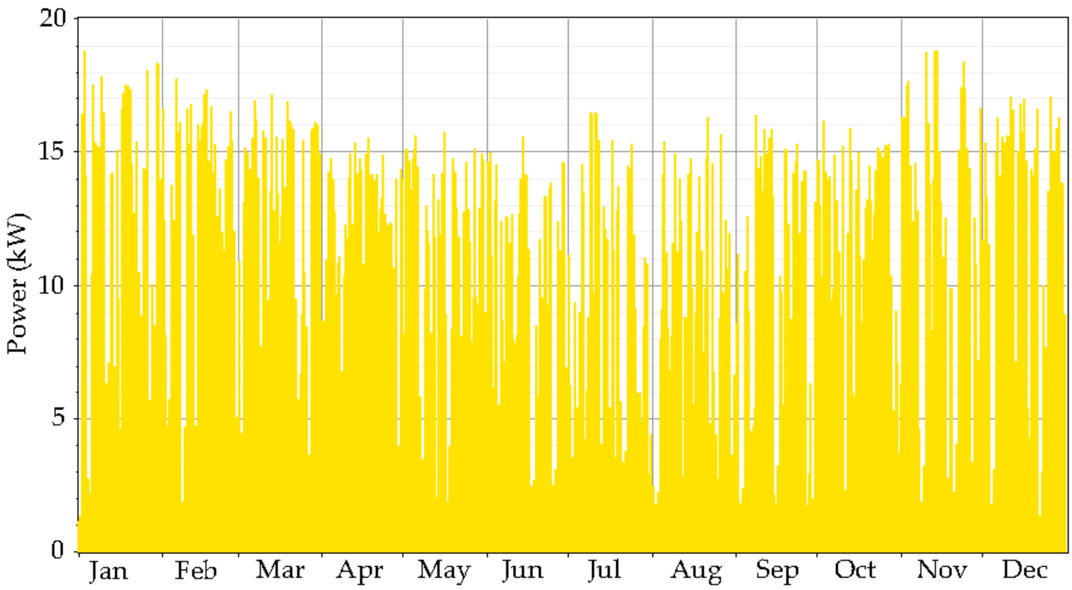


Figure 6. Time series in average hourly values of the PV array power output over a 12-month period for solar-powered GSM BS 2/2/2.

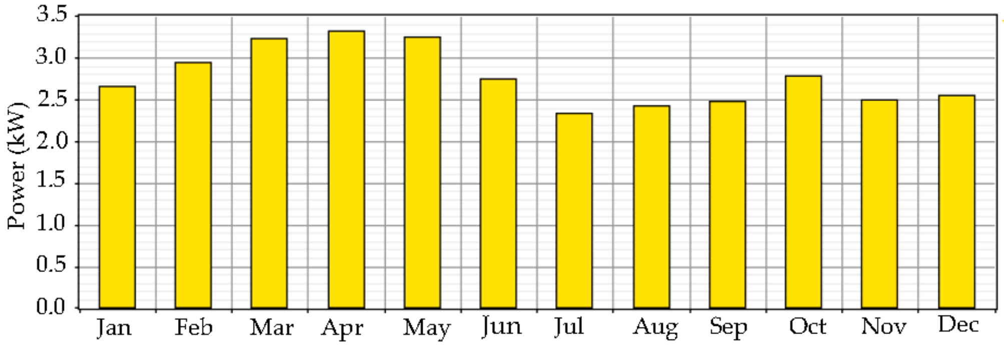


Figure 7. Monthly average of the PV array power output for solar-powered GSM BS 2/2/2.

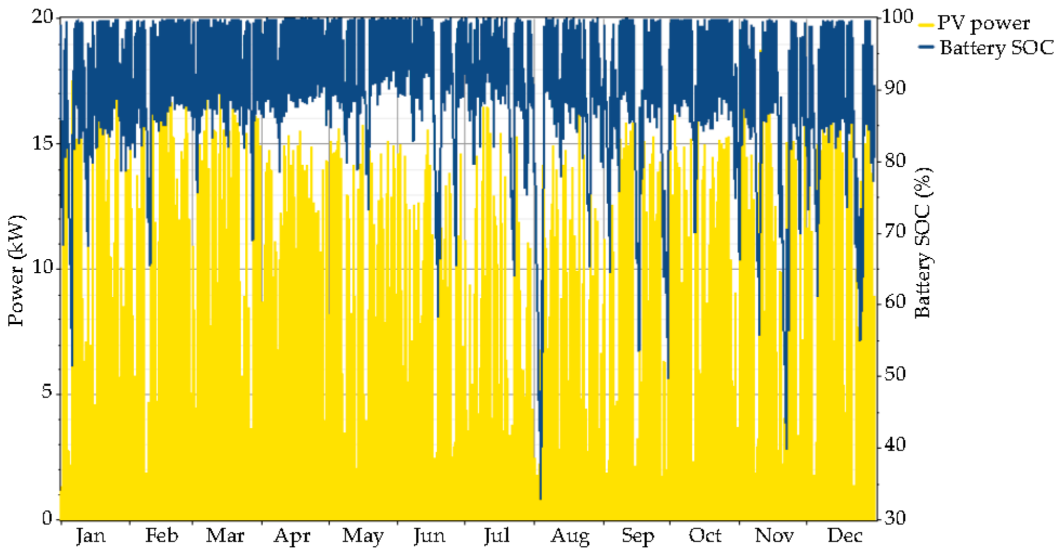


Figure 8. Time series in average hourly values of the PV array power output with SOC over a 12-month period for solar-powered GSM BS 2/2/2.

The PV array has higher capital cost than conventional energy sources. However, the global price of the PV array decreases continuously [34]. Maintenance, operation, and replacement costs also are low. Herein, the initial capital cost of the PV array is US$13,000 (size 13 kW × cost US$1000/kW), the annual O&M cost is US$130 (size 13 kW × cost US$10/kW), and the replacement cost is zero because the PV array has a lifetime of 25 years longer than the project lifetime or BS lifetime of 10 years. Furthermore, the salvage value of the PV array at the end of the project lifetime amounts to US$7800 (US$13,000 × (15 years/25 years)).

5.1.2. Battery Bank

The nominal voltage of the Trojan L16P battery is 6 V. The optimal number of batteries (64 batteries) determined by the HOMER simulation will be connected as 8 in series and 8 in parallel to be compatible with the 48 V DC bus bar.

The battery annual energy-in is 10,046 kWh, while the annual energy-out is 8558 kWh. The roundtrip efficiency is 85%. The battery bank can supply BS load autonomy for 53.76 h, which is computed using Equation (3). Moreover, the expected battery life is 10 years, as computed using Equation (4). Time series in average hourly values of the SOC with PV array power output over a 12-month period are presented in Figure 8. Obviously, the highest power contribution of the battery bank (battery bank depletion) occurs at the end of July to support the PV array that has the lowest power output in this period to feed the BS load by energy required. The details presented in Figure 9 show the reduction in the amount of energy stored in the battery bank during six consecutive days (30 July to 4 August); the lowest level is realized on 4 August.

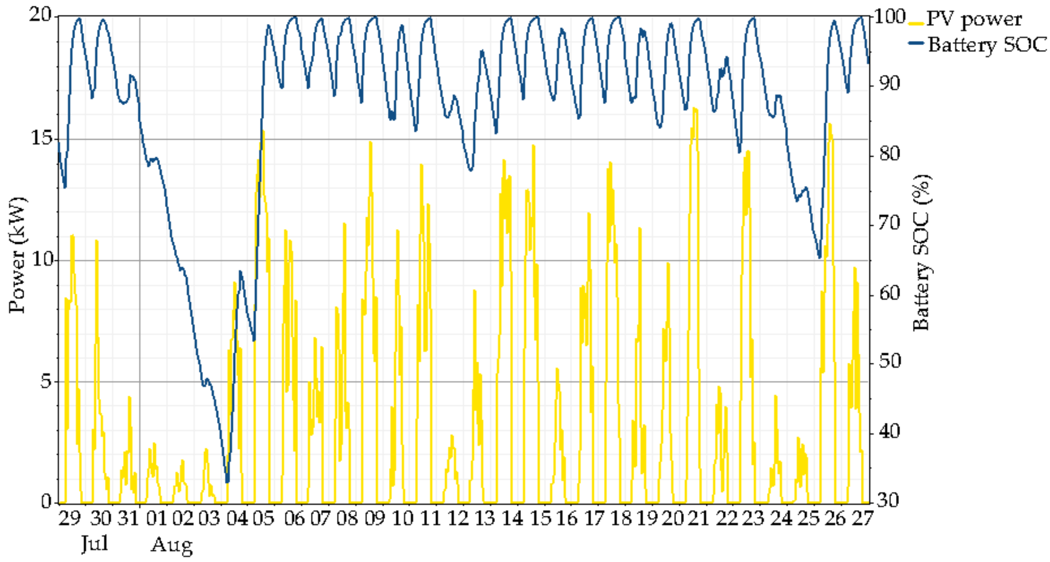


Figure 9. Time series values of the SOC for battery bank between end of July and 1 August.

The frequency histogram (Figure 10) demonstrates that the battery bank is in a minimal SOC for approximately 1% of the year and a high SOC for around 33% of the year. This result suggests potential for additional battery use, which is an important consideration given the intermittency of solar power and potential variations in solar radiation from year to year.

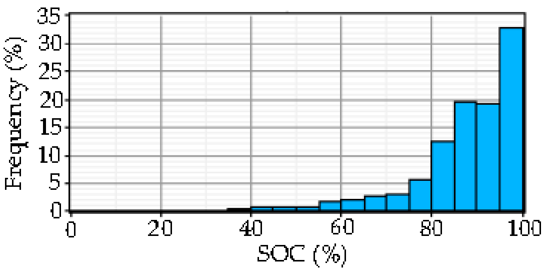


Figure 10. Annual frequency histogram for SOC.

The initial capital cost of the battery bank is US$19,200 (64 units × US$300/unit), the annual O&M cost is US$640 (64 units × US$10/unit), and the replacement cost for the battery is zero based on the solar system design proposed because the battery has a lifetime of 10 years, which is equivalent to the project lifetime. Finally, the salvage value is zero.

5.1.3. Inverter

A typical daily AC load is 220 W (air conditioner 180 W (10%) + auxiliary equipment, such as lamps 40 W (from 7 p.m. to 6 a.m.)). The required inverter must be capable of handling 0.25 kW. Monthly output power of the inverter shown in Figure 11 demonstrates that output power of the inverter is 0.18 kW during the period from 6 a.m. to 7 p.m.; this power covers the air-condition energy required given that the lamps are off in this period. During the period from 7 p.m. to 6 a.m., the output power of the inverter is 0.22 kW; this power covers the load of the air-condition and lamp. The inverter annual energy-in is 1827 kWh, while the annual energy-out is 1736 kWh, with 95% efficiency and 8759 h/year operation (operating hours 24 h × 365 days/year).

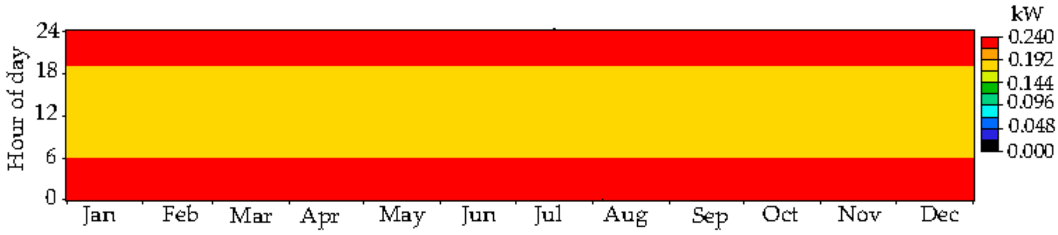
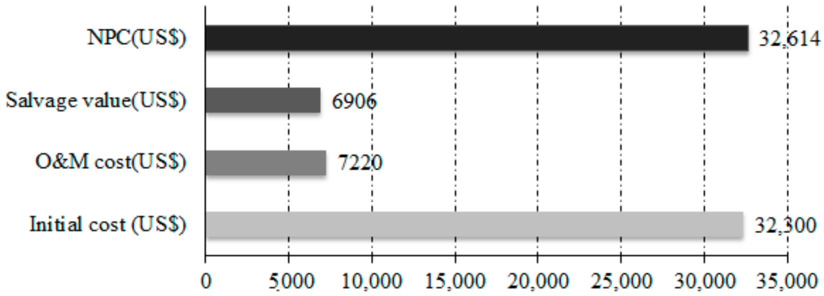


Figure 11. Monthly power output of the inverter for solar-powered GSM BS 2/2/2.

The inverter initial capital cost is US$100 (size 0.25 kW × cost US$400/kW), annual O&M cost is US$2.5 (size 0.25 kW × cost US$10/kW), and neither has replacement costs because the inverter lifetime is 15 years longer than the project lifetime. The salvage value is US$33.

Figure 12 summarizes the proposed solar power system costs. The NPC is calculated by summing up the total discounted cash flows in each year of the project lifetime, as follows: initial capital cost US$32,300 (PV array US$13,000 + battery bank US$19,200 + inverter US$100) + O&M cost US$7220 (PV array US$1215 + battery bank US$5981 + inverter US$24) − salvage value US$6906 (PV array US$6887 + inverter US$29) = US$32,614. Clearly, the batteries account for the largest part of costs. Although the number of batteries can be reduced, load autonomy also decreases.



Initial cost (US$)	O&M cost(US$)	Salvage value(US$)	NPC(US$)
32,300	7220	6906	32,614

Figure 12. Costs of the solar-powered GSM BS 2/2/2.

5.2. GSM BS 4/4/4

Similarly, optimal sizing criteria, energy yield, and economic analysis of the proposed solar system for GSM BS comprising three sectors, with each sector having four antennas, are provided in the following subsections.

5.2.1. PV Array

The optimal peak capacity of the PV array is 17 kW. The designed PV array has 68 Sharp modules (polycrystalline), and each proposed module is rated at 250 W. The 68 modules can be connected as 4 in series and 17 in parallel to be compatible with the specifications of the solar control regulator (Solarcon SPT-4820), such that the output voltage of the PV array decreases to 48 V DC bus bar.

A total of 26,582 kWh is the annual energy contribution of the PV array with a dual axis tracker mode, while the total annual energy needed by the BS is 20,148 kWh. The difference between energy production and consumption is equal to the excess energy of 4351 kWh/year (16%) plus the battery losses of 1969 kWh/year plus the inverter loss of 114 kWh/year. Figures 13 and 14 demonstrate the maximum and minimum power contribution of the PV array; the minimum output power contribution of the PV array occurs at the end of July, indicating that the maximum battery bank depletion will occur in the same month (Figure 15).

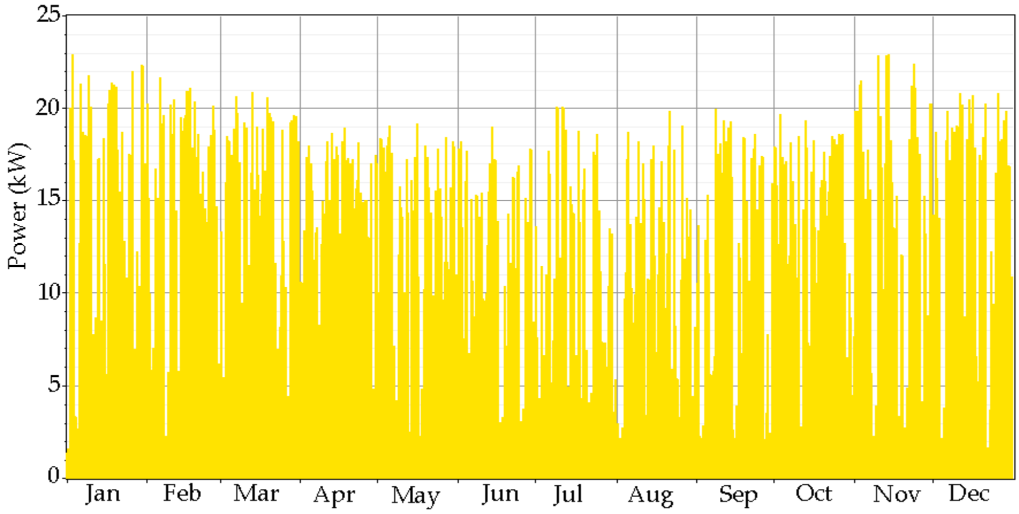


Figure 13. Time series in average hourly values of the PV array power output over a 12-month period for solar-powered GSM BS 4/4/4.

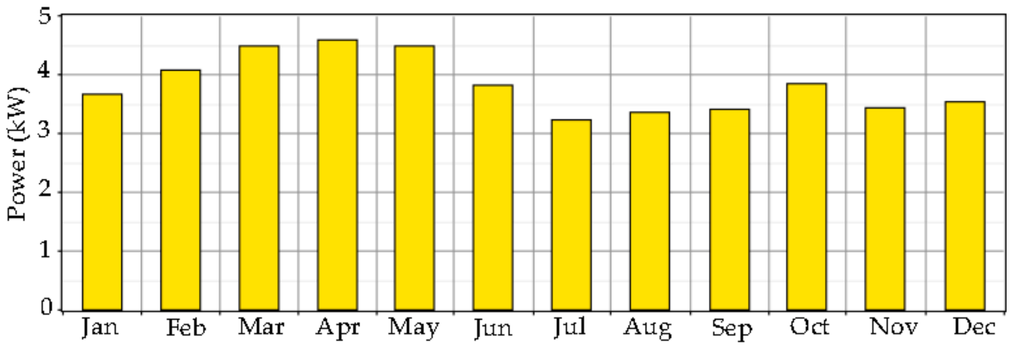


Figure 14. Monthly average of the PV array power output solar-powered GSM BS 4/4/4.

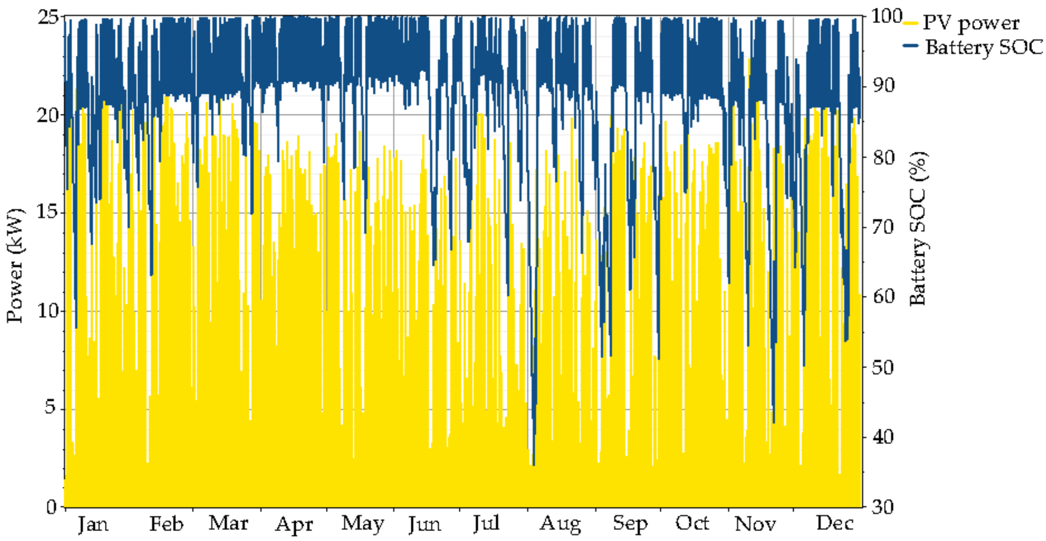


Figure 15. Time series in average hourly values of the PV array power output with SOC over a 12-month period for solar-powered GSM BS 4/4/4.

The PV array initial capital cost is US$17,000 (size 17 kW × cost US$1000/kW), annual O&M cost is US$170 (size 17 kW × cost US$10/kW), and the salvage value is US$10,200. The replacement cost is zero because the PV array lifetime is longer than the project lifetime.

5.2.2. Battery Bank

The optimal number of batteries determined by HOMER is 128, which will be connected as 8 in series and 16 in parallel to be compatible with the 48 V DC bus bar. The battery annual energy-in is 13,420 kWh, while the annual energy-out is 11,451 kWh. The roundtrip efficiency is 85%, the battery bank can supply a BS load autonomy for 84.14 h, and the expected battery life is 10 years. Figure 15 demonstrates the maximum and minimum SOC for the battery bank. More details given in Figure 16 show continuous reduction in the amount of energy stored in the battery bank for six consecutive days (30 July to 4 August), and the lowest level is realized on 4 August. However, Figure 17 demonstrates that the battery bank is in a minimal SOC for approximately 1% of the year and a high SOC for nearly 33% of the year.

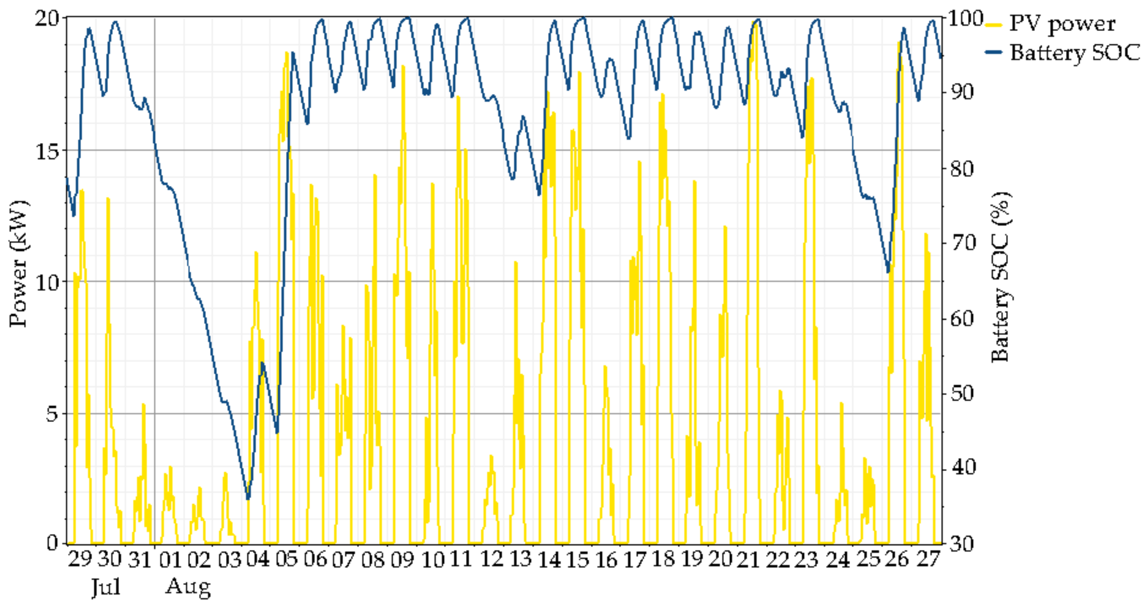


Figure 16. Time series values of the SOC for battery bank between end of July and 1 August.

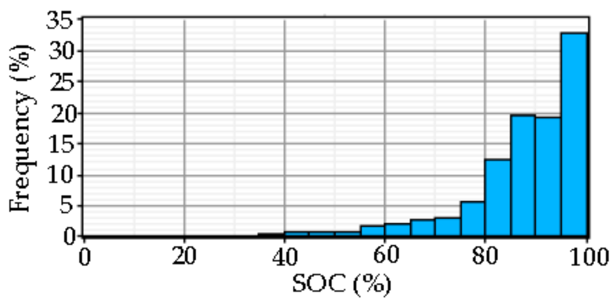


Figure 17. Annual frequency histogram for SOC.

The initial capital cost of the battery bank is US$38,400 (128 units × US$300/unit), annual maintenance and operation cost is US$1280 (128 units × US$10/unit), and the replacement cost and salvage value are zero because the expected battery life is 10 years, which is equivalent to the project lifetime.

5.2.3. Inverter

A typical daily AC load is 270 W (air conditioner 230 W (10%) + auxiliary equipment, such as lamps 40 W (7 PM–6 AM)). The required inverter must be capable of handling 0.3 kW. Figure 18 demonstrates that output power of the inverter is 0.23 kW during the period 6 to 19; this power covers the air-conditioning only because the lamps are off during this period. During the period from 7 p.m. to 6 a.m. output power of the inverter is 0.27 kW; this power covers the load of the air-conditioning and the lamps. The inverter annual energy-in is 2289 kWh, while the annual energy-out is 2175 kWh, with 95% efficiency and 8759 h/year operation (operating hours 24 h × 365 days/year).

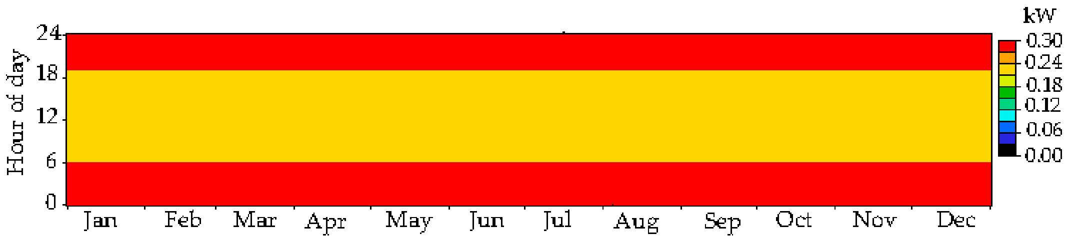
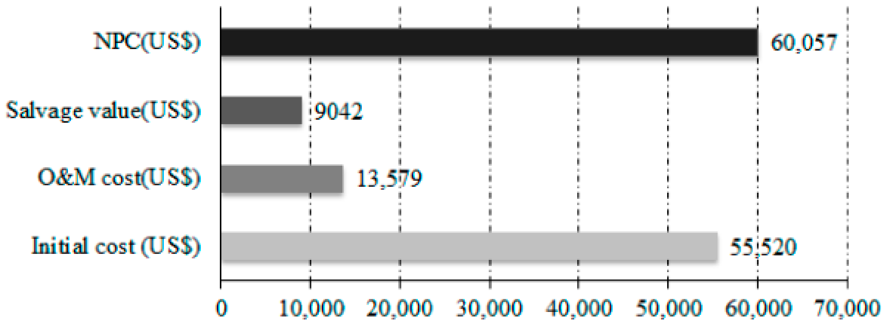


Figure 18. Monthly power output of the inverter for solar-powered GSM BS 4/4/4.

The inverter initial capital cost is US$120 (size 0.30 kW × cost US$400/1 kW), the annual maintenance and operation cost is US$3.0 (size 0.30 kW × cost US$10/1 kW) and neither has replacement costs because the inverter lifetime is 15 years longer than the project lifetime. The salvage value is US$40.

Figure 19 summarizes the proposed solar power system costs. The total discounted NPC is US$60,057, which is computed as follows: initial capital cost US$55,520 (PV array US$17,000 + battery bank US$38,400 + inverter US$120) + O&M cost US$13,579 (PV array US$1589 + battery bank US$11,962 + inverter US$28) − salvage value US$9042 (PV array US$9007 + inverter US$35). Batteries have the largest part of costs; the number of batteries can be reduced, but the load autonomy also decreases.



Initial cost (US$)	O&M cost(US$)	Salvage value(US$)	NPC(US$)
55,520	13,579	9042	60,057

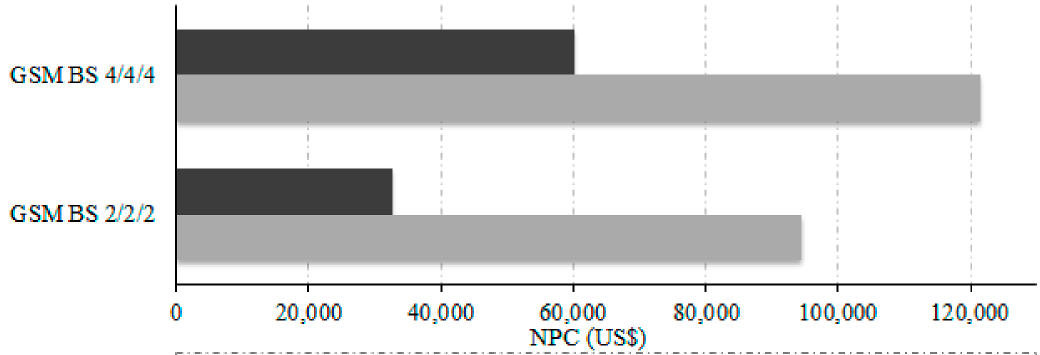
Figure 19. Costs of the solar-powered GSM BS 2/2/2.

6. Economic Feasibility Analysis of the Solar-Powered GSM BSs

Increasing profitability and reducing the OPEX in the cellular network are major issues for mobile operators. The following subsections summarize the economic feasibility of deploying the solar-powered GSM BS in urban and remote areas.

6.1. Urban Areas

The public electrical grid (EG) is typically used to power the deployed cellular BSs in urban areas. The following paragraphs provide a comparative analysis in terms of OPEX between the proposed solar system and the conventional power source for the GSM BSs. Figure 20 summarizes the NPC for various power systems.



	GSM BS 2/2/2	GSM BS 4/4/4
Solar system	32,614	60,057
Electrical grid	94,400	121,367

Figure 20. NPC comparison for both of the proposed solar system with EG.

6.1.1. GSM BS 2/2/2

a. EG: According to [41], the cost of the energy consumed by the BS of the EG over the project lifetime of 10 years amounts to approximately South Korean Won (KRW) 111.187 million. This amount is calculated on the basis of the annual BS energy consumed at 15,768 kWh × energy price in KRW/kWh × project lifetime of 10 years. KRW 111.187 million is equal to US$94,400 at a foreign exchange rate of 1 USD= 1178.57 KRW as of January 13, 2017.
b. Proposed solar power system: The total discounted NPC of the solar power system is US$32,614, which is computed as follows: initial capital costs US$32,300 + O&M costs US$7220 − salvage US$6906.

Applying the proposed solar-powered system for BSs deployed in urban areas will result in total OPEX savings of 65.45% (US$61,786 over the project lifetime) of conventional power sources.

6.1.2. GSM BS 4/4/4

a. EG: The cost of the energy consumed over the project lifetime amounts approximately to KRW 142.950 million [41], and this cost is calculated as follows: the annual BS energy consumed at 20,148 kWh × energy price in KRW/kWh × project lifetime. KRW 142.950 million equals US$121,367.
b. Proposed solar power system: The total discounted NPC of the solar power system is US$60,057, which is computed as follows: initial capital costs US$55,520 + O&M costs US$13,579 − salvage US$9042.

Applying the proposed solar-powered system results in total OPEX percentage savings of 50.52% (US$61,310 over project lifetime). The mobile operators can increase the OPEX savings by reducing the number of batteries (128 units), which comprises the bulk of the costs of a solar-powered system. However, decreasing the batteries will decrease the battery autonomy, an essential issue in a stand-alone solar-powered system.

6.2. Remote Areas

The DG is typically used to power the deployed cellular BSs in remote areas. Figure 21 summarizes the NPC for various power systems. Comparative analysis in terms of OPEX between the proposed solar system and DG is as follows.

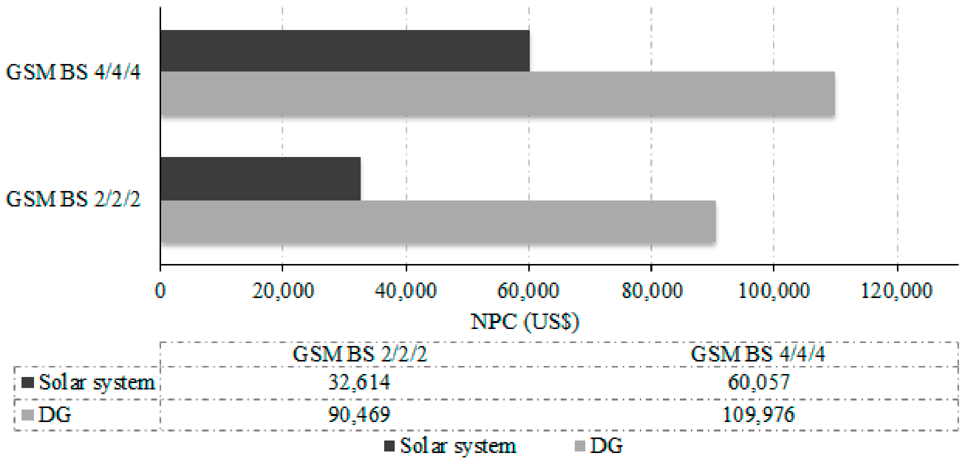


Figure 21. NPC comparison for both of the proposed solar system with DG.

6.2.1. GSM BS 2/2/2

The DG needed is approximately 6.5 kW, which is computed as (maximum BS load 1.8 kW) divided by (DG efficiency 30% [42] × converter efficiency 95%). The total NPC is US$90,469, which is computed as follows: initial capital costs US$4290 + O&M costs US$73,309 + replacement costs US$12,870.

- Initial capital costs US$4290 (size 6.5 kW × cost US$660/kW).

The annual cost for the O&M of the DG amounted to US$7331 (without counting the cost of fuel transport). A breakdown of this cost is: (1) US$438 for DG maintenance per year based on a DG maintenance cost of US$0.05/h × annual DG operating hours of 8760 h; and (2) a fuel cost of US$6893, based on the diesel price of US$1.04/L [43] multiplied by the a total diesel consumption of 6628 L/year, which is computed on the basis of a specific fuel consumption of 0.388 L/kWh × annual electrical production of the DG of 17,082 kWh/year (DG capacity size 6.5 kW × DG efficiency 0.3 × 24 h × 365 days/year). Hence, the total O&M costs over project lifetime equal US$73,309.

- A mobile operator may need to change the DG every three years, which means at least three times during the life of the project. Thus, the total DG replacement cost is 3 × (size 6.5 kW × cost US$660/kW), which is equal to at least US$12,870.

By applying the proposed solar system, the total OPEX that can be saved amounts to 63.95% (US$57,855). In addition, the total annual CO_2 emission that can be eliminated is 17,763 kg (annual diesel consumption of 6628 L multiplied by 2.68 kg CO_2/L [44]).

6.2.2. GSM BS 4/4/4

The DG needed is approximately 8 kW, which is computed as (maximum BS load 2.3 kW) divided by (DG efficiency 30% [42] × converter efficiency 95%). The total NPC is US$109,976, which is computed as follows: initial capital costs US$5280 + O&M costs US$89,216 + replacement costs US$15,840.

By applying the proposed solar system, the total OPEX that can be saved amounts to 45.39% (US$49,919). The total annual CO_2 emission that can be eliminated is 21,862 kg (annual diesel consumption of 8157 L multiplied by 2.68 kg CO_2/L [44]).

7. Conclusions

A stand-alone PV system for various GSM BSs deployed at present is studied. The simulation results show that the proposed solar-powered GSM BS 2/2/2 can achieve annual OPEX savings of up to 65.45% in urban areas and 63.95% in remote areas with 13 kW PV and 64 units of batteries. Meanwhile, the solar-powered GSM BS 4/4/4 can realize annual OPEX savings of up to 50.52% in urban areas and 45.39% in remote areas, with 17 kW PV and 128 units of batteries. The results also show that 100% of energy autonomy and long-term energy balance for BS are guaranteed. Total annual energy output of the solar array for GSM BS 2/2/2 is 20,378 kWh, which covers the needed amount of BS energy and provides 3031 kWh of excess energy. Moreover, the battery bank can supply BS load autonomy for 53.76 h. Total annual energy output of the solar array for GSM BS 4/4/4 is 26,582 kWh, which fulfills BS demand from required energy with 4351 kWh of excess energy. The battery bank can also supply BS load autonomy for 84.14 h.

In summary, the proposed solar power system is an attractive economical solution in the long-term (over the BS lifetime) for cellular network operators. The system provides increased levels of reliability and presents low maintenance needs in addition to reduced GHG. Table 2 summarizes the NPC and OPEX savings for the optimal design of the proposed solar power system and conventional power sources.

Table 2. Summary of the NPC and OPEX savings for the proposed solar power system and conventional power sources.

Description		GSM BS 2/2/2	GSM BS 4/4/4
NPC	PV (US$)	32,614	60,057
	DG (US$)	90,469	109,976
	EG (US$)	94,400	121,367
Feasibility of solar system (OPEX savings)	Urban area (%)	65.45% (US$61,786)	50.52% (US$61,310)
	Remote area (%)	63.95% (US$57,855)	45.39% (US$49,919)
Annual GHG eliminated (kg)		17,763	21,862

Notably, fifth generation (5G) technology is rapidly coming into the limelight, and commercial 5G mobile wireless networks are expected to be deployed by 2020. The 5G technology will soon fulfill many requirements, of which delivering high network energy performance is the most critical [45]. This feature is crucial to reducing operational cost and providing network access in a sustainable and resource-efficient manner. High energy performance requires a fundamental change in design principles and implementation practices within the mobile telecom industry [46]. The 5G technology will be energy efficient, and power consumption by the base station will significantly decrease. Thus, solar-powered BSs will be a long-term solution for the mobile cellular network industry.

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Conflicts of Interest: The author declares no conflict of interest.

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