# Design Strategies of an Off-Grid Solar PV Plant for Office Buildings: A Case Study of Johannesburg

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***Abstract*-Renewable energy systems based on solar resources are steering the way in grid-connected applications to meet present energy demands. This research work tends to investigate the design and feasibility of RE systems using solar resources to sustain a load in the Office Park building, at Constantia Kloof Roodepoort, Johannesburg, South Africa. This is following the provincial mandate to offset the energy usage of government buildings, including those belonging to the City of Johannesburg, by the installation of renewable energy sources in South Africa. The Cost-Benefit Analysis (CBA) on the design revealed that the fully solar RE system was the most economically possible. This was in comparison with the annual equivalent projected City Power electricity bill for the load profile.**

## I. INTRODUCTION

In recent years, the development of Renewable Energy (RE) systems has received much attention as an alternative to carbon-based conventional energy systems. Solar energy is plentiful and the power generation by these sustainable energy sources do not abuse nature [1, 2]. The severe impact of global warming and the growing demand for energy is rapidly leading to the depletion of fossil fuel reserves most especially coal as in the case of South Africa [3]. More specifically, with the technological advancement, the REs are expected to play a major role in the short term (2020) and long-term (2050) climate change mitigation [1]. Solar power seems to be steering the way to meeting present and future global energy requirements [4]. Such systems are relevant to off-network communities, remote areas as well as enhancing existing grid-connections with the aim of becoming self-sufficient or off-grid. The objective of this project is to design a suitable stand-alone RE system based on the energy consumption data for an office block building at Roodepoort, Johannesburg. The available source of renewable energy on-site is solar utilising photovoltaic array configured in a hybrid scheme [5] as shown in figure 2. This document reports the detailed design, analysis, load flows and investment study of such an RE facility for the allocated load profile. A background to solar systems is also provided with a focus on stand-alone hybrid RE systems making use of these energy forms. The feasibility of the proposed solution includes issues about the system's maintenance, core functionality and reliability. The overall benefit of this initiative is to offset the present energy usage of the building block to alleviate the utility's own power demand from the grid and to contribute towards a more sustainable economy as required by the provincial mandate [6].

## II. SOUTH AFICAN VIEW

In the South African context, solar energy systems seem to be the most viable in terms of accessibility, availability of sufficient sunlight and cost-effectiveness. South Africa also has one of the highest CO2/capital emissions in the world (Cape Town) [7]. A distributed generation approach may be an important method of managing existing energy infrastructure and provision of capacity especially after considering South Africa's recent energy crisis of inadequate generation capacity with no margin. However, distributed generation is an energy management solution that may not necessarily benefit the consumers directly. Rather, stand-alone RE systems enable self-sufficiency, and potentially reduce carbon emission impact and in many cases, provides economic benefit for consumers. For these reasons, stand-alone or off-grid energy systems are an attractive investment in industrial, institutional, residential and isolated community networks [1]. South Africa has access to sunshine throughout the year and this is only beginning to be utilised in urban areas for generating electricity for domestic and institutional applications [2]. The city of Johannesburg just like the neighbouring cities around it has good solar radiation parameters [2]. The maximum solar energy available is based on various factors such as the path of the sun, the seasons, Angle of Tilt (AOT) for each roof, roof orientation, obstructions (causing shade), air pollution, site elevation and cloud levels. The irradiation value for Gauteng is uniform and only a single value is to be utilised for all buildings since they are in close proximity.

With the view of RE goals and carbon trading under the Kyoto protocol, the growth of the renewable energy sector is expected to expand in South Africa [8]. The most prospective advantages of RE sources over fossil fuel-based generation is that it is naturally clean, i.e. non-polluting, freely available and recurring. An important consideration with RE systems is a high dependence on momentary energy sources thereby demonstrating daily and seasonal variations in their energy output [4]. This highlights the need to store excess energy produced in a period of low demand so that a fairly stable supply of energy is provided to the load in periods of high demand. Often, the mismatch between energy supply and demand is a primary contributor to the excessive cost of these renewable energy systems. Hybrid RE systems have the ability to provide 24-hour grid quality power to the load by combining two or more RE sources [9]. Additionally, they are more cost-effective than purely PV array or wind turbine systems because the energy generated in a hybrid scheme can be more closely matched to the load [10]. These systems can present higher efficiencies, flexibility and environmental compliance compared to fully solar or fully wind stand-alone systems [9]. The design of hybrid solar power systems with battery back-up requires reliable information on load profiling, solar radiation for Photovoltaic (PV) generation, initial component and installation costs, Life Cycle Analysis (LCA) and management strategies [8].

At present, there is a City Power Rooftop Solar Panel Pilot renewable energy system in the Reuven and Lenasia Depots Province of South Africa, Hluleka Nature Reserve hybrid mini-grid system, has been in operation since June 2002. It consists of two Proven 2.5 kW wind turbines and three Shell Solar PV module arrays of 56. 1kW PV modules in series. This system, therefore, gives a total generation capacity of 10.6 kW. The generation system also makes use of a control unit, battery storage and a diesel generator for backup. And the Lucingweni hybrid system making use of solar and wind energy consists of 6*6 kW mast mounted wind turbines and a solar PV array of 560*100W PV modules. This system also has a control unit and battery bank for storage and has a generation capacity of 86 kW to supply energy to 220 residences [11]. Increasing electricity costs is a threat to all South Africans [12]. The Department of Energy has examined an official definition of energy poverty for the country. This was used as a baseline to monitor and track energy poverty levels in South Africa. As was mentioned in the 2012 Budget speech, energy cost reviews are also being examined to ensure that households do not get further entrapped in energy poverty [10]. Literatures also illustrated that hybrid RE systems could be a viable option for institutions, industry and more specifically off-grid rural areas in South Africa [2, 13] [14].

## III. Solar Power System Design And Calculation

This section described the design and the calculation carried out in forming the architecture of this model.

### 1. *Grid-Tie Inverter Design*

The inverter is a critical component in the system because it is responsible for converting the DC output of the PV array into a suitable AC voltage to operate the load. The four parameters to consider before selecting a suitable inverter unit for the system are the input voltage, output voltage, peak power rating of the load and the waveform. The input voltage should be matched to the system voltage of 48 VDC whereas the output voltage rating is determined by the load operating voltages and specific mains voltage of the country. In South Africa, the mains voltage standard is 220V AC at 50 Hz. Hence, we have performed the load flow studies on the existing building supply. The power rating of the inverter should cater for the peak continuous power of the load which for the given load profile is 11.371 kW on selected loads for 8 hrs. per day all year long. Most inverters have a large overload capacity, enabling them to provide a substantially higher rated output for short periods of time. The proposed designed is given in Fig. 1. The basic characteristics of the electrical systems under which the plant should operate are as defined in the IEC 60038 and according to actual site data in Table I.

TABLE I
SYSTEM OPERATING CONDITIONS

| System | MV | LV | kVA |
|---|---|---|---|
| System Frequency: | 50 Hz | | N/A |
| Nominal System Voltage: | 11kV 3-ph | 400V 3-ph | |
| Max. Rated System Voltage: | 12kV | 420V | |
| Lightning Impulse Withstand Voltage: | 95kV peak | - | |
| Nominal Power Frequency Withstand Voltage: | - | 2.5kV | |
| Short Duration Power-Frequency Withstand Voltage: | 28kV | - | |
| System Earthling | Solid | Solid | |
| Maximum Design Load (Quadrum 1) | N/A | | 23kVA |

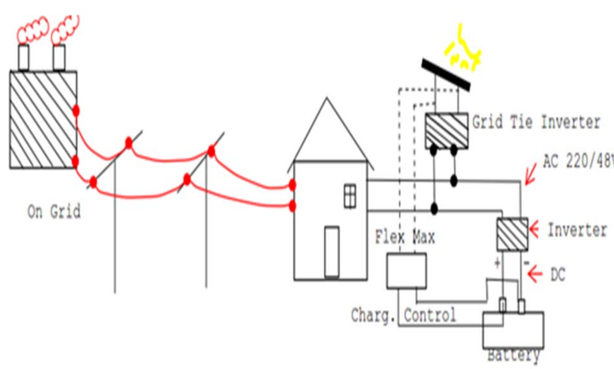


Fig. 1. Block diagram of proposed solar PV design

TABLE II

LIST OF COMPONENTS FOR POWER DISTRIBUTION

| QTY | Description | Input | Output | |
|---|---|---|---|---|
| | Height of Panel | 1.6m | | |
| | Length of Panel | 1m | | |
| | Area of Panel | 1.6m2 | | |
| | Power Input | 250W | | |
| | Area Density | 6.6kw/m2 | | |
| | Available Roof Area | 280.0m2 | | |
| | Utilized Roof space | 75% | 210.0m2 | |
| | No of panels | | 131 | |
| | Power output | | 32kw | |
| | Number of strings | 8.00 | | |
| | Panels per string | | 16 | |
| | Voc | | 591V | |
| | String Voltage Vdc | 36V | | |
| | Current/string | | 7A | |
| 2 | Combiner | | | |
| **QTY** | **Description** | **Input** | **Output** | |
| 2 | Inverter power | 23kw | | |
| | String/ inverter | 5 | | |
| | | | 33kw | load after losses |
| | | | 181 | kWh/d |
| | Cost per kWh | R 1.4 for Kwh | | |
| | annual savings | | R 92 555 | |
| | cost of the system | | R 700 000 | |
| | Break even | | 7.6 yrs | |
| | AC current | | 52A | 4mm 4 core |
| | Hour per day of useful sunlight on average | 5.52 | | |
| | | 175.64 | kWh/day | |
| | | 64107 | kWh/yr | |
| | losses | 20% | | |
| | | 51286 | kWh/yr | |
| **QTY** | **Description** | **Input** | **Output** | |
| | Height of Panel | 1.6m | | |
| | Length of Panel | 1m | | |
| | Area of Panel | 1.6m2 | | |
| | Power Input | 250W | | |
| | Area Density | 6.6kw/m2 | | |
| | Available Roof Area | 280.0m2 | | |
| 1 | Combiner Boxes | | | |
| | Surge Protection | | | |
| 2 | Meters | | | |

2. *Inverter Number*

Using (1), the total number of an inverter required can be calculated. However, the input power can be calculated by modifying (1) to become (2), which is the input power of the inverter.

$$InputPower = \frac{OutputPower}{\eta inveter} \qquad (1)$$

Where the InputPower is the power required by the inverter, the OutputPower is the power supplied the inverter, and ηinverter is the efficiency the inverter.

$$InputPower = \frac{11.371kW}{50\%} = 22.742kW \qquad (2)$$

Therefore, the input power to the inverter (22742 watts) is more than its rated 4500 watts, hence we need 5 inverters. Table 2 shows the list of power distribution components used in this paper.

3. *Number of Charge Controllers (Optional)*

Another mechanism required is the charge controller. The current rating of a charge controller is calculated using (3).

$$I = \frac{P}{V} = \frac{11371W}{220} = 51.68A \qquad (3)$$

Where I is the current flowing within the charge controller, P is the power, and V represents the voltage. The power coming out of the charge controller to the inverter is 22742 watts as seen above.

Since the charge controller capacity is 50 amps and we are drawing 51.68 amps, thus, only one charge controller is needed.

4. *Load Energy Usage*

The load consumes 11371 watts for 8 hours per day. We need to convert that to kWh per day using (4).

$$11371 \times \frac{1\ kilowatt}{1000\ watts} \times \frac{8\ hours}{day} = \frac{90.968\ kWh}{day} \qquad (4)$$

Therefore, the energy coming from the charge controller is:

$$\eta inverter = \frac{OutputEnergy}{InputEnergy}$$

$$InputEnergy = \frac{OutputEnergy}{\eta inverter} = \frac{\frac{90.968\ kWh}{day}}{50\%} = 181.96kWh/day \qquad (5)$$

5. *Cable sizing from the array to the building distribution board*

Low voltage cable of 220V rating was selected to be installed under standard conditions in air, over 200 meters.

Full Load Current

We have selected a $4mm^2$ x 4 core cable and mV/A/m of 0.3

Thus, (5) was used to calculate the voltage drop

$$Volt\ drop = 0.3 * 51.68 * 200 = 3.4V \quad (6)$$

$$\%Volt\ drop = \frac{3.4}{220} = 1.55\% \quad (7)$$

Permissible voltage drops (Usually 5%), hence the selected cable meets the volt drop requirements.

The purpose of this overall design is to offset the energy usage of buildings, by more sustainable solutions. The particular technology chosen is Solar PV as it is more suitable for the conditions on the Highveld and is a well-known alternative energy solution for 'green' buildings in dense urban areas [2]. A sustainable rooftop solar PV solution is therefore required that is technically suitable to meet the load demand while being cost-effective and requiring minimal maintenance.

The basic components of the grid-connected system without batteries and their quantity is given in Table II.

## IV. The Electrical Network

The electrical network for Roodepoort is based on the single line diagram. The existing network model in DigSilent PowerFactory power system simulation software was used to add Reuven depot and Lenasia depot in the network model and perform the load flow studies.

For the purpose of this research work, the Roodepoort building was added to the network model, based on the following assumptions as listed below used in the software simulation and validation for load flow analysis;

- Data, as collected, was correct. This includes the existing load for the building and the overall single line diagram, as mentioned above
- The network configuration of the was based on information supplied by the consulting engineer for the office park as shown in figure and placements of the transformers and LV boards. This configuration indicated a ring network with 14 MV / LV transformers, in seven groups of two transformers in parallel. Each group of transformers supplies an LV board each.
- The ratings of the transformers in the Office park was assumed to be 11/0.4 kV 315 kVA transformers, vector group Dyn11, the impedance of 4.44% and has a 5-position tap-changer. It was assumed that the transformers are operated on tap 3, the nominal tap.

A recording of the load issued by the consultant is table III including the estimated loading for LV board.

TABLE III
RECORDED LV LOAD

| Site | Average Peak Loading (kVA) | High Peak Loading (kVA) | Low Peak Loading (kVA) |
|---|---|---|---|
| Main 11kV Incomer | 1292 | 965 | 812 |
| Admin Block Board | 300.2 | 221 | 166.7 |

The LV board estimated load was calculated and table IV shows the estimated load.

TABLE IV
THE LV BOARD ESTIMATED LOAD

| Site | Average Peak Loading (kVA) | High Peak Loading (kVA) | Low Peak Loading (kVA) |
|---|---|---|---|
| E1 Block | 99.75 | 157.95 | 78.83 |
| Local Load TRFR | 45 | 60 | 30 |

At Robertsham Substation, the board supplying the Main was assumed to be the 11kV board, supplied from Robertsham 88/11 T1A. 6. The 11kV ring feeder cable was assumed to be a 6.35/11kV 3 core XLPE PVC SWA PVC 185mm2 copper cables. The size of the cables was based on the total installed capacity of the transformers. Each section of the cable was assumed to have a length of 200m, i.e. the groups of transformers are approximately 200m apart. Thus, the following steps were carried out;

- 11kV and 400V Board ratings are unknown and therefore are not included in the model.
- All LV cables for transformers were assumed to be 600/1000V 4 core PVC SWA PVC 300mm2 copper cables. The size of the cables was based on the transformer LV full load current rating. The length of each cable was assumed to be 50m.
- No de-rating factors were applied to the MV and LV cables.
- The 400V Board loads were lumped i.e. modelled as a single point load. It was also assumed that the loads are non-motor loads, therefore not contributing to fault levels.
- Overloading was taken as 100 % of the equipment nominal rating. This is applicable to load flow analysis

## V. Load Flow Analysis And Result

The load flow analysis and configuration were performed to determine problem areas in the network. The settings of the software were set to indicate overloading of equipment as well as over- and under-voltage conditions. Overloading on a branch is indicated in red when the calculated loading of the equipment exceeds 100% of the nominal rating of the equipment. Loading above 85 % of the nominal rating of the equipment is indicated in orange for information purposes. Over-voltage and under-voltage conditions on a node or bus bar are indicated when the calculated voltage is outside the + 5 % (indicated in blue) and – 5% (indicated in red) of the defined nominal voltage rating of the node or bus bar. A sustainable rooftop solar PV solution is required that is technically suitable to meet the load demand while being cost-effective and requiring minimal maintenance. Therefore, Solar PV plant for this building was designed with the view of providing 'clean' power to carry out normal operations on-site during the day, with excess power being fed back into office park connected grid during weekends only. During the night, the building shall depend on the grid for supply. However, during power outages, the building shall have a large dependence on the PV plant for power and dependence on the existing backup generators feeding critical loads. The Grid tie inverters will de-load the generator when there is sufficient power from the PV installation.

- Due to the slope of the roofs at study building, a PV-arrays shall be provided for the building roof.
- A decentralised inverter (string inverter) system is applied for reliability purposes and maximum power generation.
- Each building in the office park is fed independently from the main substation which is 2* 315kva. The PV system will be connected to the local DB board in the building basement which forms part of the mini-grid.

The load flow was performed and validated using DigSilent PowerFactory simulation software, as this is also the software used by various Electrical Engineering industries. This is represented by the Fig. 2 which represented the steady state analysis and the load profile.

## VI. Testing Procedure

Ratings, characteristics, tests and test procedures for the electrical equipment encompassed by these specifications complied with the provisions and requirements of the standards and recommendations of the NRS 097 series standards, of the International Electrotechnical Commission (IEC) standards and South African Bureau of Standards (SABS), unless otherwise expressly stated in the Technical Schedules. Order of magnitude cost estimates for the various options presented in table 5.

Compliance with the following standards for the supply, installation, testing, and commissioning of all equipment was provided as shown in table 6.

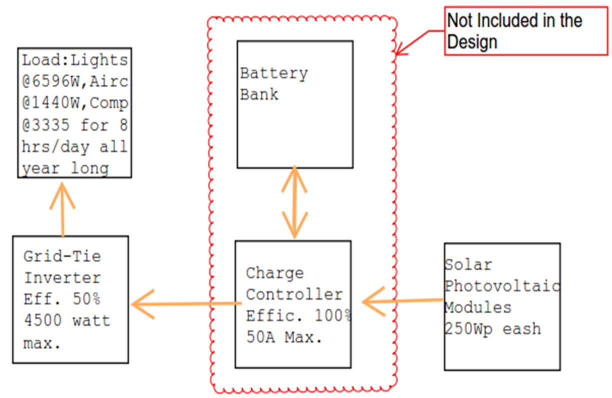


Fig. 2. Solar power functional blocks

TABLE V
COST ESTIMATE

| Grid-tie without Battery | | | |
|---|---|---|---|
| **Description** | **Qty.** | **Unit Price** | **Total** |
| Solar Module 250 W | 91 | R 2 000.00 | R 182 000.00 |
| Solar mounting frame | 1 | R 520 000.00 | R 520 000.00 |
| Bi-Directional inverter | 5 | R 65 000.00 | R325 000.00 |
| PLC power controller | 5 | R 115 000.00 | R 575 000.00 |
| Monitoring | 1 | R 22 000.00 | R 22 000.00 |
| Gen Set | 1 | R 50 000.00 | R 50 000.00 |
| Cabling and installation material | 1 | R 400 000.00 | R 400 000.00 |
| Installation and commissioning | 1 | R 500 000.00 | R 500 000.00 |
| Commissioning labour | 1 | R 300 000.00 | R 300 000.00 |
| Installation labour | 1 | R 600 000.00 | R 600 000.00 |
| TOTAL | | | R 3 474 000.00 |

TABLE VI
TYPE SIZES FOR CAMERA-READY PAPERS

| **Standards** | **Application** |
|---|---|
| SANS 10142:1 | Standard for low-voltage installations |
| IEC 61215 ed2.0 (2005-04) | Crystalline PV Module |
| IEC 61646: 2008 | Thin-film PV Module |
| VDE V 0126-1-1: 2006 | AC Inverters |
| IEC 61439 | LV Switchgear |
| EN62109-1/2 EN61000-6-2/3/11/12 | AC Inverters |
| IEC 62548 | PV Array design requirements |
| IEC 61730 | PV module safety |
| IEC 61727 | Requirements for the Utility Interface |
| IEC 60364-4-41 | Low Voltage Electrical Installations: Protection for Safety |
| IEC 62446 | Minimum requirements for PV system testing |
| IEC 62116-2008 ed1.0 | Test procedure for islanding prevention measures for utility-interconnect photovoltaic inverters |

## VII. Conclusion

The investigation and design of different off-grid RE systems, with a focus on a hybrid topology, based on solar resources to supply part of the Office Park building at the Roodepoort, Johannesburg was conducted. An analysis of the RE resources at the site revealed a relatively favourable average daily insolation of 5 kWh/m$^2$. The load profile for this particular part of the building was also investigated and results showed that the RE systems were to provide for a worst-case winter energy demand of 115.564 kWh/day. This design was based on a grid-tie PV system for an office park which will operate from sunlight. The initial suitability assessment of the site was undertaken as a desktop exercise, using the scaled aerial images as a basis. The key parameters such as the size of roofs, orientation, obstructions, type of root, the angle of tilt, the location of the feed-in point (s), and connection voltage were assessed in completing and implementation of this work. It is also recommended that battery can be included in the designed, but it will increase the overall cost.

For this installation, it was found that under voltages for all scenarios voltages were identified. Loads C2 and C4 were experiencing a lower limit of allowable Voltage i.e. 0.95pu. Loading conditions are were also identified for all scenarios. For no solar generation of 315kW Solar plant unit, the LV cable of the transformer is loaded by 2.85% while its transformer is loaded by 3.81 %. For the maximum solar generation of 315kW Solar plant unit, the LV cable of the transformer is loaded by 46.67% while the transformer is loaded by 44.67 %. For a maximum solar generation (N-1) of 315 kW Solar plant unit, the LV cable of the transformer is loaded by 87.71% while the transformer is loaded with 89.71 %. This makes the Solar PV source more efficient.

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