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Article

Powering Mobile Networks with Optimal Green Energy for Sustainable Development

Mohammed H. Alsharif[1], Mahmoud A. Albreem[2], Abu Jahid[3], Kannadasan Raju[4], Peerapong Uthansakul[5,*], Jamel Nebhen[6], Venkatesan Chandrasekaran[4] and Ayman A. Aly[7]

[1]Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, Gwangjin-gu, Seoul, 05006, Korea
[2]Department of Electronics and Communications Engineering, A'Sharqiyah University, Ibra, 400, Oman
[3]Department of Electrical and Computer Engineering, University of Ottawa, Ottawa, K1N 6N5, ON, Canada
[4]Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Sriperumbudur, Chennai, 602117, India
[5]School of Telecommunication Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand
[6]Prince Sattam Bin Abdulaziz University, College of Computer Engineering and Sciences, Alkharj, 11942, Saudi Arabia
[7]Department of Mechanical Engineering, College of Engineering, Taif University, Taif, 21944, Saudi Arabia
[*]Corresponding Author: Peerapong Uthansakul. Email: uthansakul@sut.ac.th
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Abstract: Green wireless networking is an emerging area for many societies, especially academia and industry, in light of economic and ecological perspectives. Empowering wireless infrastructures exploiting green power sources can enhance sustainability due to the adverse effects of conventional power sources and atmospheric circumstances. Moreover, the specific power supply requirements for a base station (BS), such as cost effectiveness, efficiency, sustainability, and reliability, can be met by utilizing technological advances in renewable energy. Numerous drivers and motivators are involved in the deployment of renewable energy technologies and the transition toward green energy. Renewable energy is free, clean, and abundant in most locations throughout the year. In this work, a sustainable optimal stand-alone solar-powered model envisioning green cellular BSs for urban locations in Oman is proposed. This model can extend 24 h uninterrupted power supply support to a cellular BS that fully utilizes an integrated storage device. The system analysis is conducted using a hybrid optimization model for electric renewables (HOMER) based on actual prevailing conditions of the regions and their technical feasibility. The results showed can be achieved operational expenditure savings up to 16%. These outcomes provide a huge benefit to the cellular operators of Oman economically, technically, and ecologically.

Keywords: Wireless networks; green wireless networks; green communications; sustainability; OPEX

1 Introduction

The energy consumption rate of information and communication technology (ICT) has increased rapidly over the last few decades owing to the excessive demand for multimedia services. Wireless networks are considered one of the main sources of energy consumption in the ICT arena [1]. Among the wireless network components, base stations (BSs) are considered a paramount source of energy consumption, which accounts for 57% of the total energy used [2]. In the last decade, wireless network operators have focused on providing a high data transfer rate with large radio coverage to satisfy the demand of subscribers. Therefore, wireless network operators have largely increased the BS numbers to deliver a high data rate to enormous wireless devices and access point nodes. Consequently, the energy consumption and operational expenditure (OPEX) have notably increased, that is, it has linearly scaled with the augmentation in intensive user requirements [3]. The massive connectivity of IoT devices incorporated with wireless access networks currently leads to tremendous energy consumption; it is expected to increase enormously in the future due to the diverse types of IoT applications [4]. Thus, the primary focus of wireless network operators is to provision a high data rate with attention to energy-efficient issues. Moreover, the increasing concern of wireless network operators on energy consumption is to increase savings in OPEX due to the growing awareness of global warming issues and ecological concerns [5]. Therefore, researchers and experts are endeavoring to apply approaches for diminishing the power consumption, notably for wireless networks while ensuring desired data services.

Researchers are focusing on numerous distinctive approaches to reduce energy consumption into wireless networks, such as energy-efficient hardware components, selective operation of components, efficient use of radio transmission processes, deployment of heterogeneous cells, and implementation of renewable energy resources (RESs) [6]. RESs are considered the most attractive practices in designing energy-efficient wireless networks over the long term in a cost-efficient way in existing infrastructures [7].

Researchers have suggested a mixture of various RESs or non-RESs with RESs to overcome the limitations of a single technology. For instance, researchers have recommended a combination of an electric grid with RESs or a single RES with adequate battery storage devices to empower access networks in wireless infrastructures. Tab. 1 summarizes the research investigations on renewable energy powered BSs.

The integration of a diesel generator (DG) with an RES can overcome single renewable energy source-related problems. However, fuel transportation is comparatively challenging at several sites that considerably increase the OPEX apart from toxic gas (CO_2) emissions. Meanwhile, hybrid utilization of RES with an on-grid is presented to warrant a reliable power supply to the BSs. The optimal conditions, key challenges, and viable solutions are suggested to extract the maximum power from RES to reduce the grid pressure. However, utilization of power from the electric grid, that is, conventional power production such as burning fossil fuels, extensively generates greenhouse gases and increases global warming. Therefore, researchers have recommended the hybridization of various RESs, such as solar PV, wind turbines, and biomass generator-based energy production.

Table 1: Summary of research investigations on renewable energy powered BSs

Site	Reference	Year	Technique
On-grid	[8]	2019	Distributed online energy management
	[9]	2019	Energy cooperation
	[10]	2018	Energy cooperation
	[11]	2020	Energy sharing
	[12]	2015	Green energy system sizing algorithm
	[13]	2015	Joint battery management and power allocation
	[14]	2015	Energy cost minimization of heterogeneous network
	[15]	2015	Decentralized energy allocation optimization
	[16]	2015	Low-complexity online algorithm
	[17]	2018	Energy cooperation
Off-grid	[18]	2020	Solar PV and biomass resource system
	[19]	2019	RRM and integration with smart grid
	[20]	2019	RE management with JT-CoMP technique
	[21]	2018	Parameter quantization
	[22]	2016	Resource dimensioning with RoD strategies
	[23]	2019	Power supply solutions for off-grid BSs
	[24]	2014	Adaptive resource management and distributed admission control
Combination of on-grid and off-grid	[25]	2019	Resource dimensioning with SWM data model
	[26]	2019	Distributed reinforcement learning
	[27]	2019	Load control with SCBS on–off switching
	[28]	2016	Load control with SCBS on–off switching
	[29]	2020	Traffic offloading and BS on–off switching

The desired zone for PV-powered BSs is usually in the mid-latitudes between 30° north and south. Specifically, low latitudes are recognized as the most profitable regions for PV-based BSs [2]. Considering all the aforementioned inferences, researchers have insufficiently described the total OPEX savings due to RESs. Therefore, in this study we are using solar power solution for LTE-BSs in Oman's off-grid locations to determine the net OPEX savings. Oman is positioned at latitudes between 16°40′ and 26°20′ north and longitudes between 51°50′ and 59°40′ east [30]. Fig. 1 shows the solar radiation map of Oman.

The implementation of a PV system requires intensive study due to its diverse design and uncertainty of solar parameters, such as the dynamic rate of solar irradiation that extends additional complications due to its intermittent, seasonal, and uncertain nature. To overcome these issues, the HOMER model is used by creating energy balance schemes for every hour of 8,760 h per year. Moreover, it compares the actual load demand for every hour with the generated energy. It also manages the charging and discharging features of the batteries and computes the installation and operating cost for the complete lifespan of the project. Considering all these advantages, HOMER software is adapted in this work to achieve the techno-economic feasibility of solar-driven LTE-BS. The contributions of this work are summarized as follows:

(i) To propose and determine the technical benchmarks for an optimal stand-alone solar system that guarantees energy autonomy for the BSs in urban areas of Oman.

(ii) To obtain a long-tenure energy balance for cellular networks based on the available solar irradiation in Oman that warrants sustainable green wireless networks.
(iii) To examine, analyze, and evaluate the viability of a stand-alone solar system for maximum energy yield and economic savings.

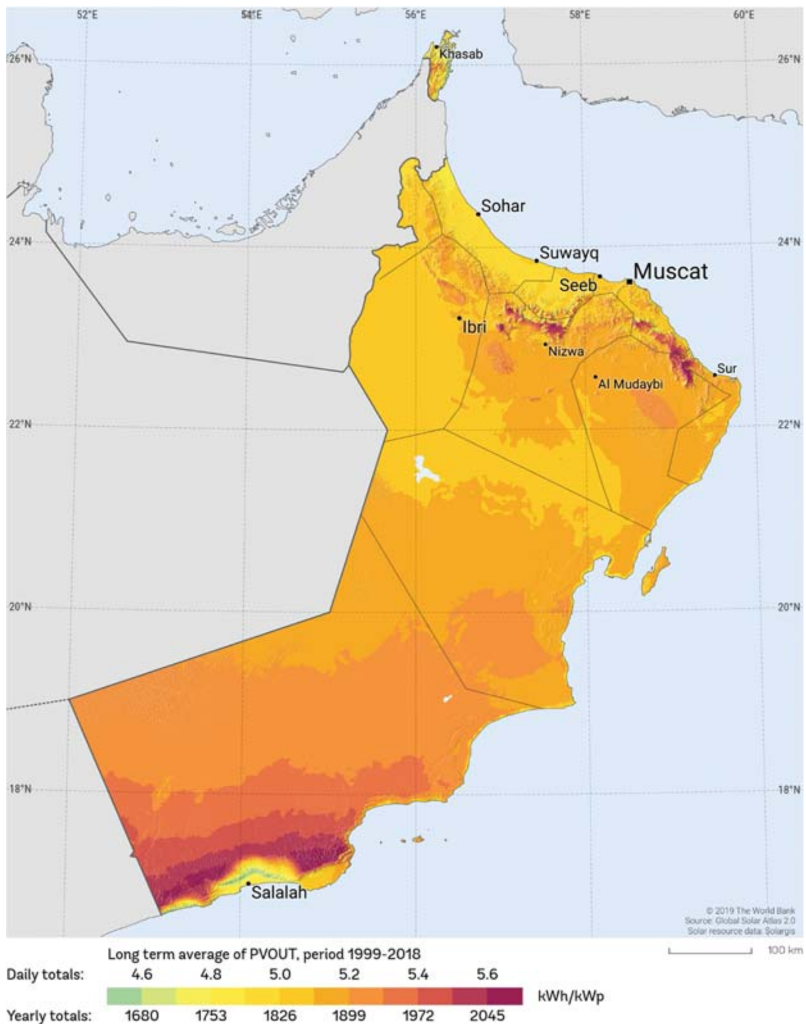


Figure 1: Solar radiation map of Oman

2 Proposed System and Mathematical Modeling

The proposed system comprises three segments, namely, sources, converters, and loads, as demonstrated in Fig. 2.

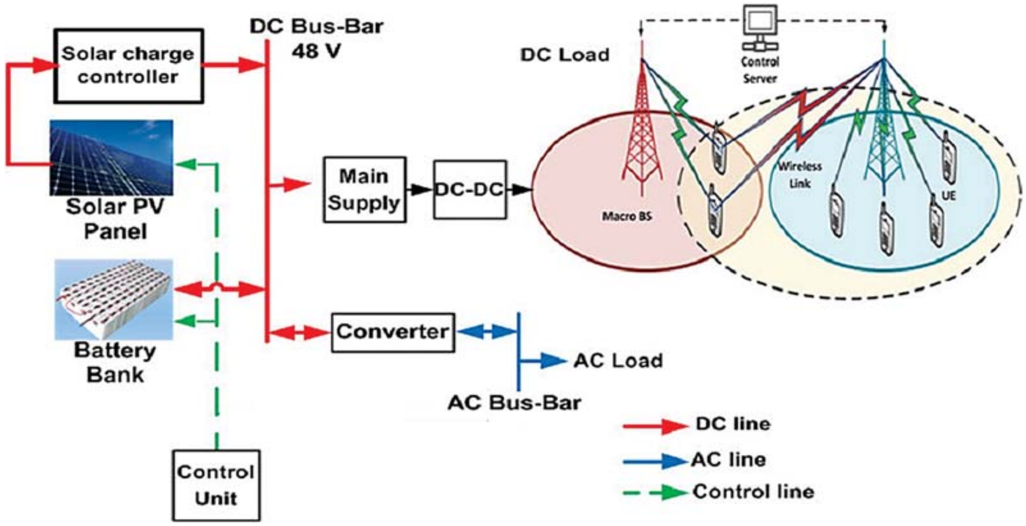


Figure 2: Schematic of the proposed system

2.1 Macro LTE-BS Subsystem

The cellular BS consists of various types of equipment that can be used to communicate with mobile/cellular units. The backhaul network has the following subunits: (i) multiple transceivers (TRXs), (ii) power amplifier (PA), (iii) radio frequency (RF), (iv) baseband (BB), (v) DC–DC power supply, and (vi) cooling systems. The TRXs comprise PA, which amplifies the signal power coming from the BB unit. The BB is adapted for internal processing and coding. A detailed of discussion in [2].

A macro BS subsystem has three sectors with two antennas based on the component level [31]. The net power consumption by the BS is derived through the following equation [31]:

$$P_{BS} = \frac{N_{TRX}\left(P_{PA}^{DC} + P_{RF}^{DC} + P_{BB}^{DC}\right)}{(1-\sigma_{DC})(1-\sigma_{cool})} \quad (1)$$

where N_{TRX} denotes the number of transmitting/receiving antennas for individual sites, that is, transceivers; P_{PA}^{DC}, P_{RF}^{DC} and P_{BB}^{DC} denote the power amplifier, radiofrequency, and baseband power, respectively. The power loss factors are approximated to be $\sigma_{DC} = 6\%$ and $\sigma_{cool} = 10\%$ for converters and air conditioners, respectively.

Tab. 2 presents the power consumption scale of the macro BS system with a 2×2 MIMO and 3 sectors.

2.2 Solar System

This system comprises several types of equipment that effectively generate green energy for a complete BS. It also saves energy and allows ease of dismantling for recycling.

Table 2: Power consumption scale of different hardware elements at bandwidth equal to 10 MHz [31]

Elements	Parameters	Unit	Macro LTE-BS
PA	P_{PA}^{DC}	Watts	102.6
RF	P_{RF}^{DC}	Watts	10.9
BB	P_{BB}^{DC}	Watts	14.8
Loss factor (σ_{DC})		%	6.0
Loss factor (σ_{cool})		%	10.0
$Total\ power/TRX = \frac{P_{PA}^{DC} + P_{RF}^{DC} + P_{BB}^{DC}}{(1-\sigma_{DC})(1-\sigma_{cool})}$		Watts	151.65
No. of transceivers $N_{TRX} = N_{Sect} \times N_{Ant} \times N_{Carr}$			6
Total power of the BS $P_{BS} = N_{TRX} \times Total\ power/TRX$		Watts	909.93

2.2.1 Photovoltaic Panels

Each panel consists of numerous solar cells that are connected in series and parallel to form a solar module or PV arrangement. The panel generates DC electric power through the absorption of shortwave irradiance. The total annual energy extraction from the PV arrangement (E_{PV}) is derived as [32]

$$E_{PV} = \mathrm{PC}_{PV} \times PSH \times DF_{PV} \times 365\ day/year, \tag{2}$$

where PC_{PV} is the size of the PV and PSH denotes the peak solar hour. DF_{PV} is a derating factor of the PV array, which considers the effect of dust and other losses.

2.2.2 Battery Bank

A solar power-driven macro LTE-BS consists of a battery bank that is allowed to charge during a sunny period with the excess power generated by the PV arrays. The BESS capacity of the BS merely depends on the depth of discharge (DOD) and must be evaluated before commissioning [33]

$$DOD = 1 - \frac{SOC_{\min}}{100}, \tag{3}$$

where SOC_{min} denotes the minimum state of charge (SOC). In this work, the Trojan L16P battery model is considered because the DOD of this battery is 70%, that is, it can effectively deliver 70% of its energy with 30% of its energy reserved. The computation of days of autonomy (A_{batt}) is essential to determine the performance of fully charged batteries. It is derived as [33]

$$A_{batt} = \frac{N_{batt} \times V_{nom} \times Q_{nom} \left(1 - \frac{SOC_{\min}}{100}\right)(24\ h/d)}{L_{prim-avg}\,(1000\ Wh/kWh)}, \tag{4}$$

where the terms N_{batt} and V_{nom} are the total number of battery units in the BESS and the nominal voltage of a single battery unit, respectively. The terms Q_{nom} and $L_{prim,ave}$ are the nominal capacity of a single battery and average daily BS load, respectively.

The lifetime of the battery plays a crucial role. The lifetime of a battery can be predicted based on the operating conditions. Specifically, the DOD during each diurnal charge–discharge cycle plays a foremost role in the battery lifetime. It can be computed as [34]

$$R_{batt} = \min\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right), \tag{5}$$

where the term $Q_{lifetime}$ represents the lifetime throughput of a single battery, Q_{thrpt} denotes the annual battery throughput, and the term R_{battf} is the battery float life in years.

2.2.3 Inverter

The total capacity of the inverter (C_{inv}) is calculated as [35]

$$C_{inv} = \left(\frac{L_{AC}}{\eta_{inv}}\right) \times \sigma_{sf}, \tag{6}$$

where the term L_{AC} represents the available maximum AC load; η_{inv} and σ_{sf} are the inverter efficiency and safety factor, respectively.

3 Cost Optimization Formula

The configuration of a solar-powered BS is based on the following considerations: (i) the essential components that must be involved in the system design, (ii) the number of components that must be adopted, and (iii) the size of each element. The HOMER micropower optimization tool aids are used to obtain an optimal system with low net present cost (NPC). The term NPC contains all incurred expenses and incomes throughout the project lifetime. The total annualized cost (C_{TAC}) exemplifies the annual price of the complete scheme in \$/year that contains the initial capital (IC) costs ($\mathrm{C}_{TAC}^{cap}\mathrm{C}_{\mathrm{ann}}^{\mathrm{cap}}$), replacement costs ($\mathrm{C}_{TAC}^{rep}\mathrm{C}_{\mathrm{ann}}^{\mathrm{rep}}$), and O&M costs ($\mathrm{C}_{TAC}^{o\&m}\mathrm{C}_{\mathrm{ann}}^{\mathrm{O\&M}}$). The complete description of the cost can be expressed mathematically as [36]

$$C_{TAC} = C_{TAC}^{cap} + C_{TAC}^{rep} + C_{TAC}^{o\&m}, \tag{7}$$

The NPC (C_{NPC}) can also be described for annualized values and can be derived as

$$C_{TAC} = C_{NPC} \times CRF\,(i, N)\,, \tag{8}$$

The term CRF denotes the recovery factor, which converts a C_{NPC} into a flow of equal annual costs over a definite period. It can be calculated based on the annual interest rate (i) and project lifespan (N), and it is computed using the following equation [34]:

$$CRF\,(i, N) = \frac{i\,(1+i)^N}{(1+i)^N - 1}, \tag{9}$$

The total NPC value is notably reduced due to the salvage value (S), which can be computed using the following equation:

$$S = C_{rep}\frac{R_{rem}}{R_{comp}}, \tag{10}$$

where R_{comp} defines the lifespan and R_{rem} denotes the remaining lifespan of the component in years; and the term C_{rep} is the replacement rate.

This study scrutinizes to minimize the total cost of NPC based on various constraints. To attain system optimization, the objective function of the NPC can be derived using Eq. (8) and formulated as

$$\min_{E_{PV}, E_{Battery}, E_{Losses}, E_{BS}} \frac{C_{TAC}}{CRF\,(i,\, N)}. \tag{11}$$

The above-derived objective function is subjected to the following constraints:

$$E_{Battery} + E_{PV} > 0, \tag{11.1}$$

$$E_{Battery} + E_{PV} \geq E_{BS} + E_{Losses}. \tag{11.2}$$

To warrant a power balance between actual demand and energy production, the power production of the sources (E_{PV} and $E_{Battery}$) must meet the demand of the BS (E_{BS}) plus losses (E_{Losses}).

4 Simulation Configuration

The simulation consists of three major parts: inputs, optimization, and outputs. The simulation configuration details are given in Tab. 3. In addition, solar irradiance for the various urban cities of Oman that are considered in this study is given in Fig. 3.

Table 3: Simulation configuration

Components	Parameters	Range
Control factors	Annual interest rate (January 2021)	1.0%
	Project lifespan (N)	10 years
PV	Sizes	2, 2.5, 3, 4, 4.5, 5, 6 kW
	Operational lifetime	25 years
	Efficiency	85%
	IC	\$1/Watt
	Replacement	\$1/Watt
	O&M price per year	\$0.01/Watt
Inverter	Sizes	100, 200, 300, 400 W
	Efficiency	95%
	Operational lifespan	15 years
	IC	\$0.4/Watt
	Replacement	\$0.4/Watt
	O&M price per year	\$0.01/Watt
Trojan L16P battery	Number of batteries	24, 32, 40, 64, 72
	Round trip efficacy	85%
	Minimum operational lifespan	5 years
	IC	\$300
	Replacement	\$300
	O&M price per year	\$10

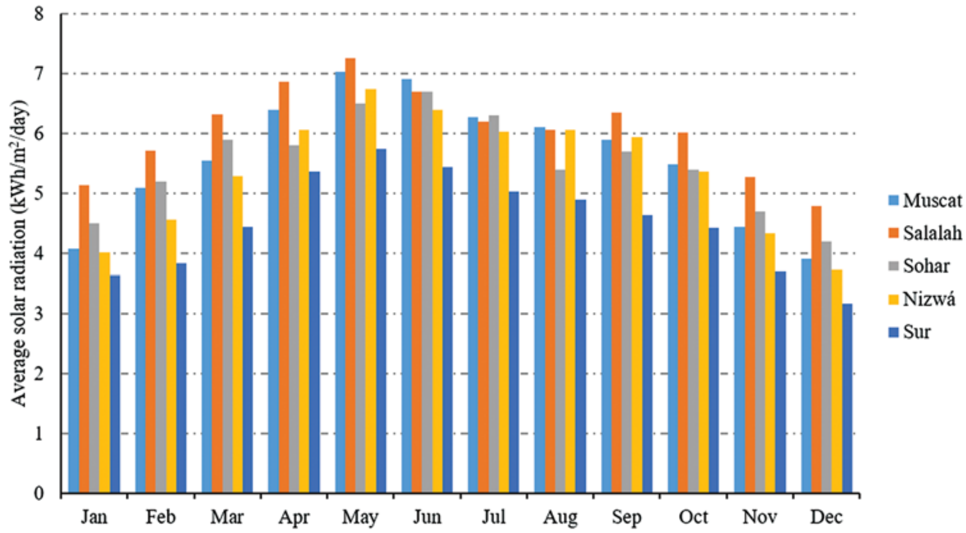


Figure 3: Solar irradiance for the various urban cities of Oman (monthly average) [30]

5 Results and Discussion

A sustainable optimal solar system envisioning green cellular BSs for urban cities of Oman is considered. This model can extend 24 h uninterrupted power supply support to the cellular BSs that fully utilize the integrated storage device. The details are given as follows.

5.1 System Architecture

Tab. 4 provides a brief comparison summary of the optimal system and NPC for green cellular BSs for urban cities of Oman.

Table 4: Optimal system and NPC of the proposed system

Optimal sizing				Costs
City	PV (kW)	Battery (unit)	Inverter (kW)	NPC ($)
Muscat (Capital)	4.0	64	0.10	27,637
Salalah	4.0	64	0.10	27,637
Sohar	4.5	64	0.10	27,930
Nizwá	4.5	64	0.1	27,930
Sur	5.0	64	0.10	28,137

As observed, the system architecture for some cities is the same size because the solar radiation rate in these cities is nearly the same. However, the energy contribution from the PV array differs from these cities due to the difference in the slight solar radiation. The contribution of energy from the PV increases with the increase in radiation rate. Details of this trend will be given in Subsection 5.2 "Energy analysis."

NPC is proportional to the size of the components of the solar system. Thus, a large part of the cost goes to the BESS. Meanwhile, the NPC decreases when the size of the PV array decreases, that is, when the solar radiation increases. Additional details will be provided in Subsection 5.3 "Economic analysis."

5.2 Energy Yield Analysis

Fig. 4 summarizes the PV array size and annual energy contribution to various cities. Higher solar radiation rates correspond to higher annual energy contributions for the same PV array size. Fig. 5 shows the annual energy input and output of the battery bank/BESS for the various cities. However, a detailed discussion and analysis of the energy yield will be given for Muscat city, which is the capital and largest city with a higher population. However, the investigation can be extended to include other metropolitan cities with small variances in solar irradiation.

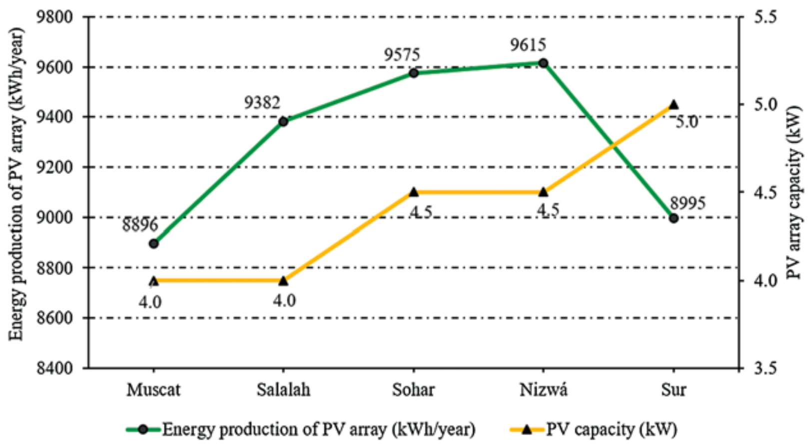


Figure 4: PV array size and annual energy contribution

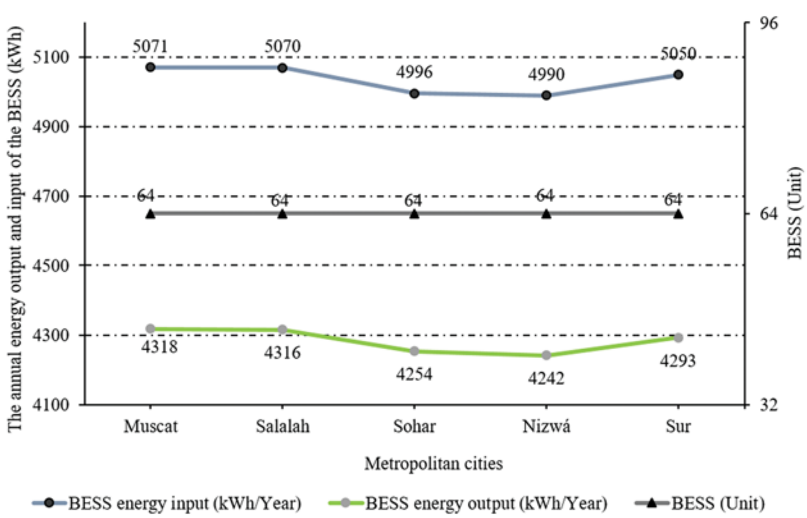


Figure 5: BESS units and annual energy input/output

The annual energy contribution of the PV array for Muscat is calculated based on Eq. (2); the PV peak capacity 4.0 kW $\times$ peak solar hours 5.6 h $\times$ PV derating factor 0.85 $\times$ 365 days/year, which equals 6950 kWh. Furthermore, the generated energy increases up to 28%, that is, 8896 kWh more annually due to using a dual-axis tracking system. This energy yield also meets the losses incurred in the system. The system has BESS and inverter losses of approximately 757 and 42 kWh, respectively. It supplies the power to the BS load (7972 kWh) and results in annual excess energy up to 125 kWh, that is, 1.41% of the total energy generation. Fig. 6 shows the monthly average output power generated by the PV array. The lowest output power contribution from the PV array is observed at the end of July and the first of August.

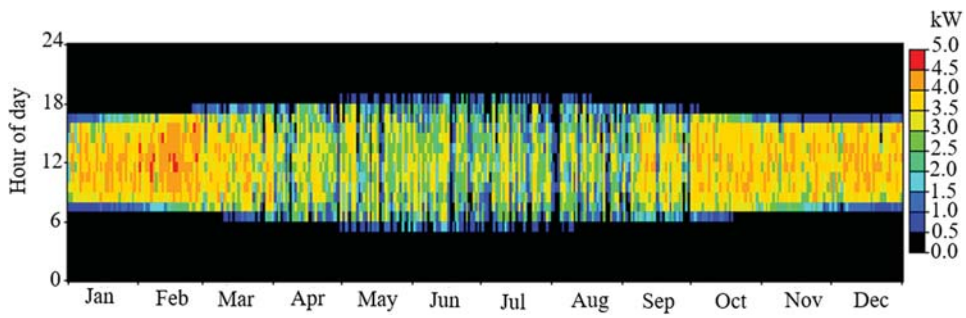


Figure 6: Average PV output power (monthly)

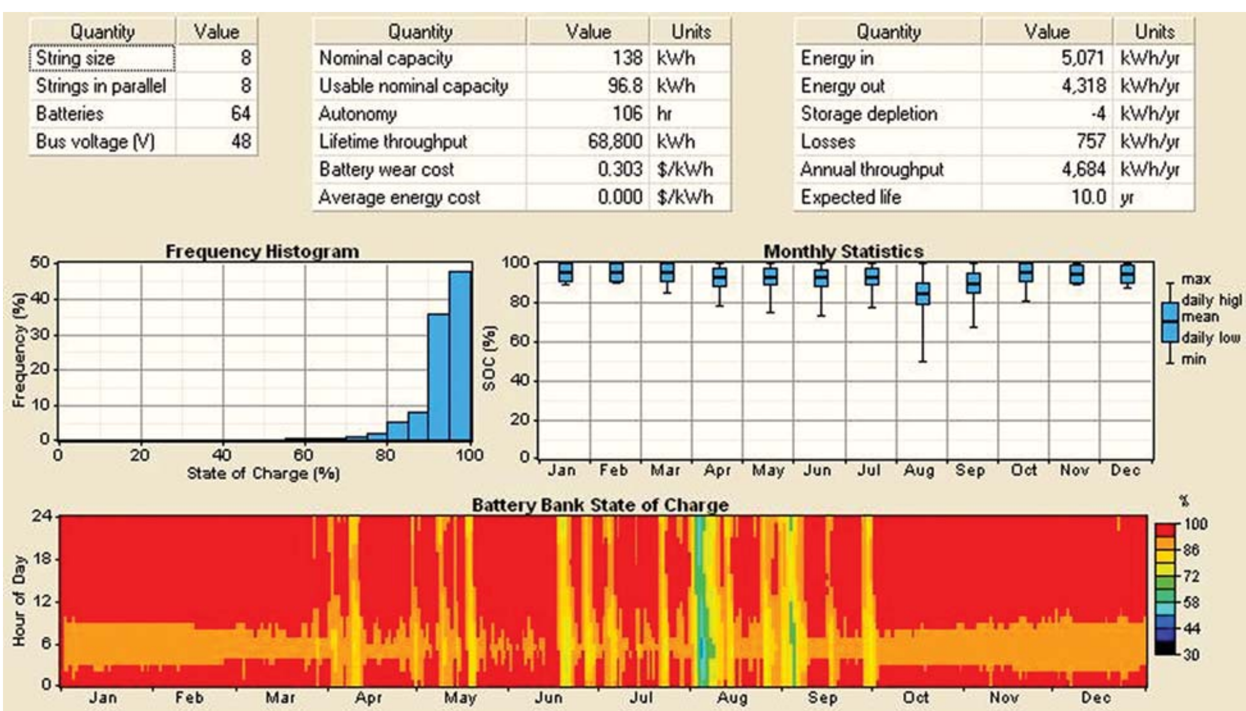


Figure 7: Summary of the BESS

The ratios of annual energy output and input of BESS are 5071 and 4318 kWh, respectively. Moreover, the BESS supplies the power to the load for nearly 106 h, specifically during the malfunction of the PV array. Fig. 7 summarizes the BESS results. The seasonal statistics show that the maximum energy contribution of the BESS is in August, while the minimum energy contribution is in February. The frequency histogram of the SOC shows that the SOC stretches to 46%.

The average hourly energy generation of the PV, BESS, and excess electricity for 12 months is presented in Fig. 8. The lowest rate of energy contribution from the PV array is observed at the end of July and the first of August; therefore, the higher rate of energy contribution from BESS is in the same period.

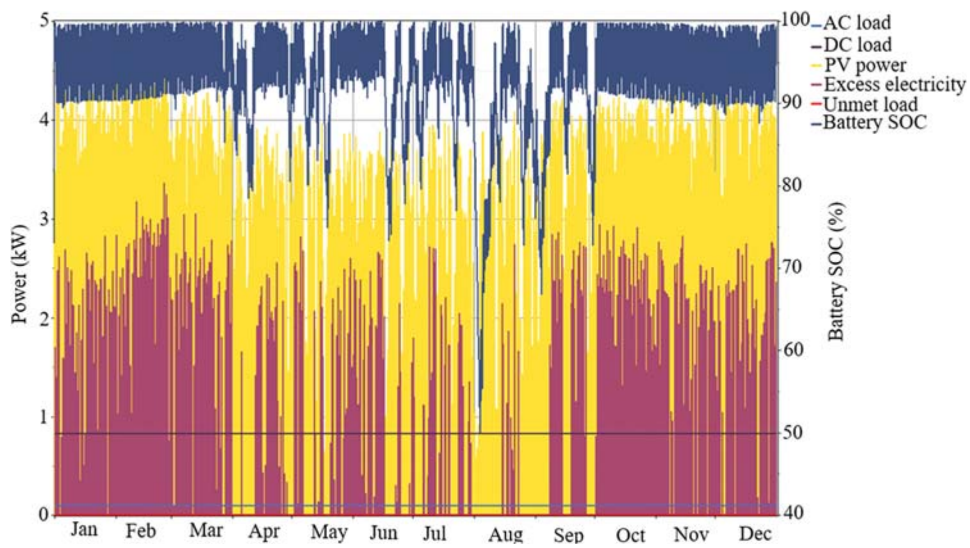


Figure 8: Average hourly energy generation of the PV, BESS, and excess electricity

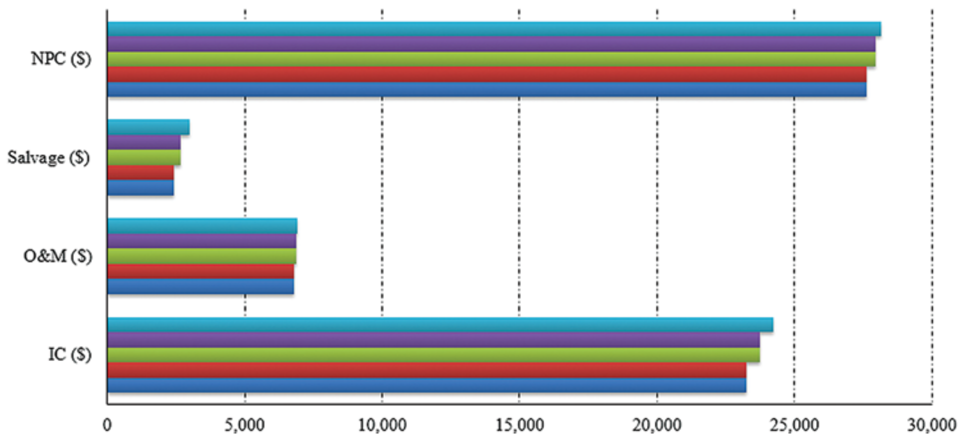
The net capacity of the inverter unit is 0.1 kW. The efficiency of the inverter unit is computed between the input (837 kWh) and output energy (795 kWh) annually and observed at 95%. The total operating hours are 8,759 h/year (24 h × 365 days/year).

5.3 Economic Analysis

Fig. 9 summarizes the total cash flow of the proposed solar system for the different urban cities. For costs, the IC cost of a solar system for some cities is fixed because the optimal system size is the same. For O&M cost, most of this cost goes toward BESS. Tab. 4 indicates that the operating cost decreases in cities that have increasing solar radiation because the PV array size decreases, which reduces the total O&M cost of the solar system. The NPC represents all costs that occur within the project lifetime. The following discussion and analysis will be given based on the capital city (Muscat). However, this investigation can also be extended to other schemes where the system cost depends on the individual component size.

The size of the system is directly proportional to the IC cost invested during the commencement of the scheme. The total IC cost of the proposed scheme is \$23,240, and its breakdown is detailed as follows:

a) For solar PV arrays (i.e., 4.0 kW (size) × \$1,000/1 kW (cost) = \$4000).
b) For BESS arrangements (64 (units) × \$300/unit (cost) = \$19,200).
c) For inverter (0.1 kW (size) × \$400/1 kW (cost) = \$40).



	IC ($)	O&M ($)	Salvage ($)	NPC ($)
Sur	24,240	6910	3013	28,137
Nizwá	23,740	6860	2670	27,930
Sohar	23,740	6860	2670	27,930
Salalah	23,240	6810	2413	27,637
Muscat	23,240	6810	2413	27,637

Figure 9: Summary of the total cash flow of the proposed solar system for the different urban cities

The O&M costs of the solar system are considered to be \$6810, and its breakdown is detailed as follows:

a) For solar PV arrays (i.e., 4.0 kW (size) × \$10/1 kW (cost) × 10 years (project lifetime) = \$400).
b) For BESS arrangements (64 (units) × \$10/unit (cost) × 10 years (project lifetime) = \$6400).
c) For inverter (0.1 kW (size) × \$10/1 kW (cost) × 10 years (project lifetime) = \$10).

The lifespans of the BESS, PV arrays, and inverter are 10, 25, and 15 years, respectively, due to the short operational lifespan of the project (10 years). No replacement costs are incurred.

The salvage value of each component at the end of the project lifespan has to be considered. With the help of Eq. (10), the salvage value of the PV array is computed and found to be \$2400, which is the highest value among those of other components. The salvage value of the inverter is estimated at \$13. Therefore, the total salvage value at the end of the venture lifespan is \$2413.

The net NPC is \$27,637, that is, \$23,240 (IC) + \$6810 (O&M prices) − \$2413 (salvage). Fig. 10 summarizes the total cash flow of the proposed solar system for Muscat.

	Component	Category	Year 0	1	2	3	4	5	6	7	8	9	10	Total
Nominal	PV	Capital	-4,000	0	0	0	0	0	0	0	0	0	0	-4,000
		Replacement	0	0	0	0	0	0	0	0	0	0	0	0
		Salvage	0	0	0	0	0	0	0	0	0	0	2,400	2,400
		Operating	0	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-400
		Fuel	0	0	0	0	0	0	0	0	0	0	0	0
		Total	-4,000	-40	-40	-40	-40	-40	-40	-40	-40	-40	2,360	-2,000
	Trojan L16P	Capital	-19,200	0	0	0	0	0	0	0	0	0	0	-19,200
		Replacement	0	0	0	0	0	0	0	0	0	0	0	0
		Salvage	0	0	0	0	0	0	0	0	0	0	0	0
		Operating	0	-640	-640	-640	-640	-640	-640	-640	-640	-640	-640	-6,400
		Fuel	0	0	0	0	0	0	0	0	0	0	0	0
		Total	-19,200	-640	-640	-640	-640	-640	-640	-640	-640	-640	-640	-25,600
	Converter	Capital	-40	0	0	0	0	0	0	0	0	0	0	-40
		Replacement	0	0	0	0	0	0	0	0	0	0	0	0
		Salvage	0	0	0	0	0	0	0	0	0	0	13	13
		Operating	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-10
		Fuel	0	0	0	0	0	0	0	0	0	0	0	0
		Total	-40	-1	-1	-1	-1	-1	-1	-1	-1	-1	12	-37
	Entire system	Capital	-23,240	0	0	0	0	0	0	0	0	0	0	-23,240
		Replacement	0	0	0	0	0	0	0	0	0	0	0	0
		Salvage	0	0	0	0	0	0	0	0	0	0	2,413	2,413
		Operating	0	-681	-681	-681	-681	-681	-681	-681	-681	-681	-681	-6,810
		Fuel	0	0	0	0	0	0	0	0	0	0	0	0
		Total	-23,240	-681	-681	-681	-681	-681	-681	-681	-681	-681	1,732	-27,637

Figure 10: Average PV, battery bank, and excess electricity output (hourly)

5.4 Economic Feasibility of the Proposed Solar System

The rating of DG should be approximately 3.5 kW, which can be computed between the ratio of maximum BS and 30% DG efficiency × converter efficiency of 95%. The net NPC is computed and recorded as \$32,900. It is observed using the summation process of \$2,310 (IC) + \$23, 660 (O&M) + \$6, 930 (replacement costs). The abovementioned costs are described in detail as follows:

(i) The IC is computed by multiplying the system size (3.5 kW) by its cost (\$660/kW).

(ii) The O&M cost (annual) of the DG is approximately \$2,366 (excluding fuel transportation cost). A breakdown of this cost is described as

- The net maintenance cost of DG is \$438/year, which is estimated using the product of a DG maintenance \$0.05/h and the annual operating hours (8,760 h).
- The total fuel cost is computed using the product of diesel price (\$0.54/L) and total diesel consumption (3,569 L/year) and found to be \$1,928. It is calculated based on specific fuel consumption (0.388 L/kWh) × annual electrical generation by the DG (9,198 kWh/year, that is, the product of DG size [3.5 kW] and its efficiency [0.3 × 24 h × 365 days/year]). Therefore, the net O&M cost for the complete project lifespan is estimated to be \$23,660.

(iii) Every 3 years, the DG needs to be replaced, that is, a minimum of three (3) times during the lifespan of the project. Therefore, the net DG replacement cost is equal to \$6,930, that is, 3 × 3.5 kW × \$660/kW.

When the proposed solar system is applied, OPEX savings between 14.5% and 16.0% can be achieved compared with a conventional power source (DG). Fig. 11 summarizes the OPEX savings.

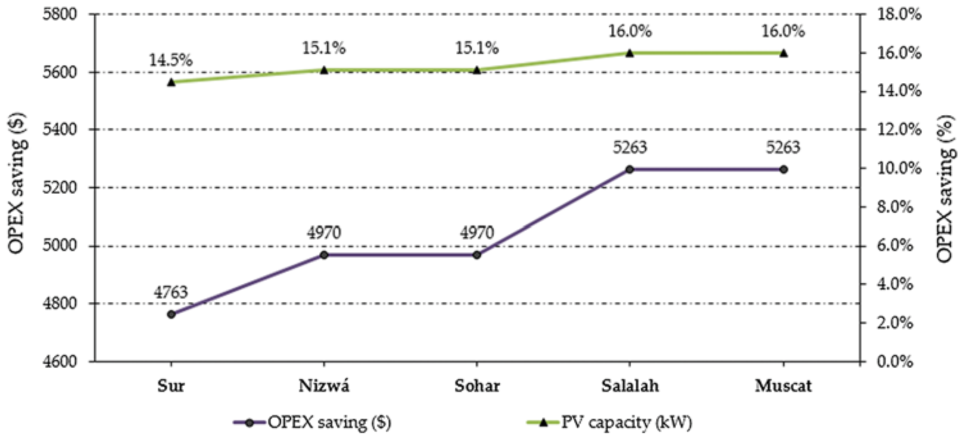


Figure 11: Summary of the total OPEX savings of the proposed solar system

6 Conclusion

This work proposed a framework for an energy-efficient RES-based cellular network for urban cities of Oman using a PV module that acts as the main and stand-alone source for the BSs to minimize the OPEX. The simulation results revealed that the proposed solar system can potentially meet the total demand of macro BS. Moreover, the BESS can supply power to the macro BS load autonomy for 106 h to fix the solar array in the case of malfunctions. Regarding the economic aspect, OPEX savings are in the range of 14.5% and 16.0%. These outcomes indicate a huge benefit to the cellular operators of Oman economically, technically, and ecologically.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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