Solar PV Powered Mobile Cellular Base Station: Models and Use Cases in South Africa

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***Abstract*—The huge costs of operating a mobile cellular base station, and the negative impact of greenhouse gasses on the environment have made the solar PV renewable energy source a sought after. In addition to cost and environmental factor, abundant supply of solar radiation in Southern part of Africa, and the drive to reduce the emission of carbon dioxide by the year 2020 and to improve the quantity of power supply are also part of many incentives to power communication base station systems with solar PV cells. To this end, solar PV powered base stations have become important integration into a mobile cellular network. Thus, this article exploits the use of solar PV powered mobile cellular base station systems in South Africa. It was also found through this feasibility study that the country has a solar radiation between 4.5 kWh/m^2 and 6.5 kWh/m^2. Also found was that the use of solar PV cellular base station will lead to about 49 % reduction in operation cost compared to using the diesel generating sets. Therefore, this article, as a feasibility study, explore the use of solar energy capacity of South Africa towards powering the mobile cellular base station. This article will also contribute to research base, as there are few number of literature found on this topic in South Africa.**

Keywords*— Base Station; Solar PV; Renewable Energy Technology (RET); Battery system; Solar radiation

I. INTRODUCTION

Over the years, there has been a rapid increase in the energy utilization in telecommunication networks around the world. The telecommunication industry alone had experienced an estimated global electrical consumption yearly increase of about 20% between the year 2012 to this moment as reported by [1]. The increase is because of high expansion in the use of mobile cellular networks by the mobile subscribers all over the world in terms of global mobile data traffic. The demand for cellular mobile data had also grown three times faster from the year 2008 to the year 2017 as illustrated in Fig. 1 below, especially in the developing continents such as Africa, Asia, and the Middle East [2]. This scenario continues to trend as more mobile cellular base stations (BSs), are continually deploy.

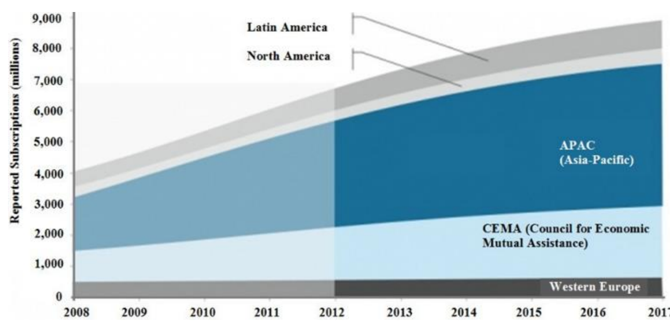

Fig. 1. Mobile Cellular data subscription [2, 3]

Consequently, the cellular mobile operators are always developing and sending out new technological infrastructures from 1G to 5G, to be able to support their ever-increasing network capacity. Currently, it is estimated that there are over 6 billion mobile subscribers with a corresponding increase in the number of base state (BS) to support the network coverage and capacity worldwide [7]. For an operator of a mobile cellular network to provide seamless and uninterrupted mobile services to the subscribers, they must utilize several BSs, hence, the increase in the number of BSs globally. However, a single BS is said to be responsible for about 75-80% of the total cost of energy consumption in mobile cellular networks according to DOCOMO's analysis [4], consuming 25 MWh of electrical energy per year per an estimated four million deployed BS worldwide [5]. To this extent, mobile cellular BS has been the major reason for the increase in energy consumption, greenhouse gasses (GHG), and emission, leading to a huge cost of operation in the mobile cellular network [6]. The increase in a number of mobile cellular BS causes a huge increase in energy consumption within a mobile cellular network as well as leading to high cost of operation. The high cost of operation and emission carbon dioxide are huge problems facing the mobile cellular operators and the society at large.

The mobile cellular networks on Africa continent remains one of the fastest growing industries in the world. This growth has made the network to expand beyond the supply capacity of grid electricity system only. Thus, prompting the network providers to deploy many of their equipment in the areas where there is limited access to electric grid system according to the

Groupe Speciale Mobile Association (GSMA), explanation and research [8]. The GSMA further estimates that the total percentage of mobile cellular networks coverage across sub-Saharan Africa remains 70% as a result of BS tower of 240,000 which is expected to increase to a total number of 325,000 at the end of the year 2020. The GSMA further stated that Africa has about 145,000 deployed off grid BS sites which are expected to grow to 189,000 by the end of 2020. Out of the number estimated - 84,000, expected to grow to 100,000, are said to be on faulty bad-grid [8]. This is the major cause of unreliable power, frequent power outage, voltage fluctuation, loss of phase and degradation of mobile signal coverage and capacity in the developing countries of the world. Consequently, the use of diesel generating set as a power backup which causes high cost of operation and emission of carbon oxides. However, further, observation shows that most of these countries in Africa region have abundant solar energy resource as compared to other sources of renewable energy such as the wind, fuel cells, etc. Hence, energy harvested from the solar seems to be a viable option to power the BS.

Of all the Renewable Energy Sources (RES), energy harvested from the solar irradiance converted by the means of the PV panel has become a major energy source to power BS. Solar PV energy source is usually supported by an array of batteries to store extra energy harvested. Some advantages of using solar PV system in mobile cellular operation are; Self-sustainability nature of solar energy, its availability virtually in all locations, little or no emission of CO_2, and affordable to implement. Solar PV energy source also requires little maintenance. Hence, for most developing countries, solar BS implementation is seeing as an alternative means of powering BS. Other advantages of using solar PV to powered mobile cellular BS were also highlighted in [2, 7, 9, 14, 23].

Solar PV utilization is not new in South Africa. However, little has been done towards powering the mobile cellular base station. Therefore, it is the focus of this article to present an overview of using solar PV powered mobile cellular BS in South Africa with the aim of encouraging its adoption and deployment. To do this, the article supplies the overview information on solar PV powered mobile cellular BS model major items, its current deployment in mobile cellular network in South Africa and a case study to highlight its advantage over traditional uses of diesel.

II. Overview Of Solar PV Powered Mobile Cellular Base Station Model

The aim of this section is to give an overview of some major components of a typical solar PV powered BS. In describing these essential components that made up a solar PV powered BS, it should be noted that the generation and the energy consumption within this BS, just like any other RES, are dynamic in nature. This means the energy harvested through solar PV is dependent on the weather condition of a geo-location, while the energy consumption changes per load or the number of mobile subscribers on the network. Therefore, before carrying out any design or modeling, it is essential to carry out the geo-location pre-feasibility study. Fig. 2 is a schematic representation of a typical solar PV powered mobile cellular BS. It consists of two subsystems, which are; solar PV system and the BS system.

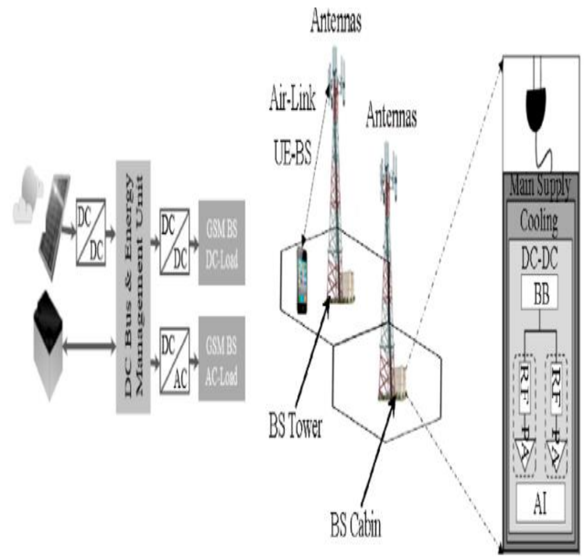

Fig. 2: Schematic diagram of Solar PV Powered Base Station [9].

A. Solar PV System

Solar PV system comprises of photovoltaic panels, the battery system, and the converters. Photovoltaic panels can be described as an array of solar PV cells which convert solar energy to electricity. These cells are arranged in form of modules of many interconnected solar cells in series or parallel connections. The PV panels are rated for direct current (DC) based on the power it can generate when the solar power available on its power is 1 kW/m2. Presently, commonly used PV cells with an efficiency of about 15-19 percent are mono and polycrystalline silicon, in large scale applications [7]. To have PV cells with efficiency above 40% is still an open research. According to [10-11], the output power of the PV modules is determined by the PV cell material, the cell temperature, the solar radiation incident on the PV modules, the DC-AC loss factor, the tilt of the PV panel as well as the geographical location of the site. The mathematical model to generate this out power can be calculated using (1) as given by [12, 13]

$$E_{pv} = A \times \eta_m \times P_f \times \eta_{PC} \times I \quad (1)$$

Where A is the total area of the PV generator (m^2), η_m is the module efficiency (0.111), P_f is the packing factor (0.9), η_{PC} is the power conditioning efficiency (0.86), while I is the hourly irradiance (kWh/m^2).

B. Battery System

Battery system consists of batteries, controllers, and converters. A battery system is essential in this arrangement. The battery is an electrochemical energy storage device that stores and converts excess electrical energy (DC) from the solar panel or grid in form of electrochemical for later usage.

However, each battery technology has different ways in which it should be treated. Majorly, the mathematical modeling of a battery system in a solar PV depends on the battery state of charge (SOC), the depth of discharge (DOD), and the state of health (SOH). The SOC is the cumulative sum of charge or discharge transfers of the battery daily. The mathematical model of the battery, the fitted controller, and the converter is model according to (2) and (3) given in [14-17]

$$S_b = N_b \times E_{BAT} \tag{2}$$

where;

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{CC-OUT}(t) \times \eta_{CHG} \tag{3}$$

S_b is the size of the battery, N_b is the total number of batteries within the battery bank, $E_{BAT}(t)$ is the energy stored in a battery per hour t, kWh as given in (2). In (3), $E_{BAT}(t-1)$ denotes the energy stored in a battery per hour t-1, kWh, E_{CC-OUT} is the hourly energy output from the charge controller, kWh, and η_{CHG} is the battery charging efficiency.

Also, the available energy at the battery bank during the discharge at any time, t, can be model by (4);

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{Needed}(t) \tag{4}$$

where $E_{Needed}(t)$ denotes the energy needed at a particular period of time.

The DOD which is measured as the percentage of how much energy can be withdrawn from the battery can also be denoted by (5) and (6);

$$DOD = (1-d) \times 100 \tag{5}$$

$$SOC_{Min} = 1 - \frac{DOD}{100} \tag{6}$$

Where d is the ratio of minimum allowable SOC voltage limit to the maximum SOC voltage across the battery terminals when fully charged and SOC_{Min} is the minimum state of charge of the battery bank.

Therefore, the power available with the battery bank is mathematical model using (7);

$$P_{BAT,Avail}(t) = \frac{E_{BAT}(t)}{\Delta t} - SOC_{Min} \tag{7}$$

where Δt is the simulation step time.

The aim of the charge controller is to prevent overcharging of the battery system. It also serves battery management unit. It is expressed mathematically by (8) and (9);

$$E_{CC-OUT}(t) = E_{CC-IN}(t) \times \eta_{CC} \tag{8}$$

$$E_{CC-IN}(t) = E_{REC-OUT}(t) + E_{SUR-DC}(t) \tag{9}$$

In (8), E_{CC-OUT} is the hourly energy output from the charge controller; kWh, E_{CC-IN} is the hourly energy input to charge controller; kWh, η_{CC} is the efficiency of the charge controller. $E_{REC-OUT}(t)$ is the hourly energy output from the rectifier - kWh, and, $E_{SUR-DC}(t)$ denotes the amount of surplus energy from DC sources, kWh in (9).

The converter which contains both rectifier and inverter is also necessary for this model. The advantage of adding this converter is to convert the DC power from the battery to AC power of constant voltage. The mathematical models associated with converters used for modeling solar PV are given by (10), (11), and (12)

$$E_{REC-OUT}(t) = E_{REC-IN}(t) \times \eta_{REC} \tag{10}$$

$$E_{REC-IN}(t) = E_{SUR-AC}(t) \tag{11}$$

$$E_{SUR-AC}(t) = E_{GRID}(t) - E_{LOAD}(t) \tag{12}$$

Where, $E_{REC-OUT}(t)$ is the hourly energy output from the rectifier - kWh,$E_{REC-IN}(t)$ is the hourly energy input to the rectifier - kWh, η_{REC} is the efficiency of the rectifier, $E_{SUR-AC}(t)$ is the excess energy from AC sources - kWh, and, $E_{GRID}(t)$ is the hourly energy supplied by the grid (optional).

Both the Solar PV array and the battery system supply the energy requirements of the BS. The energy demand of the BS is the energy needed to supply the light loads, the cooling load, and the transceiver hardware. The integrated power unit (IPU) coordinates the load demand, energy supply, conversion, as well as the storage of the excess energy within the BS [1]. Thus, IPU consists of the battery monitoring system (BMS), the converters, the controllers, and all other power management units.

C. *The BS System*

As seen in Fig. 2, the BS can be described as an access link that uses a microwave to connect between the mobile station site and the core network [9, 18, 19]. It contains a transceiver which includes both the transmitting and receiving antennas (RF) for signal transfer in and out of the cellular mobile station; the baseband which does the system coding and processing; the equipment for amplifying the signal transmitted known as power amplifiers (PA); the lighting; the cooling equipment as well as the power units for each of the equipment [9, 18, 19]. BS can be subdivided into macro, micro, mini, and femto in descending order per size and energy consumption [7]. Macro BS is widely used in mobile cellular networks due to its super quality, lower cost rate, and wider coverage capacity. However, it possesses high energy consumption rate. As a result, the macro BS cells are often overburdened, emitted high GHG, and consequently, degraded the end user's performance QoS experience [20-22]. Furthermore, energy consumption of the BS can be categorized into two; static energy consumption and dynamic consumption. They are the fixed parts which are due to the cooling system, signal processing, the energy dissipated by cable feeders etc., and variable parts as a result of the traffic loads, and the power amplifiers [23, 24]. The author in [25] gave the example of power consumption in a macro cell BS to be 10.7 kW. This is broken down as;

- Radio unit (radio frequency (RF) conversion and power amplification) = 4160 W
- Base Band (signal processing and control) = 2190 W
- Power supply and rectifier = 1170 W
- RF feeder = 120 W
- Remote Monitoring and safety = 100 W
- Signal Transmitting = 120 W
- Climate Equipment (Air Conditioning) = 2590 W
- Security and Lighting = 200 W

Therefore, the power consumption of a BS can be modeled mathematically by (13) given by [23] as;

$$P_{BS} = N_{TRX}\,(P_o + \Delta_P P_{\max} K), 0 \le K \le 1 \quad (13)$$

In (13), N_{TRX} is the number of transceivers, P_O is the power consumption at zero traffic; Δ_p is a constant for a given BS; P_{max} is the output of the power amplifier at maximum traffic; while K denotes the normalized traffic at any given time.

Several authors have utilized the models above to harvest the energy needed to support a mobile cellular BS. However, it is important to carry out a feasibility study to prevent over budgeting of energy or to produce insufficient energy to power a BS site [9-10, 23]. As already established by many research work, solar radiation is location dependent. As such, the solar radiation parameters are important [9-14, 23]. The solar radiation data are often provided by each nations' weather agency or obtained via NASA website. Thus, we need to examine the availability of solar in South Africa.

III. South Africa Current Solar PV Powered Mobile Cellular BS Utilization

Out of about 42, 951 already deployed solar-powered base stations (BSs) globally as at 2014, South Africa has about 23 stations [27]. There should be a drive for more solar powered BS given the abundant resource at the disposal of the country. South Africa occupies a land mass of 12196022 km between the latitudes of 2200S 3500S and longitudes of 1700E 3300E. The geographical coordinates enable the country to have an abundance of solar radiation which can be used to provide clean and renewable energy to different consumer categories. Looking closely at this resource, the installed capacity is expected to reach 8400 MW by the year 2030. Latest solar maps of South Africa in Fig. 3 and Fig. 4, created by Stellenbosch University, in cooperation with GeoSUN Africa and GeoModel Solar, shows both Direct Normal Irradiation (DNI) and Global Horizontal Irradiation (GHI) in different regions of South Africa [26].

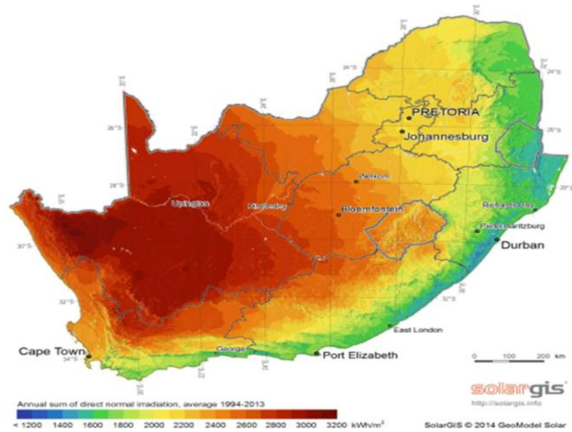

Fig. 3: Direct Normal Solar Irradiation (DNI) map of South Africa, Lesotho and Swaziland [26]

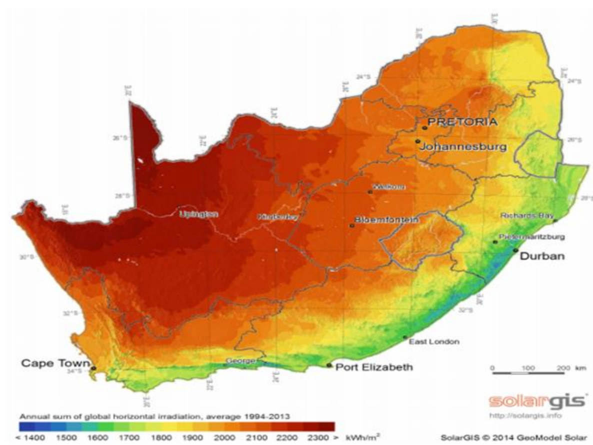

Fig. 4: Global Horizontal Solar Irradiation (GHI) map of South Africa, Lesotho and Swaziland [26]

Both Fig. 3 and Fig. 4 reveal 3% increase per year in GHI and about 10% yearly increase in DHI with Northern Cape having the highest DNI of 3200 kWh/m^2 per annum [26]. Furthermore, most areas in the South African region has more than an average sunshine of 2500 hours yearly, and more than an average daily solar radiation level between 4.5 kWh/m^2 and 6.5 kWh/m^2 [26]. When this average daily solar radiation is compared to a country such as South Korea with daily solar average estimation of between 4.01 kWh/m^2 to 5.622 kWh/m^2 [9] where solar PV powered BS is widely deployed, it shows that it can be achieved here in South Africa as well. Although, there are many solar plant stations within the country such as; (i) 75 MW Kalkbult solar power station located near Petrusville in the Northern Cape; (ii) 75 MW Lesedi solar power project near Kimberley; (iii) 75 MW Letsatsi Solar Power Project near Bloemfontein; (iv) 96 MW Jasper located in the Northern Cape; (v) 75MW Kathu Solar PV facility also based in the Northern

Cape; and (vi) Sishen Solar Energy Facility. However, more needs to be done in the telecommunication sector.

IV. Case Study of Telco Base Stations

In a case study carried out by Cellstrom Company of GmbH, in [28] for Telco BS of South Africa, the authors showed how much cost can be saved using solar PV powered BS. It was carried out on a BS having a DC load profile of 1 kW 48 V for 24hrs, and AC profile load of 2 kW 240 V between 6 am to 10 pm, using their FB10/100 solar PV storage product, as shown in Fig. 5.

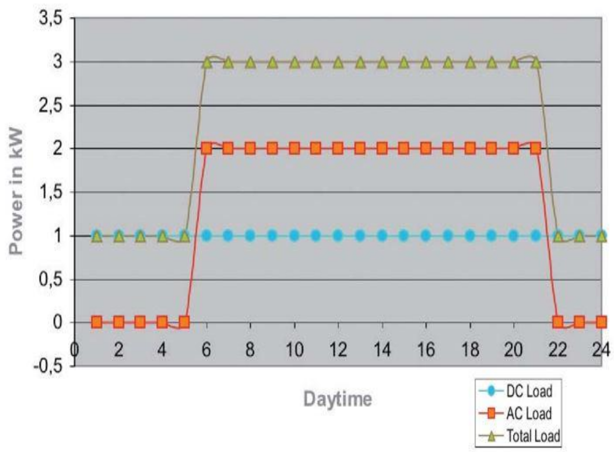

Fig. 5: Solar powered BS load profile [28].

For a solar PV installation of 15 kWp capacity by FB10/100 from Cellstrom, this can replace 12 diesel generating sets in a mobile cellular site over a period of 20 years. Thus, leading to about 203,000 liters of diesel saving. Comparing this to using diesel generating set as a power backup, it is a huge reduction in the cost of operation [28].

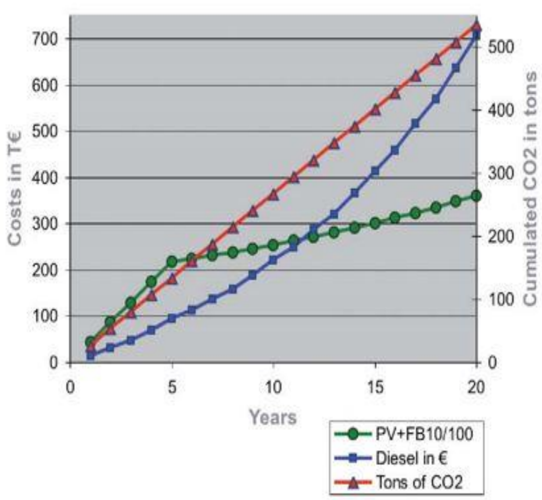

Fig. 6: Cost of operation comparison between the solar PV and diesel [28].

As seen in Fig. 6 over the period of 20 years, there will be significant steady growth on the cost incurred using diesel, which will consequently lead to increase in emission of carbon dioxide. To Compare diesel with using the solar PV, there will be an initial high cost on the purchase of the solar PV system. But, this will be recovered and thus, leads to more gain over the period of 20 years as seen in Fig. 6. Operating cost comparison for running the solar PV powered mobile cellular BS and the diesel generating set is given in TABLE I

TABLE I. OPERATING COST COMPARISON BETWEEN THE SOLAR PV AND DIESEL [28].

20 years	Diesel in €	PV+FB10/100
Capital invests. For 60 months' lease	9,368	188,690
Replacement cost	12	0
Repl. Cost val. 5 %	78,861	99,198
Operation and maintenance 5 %	34,719	66,132
Fuel val. 5 %	582,200	0
Insurance val. 5 %	1,984	6,613
Total cost	707, 144	360,633

As observed in TABLE I, there is a total sum of €346,511 amount gained by using solar PV on one station. According to [29], R/€ exchange rate is R15.1922. This show that a total sum of R5,264, 264.414 will be saved on a BS, using a solar PV system. This is about 49 % gain on a single BS. If this is applied to other stations, there will be more gain for the operator of the BS. This will bring about a reduction in the cost of operation, increase profit, and reduction in the cost of mobile data for the subscribers of mobile services.

V. Conclusion

This study has been able to provide an insight into the potential ability of South Africa to switch from traditional BS into solar PV powered BS. South Africa with daily solar radiation estimation of between 4.5 kWh/m2 and 6.5 kWh/m^2 as compared to South Korea of daily solar radiation estimation of 4.01 kWh/m^2, has a potential to develop into a country of solar PV powered BS. In this work, the potential solar capacity of South Africa was provided. An example cited was the 49 % difference in the favor of solar PV powered mobile cellular BS as compared to the traditional usage of diesel generating set powered BS over a period of 20 years as seen in TABLE I [28]. Thus, one can encourage more investment into solar PV powered mobile cellular BS. In conclusion, the solar PV powered BS is an economically attractive option in the long term as compared to other sources of power for a mobile cellular network operation.

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