# Techno-economic evaluation of a grid-connected microgrid system

T. Adefarati[a,*] and G.D Obikoya[b]

[a]Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa;
[b]Department of Electrical and Computer Engineering, University of Delaware, Newark, DE, USA

*CONTACT: T. Adefarati, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa. email; adefrati@gmail.com

## Abstract

The availability of solar resources has led to the utilization of photovoltaic (PV) system for the generation of a clean electricity and reduction of greenhouse gas (GHG) emissions. The techno-economic assessment of a medium scale microgrid system is investigated in this work by utilizing some key performance indicators (KPIs). These KPIs are used as the benchmarks to study the economic impacts of PV in the grid-connected power system for 10 selected locations across the nine provinces of South Africa. The HOMER package is utilized in the study to obtain viable solutions that will mitigate the undesirable technical and economic issues that come up during the grid integration. The research work is carried out by utilizing the surface meteorology and solar energy data provided by the National Aeronautics and Space Administration (NASA) for assessment of the proposed microgrid system. The outcomes of the study show that the annual average daily radiation varies from 4.3 kWh/m2/day in Durban to 5.749617 kWh/m2/day in De Aar. It is deduced from the work that De Aar is the most feasible location among the 10 selected sites for the installation of PV in terms of cost of energy (COE), net present cost (NPC), net energy purchased, energy purchased, energy sold, energy charge, annual utility bill savings and revenue with the following values: 0.181 R/kWh, R 219244.90, 3676 kWh, 32979 kWh, 29303 kWh, R7942.9891, R62473.0109, and R22759.6401. The outcomes of the research work indicate that exploitation of solar resources is an efficient means of accomplishing sustainable energy development.

KEYWORDS: Battery storage system, grid, photovoltaic, renewable energy technologies

## 1. Introduction

The application of PV system has been experiencing rapid growth in different parts of the world, owing to increase in population, public concerns about GHG emissions, sustainability of energy, economic benefits, diversification of fuels for power generation, shifting from brown technologies to green technologies and development of various models for renewable green energy path (Adefarati and Bansal 2017a). The proliferation of PV technologies in the off-grid and grid-connected power systems has been attributed to reduction of COE and power consumption from the utility grid, reduction or elimination of the costs that related to extensions of transmission and distribution (T&D) lines, reduction of T&D line congestion, power generation near or at the load points, monthly or yearly credits received from the utilities by each household that has PV panel installation, improvement in the possibility to generate revenue from selling excess power produced by each consumer, absence of fuel cost, reduction of over-dependence on fossil fuels, low operation and maintenance costs owing to few numbers of the moving parts and reduction of environmental impacts that are associated with transportation of fossil fuels and operation of conventional power plants (Adefarati and Bansal 2017b). Moreover, the utilization of PV system has improved tremendously in some countries based on the installed capacities of the top-rated nations from as shown in Table 1. The statistical data that is made available in (Statista 2017) shows that China accounted for 60.07% of the global grid-connected PV system that has been recently installed, followed by the US with about 11.99%. The current installed capacity of PV system in South Africa is about 1,800 MW, this figure indicates that PV technologies have been underutilized in South Africa despite the average solar radiation of 4.5 to 6.5 kWh/m$^2$ that is annually recorded in the country (Thopil et al. 2018). The utilization of PV system for grid connection is limited in South Africa owing to the strict compliance with grid code, high cost of PV modules, prohibition of individual or organizations to generate electricity or charge for electricity without a license from the appropriate agency such as the National Energy Regulator of South Africa (NERSA) and the power supply in South Africa is predominantly coal-based owing to the availability of coal that will eventually deplete by 2050 (Department of Energy 2011).

The socio-economic activities of the countries that are mainly depending on the application of fossil fuels for the generation of power will be impaired owing to unstable global crude oil prices (Adefarati and Bansal 2017c). The depletion rate of fossil fuels has motivated many countries to look for the potential alternatives that are environmentally friendly and renewable to meet the load demands of their citizens (Hemmati and Hooshmand 2017). The public concerns for a clean energy source and high demand of a stable power supply have encouraged many nations in the Southern African Development Community (SADC) to set the targets

**Table 1.** Ten top countries with their solar PV capacities (Wikipedia 2018; Interesting Engineering 2017).

| Rank | Country | Capacity (MW), 2014 | Capacity (MW), 2015 | Capacity (MW), 2016 | Capacity (MW), 2017 |
|---|---|---|---|---|---|
| 1 | China | 28,100 | 43,530 | 78,070 | 131,000 |
| 2 | United States | 18,300 | 25,620 | 40,300 | 51,000 |
| 3 | Japan | 23,300 | 34,410 | 42,750 | 49,000 |
| 4 | Germany | 38,200 | 39,700 | 41,220 | 42,000 |
| 5 | Italy | 18,500 | 18,920 | 19,279 | 19,700 |
| 6 | India | 800 | 5,050 | 9,010 | 18,300 |
| 7 | United Kingdom | 5,100 | 8,750 | 11,630 | 12,700 |
| 8 | France | 5,700 | 6,580 | 7,130 | 8,000 |
| 9 | Australia | 4,100 | 5,070 | 5,900 | 7,200 |
| 10 | Spain | 5,380 | 5,400 | 5,490 | 5,600 |

that will enable them to generate the large percentage of electrical power from renewable energy technologies (RETs). The renewable energy resources are substantially available in many countries in SADC, but these resources are not fully utilized for power generation applications owing to some barriers. Presently, South Africa generates about 229,200 GWh electricity per annum and complements its energy supply by importing around 9,000 GWh per annum from Mozambique Wikipedia (2019). The total power generation capacity of South Africa is 52, 811 MW, in which conventional power sources such as gas turbines and thermal power plants contribute 82.34% while low GHG emissions such as hydro, solar PV, wind, solar CSP, landfill gas and nuclear contribute 17.66% (Wikipedia 2017). This indicates that South African power sector is mainly dominated by coal-fired power plants that are major causes of GHG emissions such as sulfur dioxide ($SO_2$), nitrogen oxides (NOx) and carbon dioxide ($CO_2$) (Pretorius 2015). Moreover, Renewable Energy Independent Power Producer Procurement (REIPPPPP) was inaugurated in 2013 to develop the preferred energy mix that would meet the electricity needs of the citizens for over a 20-year planning horizon (Walwyn and Brent 2015). The REIPPPP is a good platform to increase the power generation capacity of South Africa and reduce about 8.1 million tonnes of $CO_2$ per annum through the public–private partnership (PPP) or private sector initiative with the application of low carbon sources (Department of Energy 2019). The exigency of power supply in South Africa has stimulated the government to invest heavily in the energy facility that has a major impact on the socio-economic development and combating atmospheric pollutions that are related to the operations of the conventional power plants (Eskom 2018). Similarly, the South Africa Department of Energy had projected additional 10, 000MW electricity capacity to be integrated into the grid by 2025 as a measure to increase the present baseline (IPP Projects 2019; Chauhan and Saini 2014). The main objective of the programme is to minimize GHG emissions and enhance the generation capacity, economic development and job creation opportunities (Cabrera-Tobar et al. 2016).

In recent times, the power generation of South Africa has slightly improved owing to the initiatives introduced by the government agency to integrate RETs into the grid that is predominantly dominated by coal-fired power plants (CSIR 2018). The application of renewable energy distributed technologies at the load points is a roadmap to move the country forward in terms of power generation capacity, green energy revolution and a sustainable energy path (EGIS 2017). The grid integration allows consumers to draw electricity from the grid and the surplus power from the RETs will be reabsorbed by the grid through net metering or feed-in tariff. The bi-directional flow of current between the grid and consumers will reduce congestion of the transmission and distribution lines. The congestion of T&D networks and the shortage of electricity supply in some places have become major constraints to economic growth and development since there is a cordial relationship between the access to electricity and economic growth (Adefarati and Bansal 2017b). This affects the ability of the power sector to increase its production capacity. The shortage of electricity in some SADC countries has become a critical issue due to load-shedding or load curtailment and economic barriers to connect some places to the grid (Adefarati and Bansal 2017a, 2017d). The remote areas are characterized by inferior infrastructure and low income owing to no access to electrical power supply; this has affected the economic activities of the rural dwellers. It has been reported that approximately 31% of the South African population live in remote communities of the nation, where over 60% of rural dwellers have no access to power supply due to technical and economic barriers (Jamal 2015). Owing to this, access to electricity is a vital factor that must be included in the pro-poor rural development of South Africa. In view of this, the best solution to enhance the capacity of power generation in South Africa and to meet the power requirements of the consumers is to integrate PV technologies into the grid and to roll out some policies that will allow individual to generate power and sell the excess in the grid through any platform created by NERSA and Eskom (Africaportal 2017).

The RETs that are located very close to the consumers provide a prospective alternative to enhance the performance of the traditional power system. The technical benefits derive from utilizing RETs have made them to be considered for the power system integration and sustainability (Tazvinga et al. 2017). The high COE of the conventional power system and fluctuation in the cost of fossil fuels, as well as the uncertainty of the fuel supply and the cost of power interruptions have prompted many utilities to source for a better alternative on the basis of environmental and economic benefits (Adefarati and R Bansal 2017a). As a result of this, the utilization of PV technologies has become a promising solution for power generation in the electricity deficient areas, by harnessing the available solar resources to reduce the numbers of people that have no access to the power supply. In this work, a grid-connected microgrid system that has numerous sources such as battery storage system (BSS), utility grid and PV is implemented. The microgrid system is designed to satisfy the load specifications of the consumers while the grid will absorb the excess power generated by the individual household (Adefarati, Bansal, and Justo 2017a). The techno-economic benefits of green technologies and the high costs of fossil fuel combined with their fluctuating prices have prompted the proliferation of the traditional power system with multiple PV units (Farret and Simoes 2006). A sustainable energy system can be designed by considering the reliability of the system, COE, operating and maintenance costs, annualized cost of the system and NPC (Adefarati and Bansal 2019). The RETs are very flexible because they come in different forms and it is possible to integrate a number of distributed energy resources into a traditional power system in a manner to match the power balancing needs of the system more than conventional generating units. The PV and BSS units can be combined together to provide a reliable power supply during a predefined time (Adefarati and R Bansal 2017d).

The electrification project at reduced operating costs and GHG emissions has become a significant subject when carrying out a feasibility analysis and design a power system (Leung, Caramanna, and Maroto-Valer 2014). Due to this, the high cost of fossil fuels and the large quantity of the GHG pollutants emitted into the atmosphere have discouraged the utilization of fossil fuels based generating units in some locations. The reduction of soil degradation, ozone depletion and substitution of fossil fuel produced energy can be achieved with the utilization of PV system (Owusu and Asumadu-Sarkodie 2016). In addition to this, RETs can be considerably utilized to reduce the COE in the grid-connected microgrid system. However, the major weakness of the PV system is the intermittent nature that has raised a serious apprehension about the reliability of a power supply. Consequently, the combined operation of the BSS and PV is a promising solution to improve the optimal operation of the microgrid systems (Adefarati, Bansal and Justo 2017a). Moreover, the BSS is utilized to smooth out the fluctuating nature of solar resources in a grid-connected microgrid system. In view of this, the PV system can be integrated into the utility grid where there is no danger to security and reliability of the power supply. In such a situation, no power system facility upgrading is required. In some circumstances, grid modernization is required to safely incorporate PV units into the grid ARENA (2016). The integration of PV system into the grid will increase global power capability, provide access to electricity and acts as an enabler for economic growth (Brent and Rogers 2010). The immediate benefits include energy security, energy savings, cost reduction and sustainability of energy for the residents.

The feed-in-tariff is a concept that involves many stake holders in the power sector such as utilities, investors, independent power providers (IPPs), financial institutions, power system regulators and local and international organizations. The objective of feed-in-tariff is based on the technologies to be adopted, pre-determined prices and cost savings from upgrading of existing traditional power systems. The feed-in-tariff is proposed in South Africa so that it will allow the Renewable Energy Purchasing Agency such as Eskom to purchase renewable energy from the licensed IPPs based on the power purchase agreement (PPA). This acts as an incentive for the development of renewable energy projects and reduces the private investment risk and market uncertainty. The Renewable Energy Feed-in Tariff (REFIT) was developed in 2007 by the NERSA for regulation of electricity tariff in South Africa. The REFITs Phase I that was approved by NERSA in 2009 includes the small hydro, wind, landfill gas methane, plant parabolic and concentrated solar. The application of feed-in-tariff is a concept created by NERSA for provision of an enabling environment for renewable energy project in South Africa. The utilization of feed-in-tariff provides easy access to the grid by the IPPs so the power generated can be purchased. This policy established a level playing ground for the renewable energy to compete with the electricity generated from the conventional generating units. The mechanism created by NERSA allows market and economic development of green technologies in South Africa; this can be attested from a stable income and an adequate return on investment of renewable energy-related projects.

Many research works have been implemented on the economic evaluation of the microgrid power systems. Shezan, Das, and Mahmudul (2017) have carried out a technical and economic analysis of a smart grid system with the utilization of PV-WTG-BSS-diesel generator. The outcomes of the investigation demonstrate that COE, NPC, and GHG emissions have been reduced considerably with the application of RETs when compared with the fossil-based generating units. Madziga, Rahil, and Mansoor (2018) have proposed a model for an optimum operation of a microgrid power system that takes care of the power demand of a standalone community in Gwakwani, South Africa. Longe et al. (2014) have proposed a microgrid system as a better solution to improve access to the electric power supply in the communities that are not linked to the utility grid in Umhlabuyalingana local municipality rather than expending a lot of money on grid extension. Bokanga, Raji, and Kahn (2014) have proposed an optimal design of an islanded power system for remote areas electrification project in South Africa, based on PV panel selection, power demand estimation and battery sizing of the distribution system. Longe et al. (2017) have done the cost analysis of a microgrid system in contrast to the extension of utility grid to provide electric power supply to the people that live in Ntabankulu local municipality, Eastern Cape, South Africa. It is established from their work that standalone microgrid with RETs is the most feasible solution for the location. Musango and Brent (2011) have implemented a system dynamics approach for energy evaluation practice and theory within the context of sustainability improvement. Votteler and Brent (2017) have studied the economic prospect of renewable resources in the mining sectors of South Africa. The research work is designed to combine current information about the macroeconomics and environments as well as to provide a clear picture of how the impacts of RETs could be investigated from the perception of the mining sectors in South Africa.

Akinyele and Rayudu (2016) have proposed some benchmarks such as life cycle cost, loss of energy probability and life cycle impact as a measure to carry out the techno-economic and environmental evaluation of a PV microgrid system that served Gusau, a remote community in Nigeria. Chaurey and Kandpal (2010) have carried out a techno-economic of rural electrification project having considered the annualized life cycle costs. The simulation is implemented by utilizing the load profile of consumers and persistent variation in the costs of the distribution system on the basis of length. Moreover, Roche and Blanchard (2018) [40] have proposed a solar power system that provided basic lighting and mobile charging for the rural dwellers in a remote village in Kenya. Esan et al.

(2018) have presented a novel method in evaluating the reliability of a hybrid mini-grid system that served a remote community in Kwara State, Nigeria. The model was designed for residential and commercial loads with the application of the HOMER software. While Shoeb. and Shafiullah (2018) have proposed a techno-economic evaluation of green technologies that support remote areas electrification projects. The HOMER analysis tool is used in the study to assess the performance of the proposed power system by utilizing some matrices such as renewable energy fraction, COE, NPC, and GHG emissions. The above-mentioned studies have provided a substantial concept for techno-economic analysis of green technologies in the standalone and grid-connected power systems. Some of them proposed a number of techniques to analyze the COE, loss of energy probability, life cycle cost, NPC, life cycle impact and GHG emissions from the point of view. However, we realized that the aforementioned studies do not carry out the techno-economic evaluation of a microgrid system by utilizing some benchmarks such as net energy sold, energy purchased, energy charged, annual utility bill savings and revenue that should have been the useful tools for conceptual and design of the viable microgrid system in undeveloped and developing counties. Despite the various numbers of the research work that carried out solar resources analysis, only a few numbers focused on the economic assessment based on different cities and towns. In view of this, this study is designed to address these research gaps and add values to the current body of knowledge.

In this research work, a brief review of solar resources in some selected cities and towns in South Africa is presented to obtain the feasible and cost-effective solution that will reduce the number of people that have no access to electricity in the country with the application of RETs. The techno-economic assessment of PV and BSS microgrid system is investigated with the application of solar resources. The economic analysis of the proposed microgrid system is implemented by comparing some indicators such as COE, NPC, net energy purchased, energy purchased, energy sold, energy charge, annual utility bill savings and revenue. The RETs are clean power sources that can be regenerated for an indefinite period of time and economic drivers and producers of job opportunities for many South African citizens. Owing to this, 10 locations from 9 provinces of South Africa are selected for this research work. The selected locations are as follows: Pretoria in Gauteng province, Upington in Northern Cape province, Cape Town in Western Cape province, Durban in KwaZulu Natal province, Bloemfontein in Free State province, Klerksdorp in North West province, Polokwane in Limpopo province, Port Elizabeth in Eastern province, Nelspruit in Mpumalanga and De Aar in Northern Cape province, respectively.

In this research work, a grid-connected microgrid system is proposed to enhance the availability of electricity and improve the commercial and industrial activities that can offer a source of revenue for the investors. This will improve the financial viability of the IPPs by increasing their revenues and guarantee the sustainability of a continuous power supply. The net metering is applied in this work to facilitate investment in PV technologies by allowing the power generated by the consumers to be compensated by the power feedback from the utility grid. This research shows that the electricity drawn from the utility grid and the surplus power produced by the consumers are fed back to the grid will be recorded with the aid of net metering. The net metering facilities allow electricity consumption and electricity generated by the individual to be priced on a monthly or yearly basis. This research work is designed to investigate the economic impacts of PV penetration in the grid by using different locations in South Africa. The outputs of this study can serve as contributions to the global energy strategic plans to promote and strengthen energy security and reliability, the transformation of the energy sector, improve access to a power supply and contributions toward the world energy development schemes. The results obtained from this work can be used by the government agency and many international renewable energy organizations as benchmarks for renewable energy sustainability projects.

## 2. Overview of available solar resources in South Africa

The availability of solar resources is one of the prospects that make the production of electricity to be possible in South Africa. There are many locations in South Africa, where the large quantity of power can be generated owing to readily available solar resources. The Southern African region has sunshine throughout the year, with an average of more than 2 500 h of sunshine per year in some areas. The average solar radiation received in South Africa is estimated to be 4.5–6.5kWh/m$^2$ per day when compared with other countries in the world (Thopil et al. 2018). This makes South Africa solar resources to be one of the highest and most readily available and accessible sources in the world. The locations that are suitable for PV installations based on the South Africa annual solar radiation are presented in Figure 1. The South Africa solar resources are sufficient to have the capacity to generate universally competitive solar output power in light of their ability to deliver a smooth power output when the power plants are scattered over an expansive territory. The solar energy resources integration has a significant effect on the South Africa sustainability of energy (Department of minerals and energy 2003). The integration of PV systems into the grid can technically and financially supply bulk power to meet extensive parts of the nation's power prerequisites. However, the solar resources are only available during the day and depend on the season and weather conditions, this requires the integration of the battery system to smooth out the effects of their intermittent characteristics. The economic importance of RETs has encouraged the installation of roof-mounted PV technologies by many organizations as measures to reduce the COE as presented in Figure 2a. The construction of a PV farm at De Aar with the installed capacity of 50 MW to meet the power requirements of about 30,000 households in Northern Cape of South Africa is presented in Figure 2b.

### *2.1. Grid-connected microgrid system*

The consequences of power interruptions and the unbearable Eskom tariff have increased the optimal power solution that will permit better utilization of the PV and BSS as

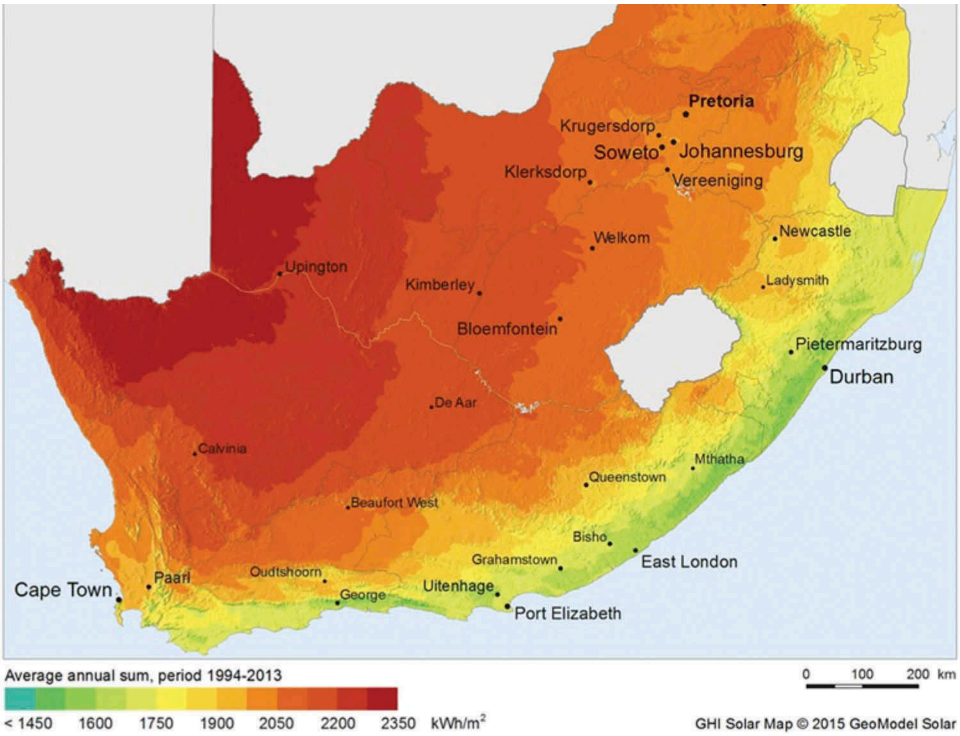


**Figure 1.** Average annual solar radiation in kWh/m$^2$ recorded for the years 1994–2013 in South Africa (CSIR energy 2016).

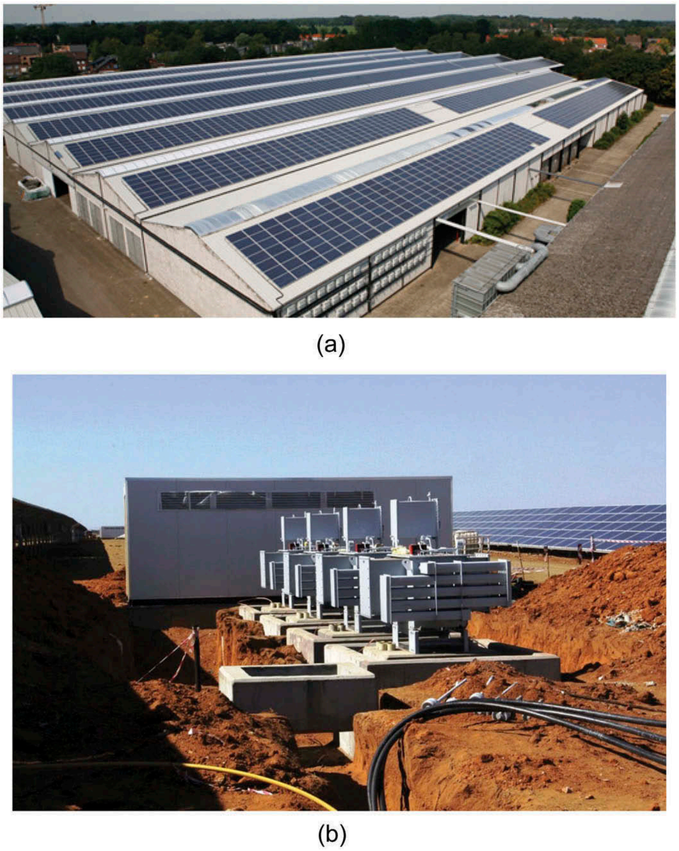


**Figure 2.** (a) Roof-mounted Solar farm (Exonconsulting 2017). (b) De Aar solar farm under construction (Jgafrika 2018).

presented in Figure 3. The application of the BSS in a microgrid system will allow the excess generated from PV system to be stored and use when power demanded by the consumers is high while the rest is exported to the grid. The proposed grid-connected microgrid system is an ideal power solution for the numbers of customers that have already been connected to the grid but need the backup units to enhance the reliability of their power systems and to generate revenue from selling excess electricity in the grid. The proposed power system is good for the customers that are prone to the economic impacts of grid failure and the only solution to prevent their sophisticated equipment from exposure to the menace of power outages is with the application of grid-connected microgrid system. The proposed microgrid plays a pivotal role to charge the battery, supply the load and send the excess power to the grid owing to the economic and environmental benefits of RETs.

### *2.1.1. Net energy purchased*

The net energy purchased is different between energy purchased by the consumers from the grid and energy sold by the consumers. This implies that the net energy purchase is equal to the grid energy purchase by the consumers from the grid minus the grid energy sale by the consumers to the grid (Homer 2017). In a situation where the consumers sell more power to the grid than they purchase from the grid within a stipulated period, this indicates that the net grid energy purchase is negative. The net energy purchased can be estimated as follows (Homer 2017):

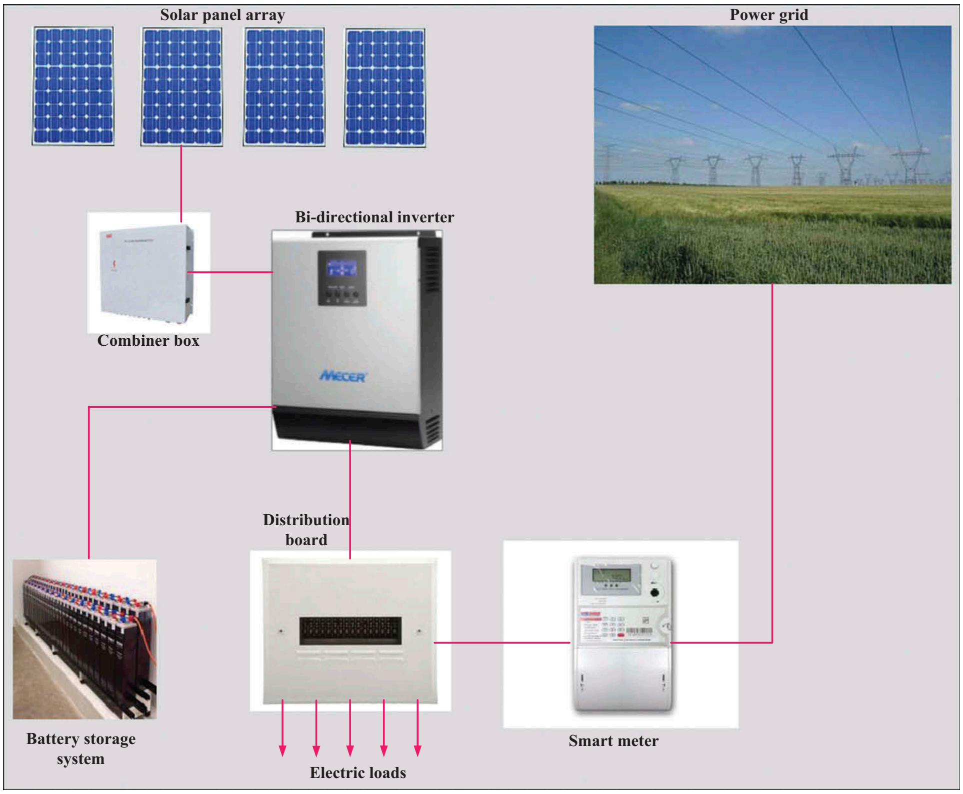


Figure 3. Schematic diagram of grid-connected microgrid system.

$$NEP_{kwh} = \left. \sum_{i=1}^{n} Energy_{purchased,\,i} - \sum_{i=1}^{n} Energy_{sold,i} \right) \qquad (1)$$

where $NEP_{kwh}$ is the net energy purchased (kWh) in a month, $Energy_{purchased,\,i}$ is the energy purchased in a month $i$ (kWh), $Energy_{sold,i}$ is the energy sold in the month $i$ (kWh) and $n$ is number of months.

### 2.1.2. Energy charge

The average commercial rate of electricity provides by Eskom is assumed to be R 1.0918/kWh while the energy is sold at the retail price based on the mutual agreement between the utility and the consumers. In this work, the energy sold price in the grid is assumed to be R 0.9577/kWh. The monetary values of the net energy purchases can be estimated by further simplify Equation (1) as follows:

$$\begin{aligned} Energy_{charge} = {} & \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{purchased,i} \times C_{purchased,k} \\ & \left. - \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{sold,i} \times C_{sold,k} \right) \end{aligned} \qquad (2)$$

where $Energy_{charge}$ is the energy charge (R), $C_{purchased,k}$ is the COE purchased from the grid in the month $i$ with the rate k in R/kWh and $C_{sold,k}$ is the COE sold to the grid in month i with applied rate k (R/KWh).

### 2.1.3. Annual utility bill savings

The annual utility bill savings are the differences between the actual utility bill without utilizing the RETs and the cost of electricity with the utilization of the RETs.

$$Utility_{savings} = \left\{ \begin{array}{l} \left( \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{grid,i} \times C_{grid,k} \right) - \\ \left( \begin{array}{l} \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{purchased,\,i} \times C_{purchased,k} \\ \qquad - \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{sold,i} \times C_{sold,k} \end{array} \right) \end{array} \right\} \qquad (3)$$

where $C_{grid,k}$ is the energy charge by the utility without application of microgrid system and $Energy_{grid,i}$ is the energy purchase from the grid without application of PV and BSS.

### 2.1.4. Revenue

The revenue of the microgrid system is defined as the financial gain from selling the excess power in the grid based on the retail price of electricity and the actual cost of electricity with the RETs. It is expressed in Equation (4) as:

$$\begin{aligned} R_{annaul} = {} & \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{sold,i} \times C_{sold,k} \\ & - \sum_{k}^{rate} \sum_{i=1}^{n} Energy_{sold,i} \times COE_{sold,k} \end{aligned} \qquad (4)$$

where $COE_{sold,k}$ is the production COE from the microgrid system.

## 3. Microgrid system

A microgrid system consists of various sizes and designs of the distributed generation technologies such as WTG, PV, BSS and small hydro (Adefarati and Bansal 2017a). It can provide a backup for the utility grid during the peak load periods as well as use to reduce operating costs and congestion of the utility grid. The microgrid system is designed to operate while connected to the grid, it can also be isolated from the utility grid and operate autonomously by using the green technologies for emergency reasons like storms and power outages. A switch is incorporated into a power system as a measure to disconnect the microgrid from the utility grid either manually or automatically so that it can operate effectively in the off-grid mode. The microgrid systems with smart grid features are characterized by the state of art of the technologies to prevent power system interruption. The components of a microgrid system are briefly explained as follows:

### 3.1. Photovoltaic system

A photovoltaic is a semiconductor material that converts the energy contained in photons of light into electricity. The conversion of solar energy into electrical energy is an important source that can be used for various applications. The PV system is environmentally friendly, reliable, involves no moving parts, silent operation and low operation and maintenance costs can be quickly installed. The PV system has some setbacks such as high capital cost and power production intermittency. Owing to this, the selection of PV system must be based on the availability of solar radiation at a particular site, weather conditions, cell temperature, cloud, snow and shading effects, rated efficiency, etc. The power generated by the PV system can be expressed as (Homer 2017; Islam, Akhter, and Rahman 2018):

$$P_{pv} = C_{pv} DF_{pv} \left( \frac{I_T}{I_{,STC}} \right) \left[ 1 + \alpha_T \left( T_c - T_{c,STC} \right) \right] \tag{5}$$

where $C_{pv}$ is the rated capacity of the PV array (kW), $DF_{pv}$ is the PV derating factor (%), $I_T$ is the solar radiation incident on the PV array in the current time step (kW/m$^2$), $I_{,STC}$ is the incident radiation at standard test conditions (1 kW/m$^2$), $\alpha_T$ is the temperature coefficient of power (%/°C), $T_c$ is the PV cell temperature in the current time step (°C) and $T_{c,STC}$ is the PV cell temperature under standard test conditions (25°C).

The temperature coefficient of the PV system is assumed to be zero whenever the impact of temperature on the PV system is negligible (Adaramola. 2014). Hence, Equation (5) can further be simplified as (Homer 2017):

$$P_{pv} = C_{pv} DF_{pv} \left( \frac{I_T}{I_{,STC}} \right) \tag{6}$$

The radiation that strikes the PV array and the PV cell temperature from the ambient temperature and can be estimated as follows (Homer 2017):

$$T_c = T_a + I_T \left( \frac{T_{c,NOCT} - T_{a,NOCT}}{I_{T,NOCT}} \right) \left( 1 - \frac{\eta_c}{\tau \alpha} \right) \tag{7}$$

where $T_{c,NOCT}$ is the nominal operating cell temperature (°C), $T_{a,NOCT}$ is the ambient temperature at which the NOCT is defined [20°C], $I_{T,NOCT}$ is the solar radiation at which the NOCT is defined (0.8 kW/m$^2$), $\tau$ is the solar transmittance of any cover over the PV array [%], $\alpha$ is the absorptance of the PV array [%], $I_T$ is the solar radiation striking the PV array [kW/m$^2$], $\eta_c$ is the electrical conversion efficiency of the PV array [%], $T_c$ is the PV cell temperature [°C] and $T_a$ is the ambient temperature [°C].

#### 3.1.1. Clearness index

A clearness index is a dimensionless number somewhere in the range of 0 to 1 demonstrating the portion of the solar radiation that strikes the highest point of the atmosphere and endures the atmosphere to strike the Earth's surface. The monthly average clearness index can be expressed in Equation (8) as (Fantidis et al. 2013; Homer 2017):

$$K_T = \frac{H_{ave}}{H_{o,ave}} \tag{8}$$

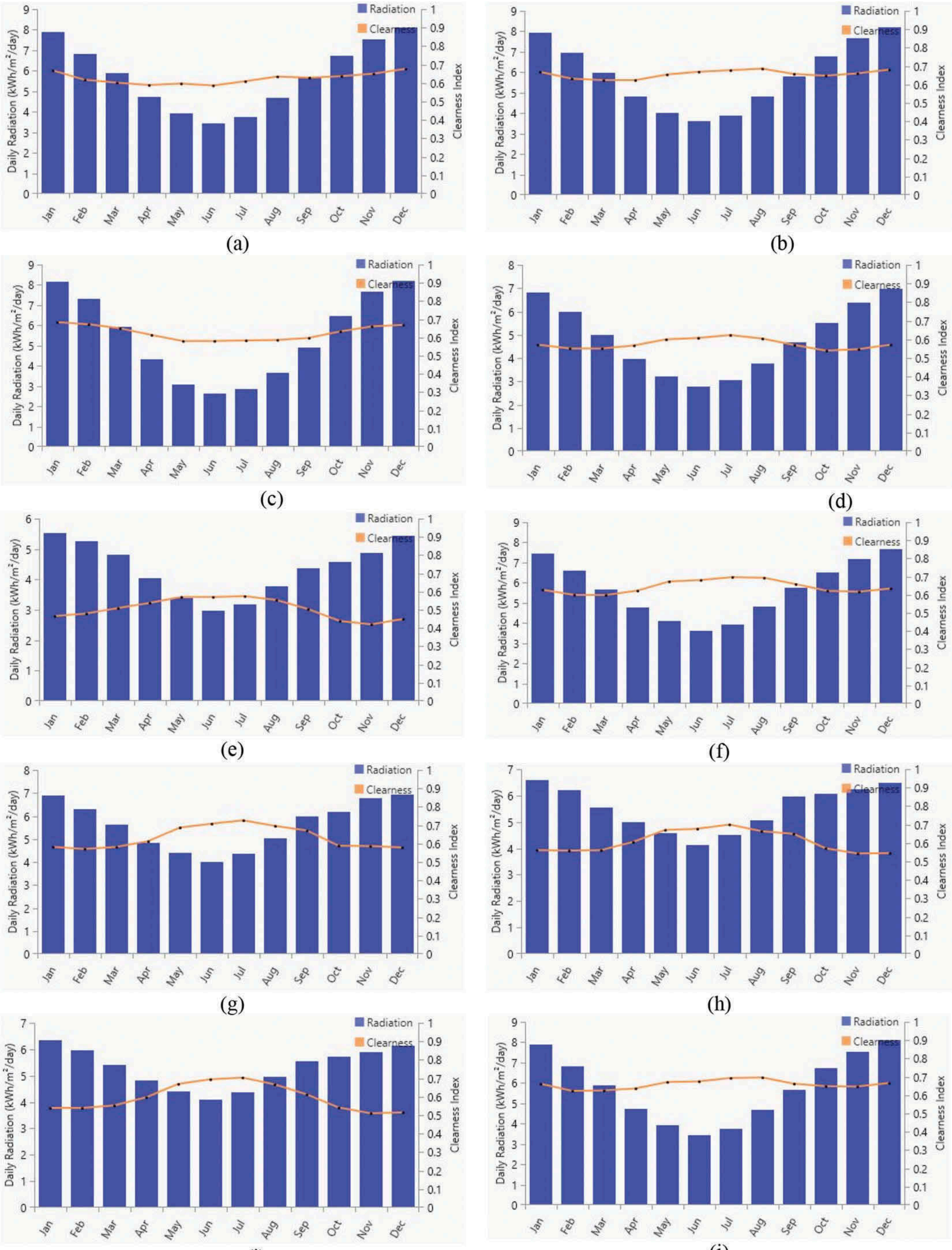
where $H_{ave}$ is the monthly average radiation on the horizontal surface of the earth (kWh/m2/day) and $H_{o,ave}$ is the extraterrestrial horizontal radiation, meaning the radiation on a horizontal surface at the top of the earth's atmosphere (kWh/m$^2$/day).

The monthly average solar global horizontal irradiance of the selected locations is presented in Figure 4(a–j). Owing to the seasonal variation, it can be observed from Figure 4(a–j) that daily radiation is highest in the months of January, February, November, and December while the least value of daily radiation is recorded in the months of May, June and July. This indicates that the highest value of daily radiation is observed in the summer and the least is observed in the winter. The monthly average temperature of the selected locations is presented in Figure 5 (a–j). It can be established from Figure 5 (a–j) that months of January, February, November, and December have the highest value of daily temperature. It is depicted from the figure that months of May, June, and July have the lowest daily temperature. With the highest values of solar resources obtained in the summer as presented in Figure 4(a–j) and 5(a-j), more electrical power is produced from PV system during this period.

### 3.2. Battery storage system

The BSS is integrated into the grid-connected microgrid system to satisfy the surge power requirements and provide a constant output voltage. There are many different types of batteries in the market for renewable energy projects, but the selection of the best battery storage system for the grid applications depends on the following factors: depth of discharge (DOD), efficiency, temperature performance, discharge rate, recharging rates, cost/per kWh, deep cycle, charge time, etc. The required battery storage capacity $B_{cap}$ (Ah) can be expressed as (Homer 2017; Kumar et al. 2018):

$$B_{cap} = \frac{E_{L(Ah)} D_A}{DOD_{\max} \eta_{temp}} \tag{9}$$



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

**Figure 4.** Monthly average solar global horizontal irradiance of (a) Pretoria, (b) Upington, (c) Cape Town, (d) Port Elizabeth, (e) Durban, (f) Bloemfontein, (g) Klerksdorp, (h) Polokwane, (i) Nelspruit and (j) De Aar.

where $D_A$ is battery autonomy, $EL$ is load consumption (Ah), $\eta_{temp}$ is the battery temperature correction factor and $DOD_{\max}$ is the maximum battery depth of discharge.

The discharging or charging of the battery storage system is a distinction between the power produced by the PV system and load at the time $t$ is given as (Homer 2017).

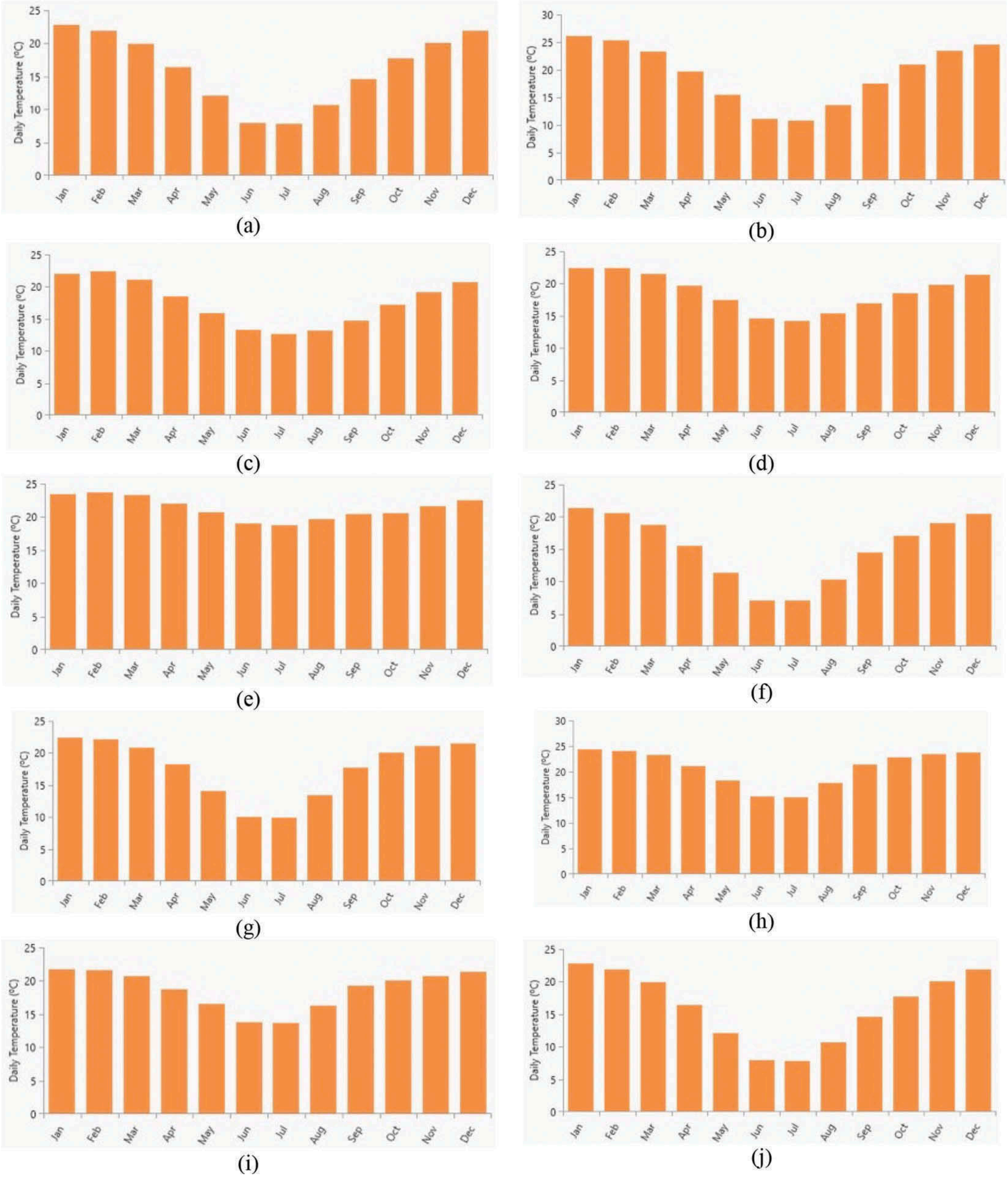
$$E_B(t) = E_B(t-1)(1-\sigma) + (E_G(t) - E_{Ld}(t)/\eta_{inv})\eta_B \tag{10}$$

where $E_{Ld}$ is load demand at time t, $\sigma$ is hourly battery self-discharge rate, $E_G$ is generated energy by renewable source, $E_B(t)$ is the charge quantity at time $t$, $E_B(t-1)$ *is the* charge quantity at time ($t$-1), $\eta_{inv}$ are inverter efficiency and $\eta_B$ is the battery charging efficiency.

The BSS autonomy which is the proportion of the BSS size to the electric load can be expressed as (Homer 2017):

$$A_{bss} = \left\{ \frac{N_{bss} V_n Q_n \left(1 - \frac{q_{\min}}{100}\right)(24h/d)}{L_{av}(1000Wh/kWh)} \right\} \tag{11}$$

where $N_{bss}$ is the number of batteries in the storage bank, $V_n$ is the nominal voltage of a single storage [V], $Q_n$ Is the



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

**Figure 5.** Monthly average temperature of (a) Pretoria, (b) Upington, (c) Cape Town, (d) Port Elizabeth, (e) Durban, (f) Bloemfontein, (g) Klerksdorp, (h) Polokwane, (i) Nelspruit and (j) De Aar.

nominal capacity of a single storage [Ah], $q_{\min}$ is the minimum state of charge of the storage bank [%] and $L_{av}$ is the average primary load [kWh/d].

The battery storage bank lifetime can be limited by the storage float life and lifetime throughput (Diab et al. 2016). This shows that the lifetime of the batteries is a function of either usage or old age. The selection of new battery storage should be based on whether the lifetime of the battery storage is restricted by either or both time and throughput. The lifetime of the battery storage bank can be expressed as (Homer 2017):

$$R_{ss} = \begin{cases} \frac{N_{bss} \times Q_{lt}}{Q_{th}} & \text{If limited by throughput} \\ R_{bss,f} & \text{If limited by time} \\ \min\left(\frac{N_{bss} \times Q_{lt}}{Q_{th}}, R_{bss,f}\right) & \text{If limited by through put and time} \end{cases} \tag{12}$$

$R_{ss}$ is the storage bank life (yr), $N_{bss}$ is the number of batteries in the storage bank, $Q_{lt}$ is the lifetime throughput of a single storage (kWh), $Q_{th}$ is the annual storage throughput (kWh/yr) and $R_{bss,f}$ is the storage float life (yr).

## 4. Techno-economic analysis of a grid-connected microgrid system

The detailed engineering design and financial analysis are the prerequisites to prevent failures of renewable energy projects that are generally caused by wrong sizing of the components that constitute the microgrid system (Kumar et al. 2018). For effective utilization of RETs in a microgrid system, it is mandatory for the utilities to carry out the financial feasibility of the project based on the cost of energy, operation and maintenance costs, replacement cost, NPC, capital cost and the annualized cost of the system (ACS). The aforementioned performance indicators are necessary to globally increase the renewable energy investment.

### 4.1. *Capital recovery factor*

The capital recovery factor (CRF) is a proportion utilized to assess the present estimation of an annuity of each component of a microgrid system. It is expressed in Equation (13) as (Adefarati and Bansal 2017a):

$$CRF(i, \mathrm{Proj}) = \frac{i(1+i)^{\mathrm{Proj}}}{(1+i)^{\mathrm{Proj}} - 1} \tag{13}$$

where *Proj* = number of years and *i* = real discount rate.

### 4.2. *Annualized capital cost*

The annualized capital cost of a microgrid system project is the initial cost of the components that constitute the system. Mathematically, it is defined as a product of the capital recovery factor and the capital cost as expressed in Equation (14) (Adefarati and Bansal 2017a).

$$\mathrm{ACC} = CRF\,(i, \mathrm{Proj}) \sum_{i=1}^{n} Cap, i\,(R/\mathrm{yr}) \tag{14}$$

where $Cap, i$ is the capital cost of each component that constitutes a microgrid system.

### 4.3. *Annualized cost of the system*

The annualized cost of the system is the sum of annualized capital cost, annualized operational cost, and annualized replacement cost minus salvage value (Adefarati and Bansal 2017a; Chauhan and Saini 2014).

$$ACS = \sum_{i=1}^{n} ACC_i + AOMC_i + ARC_i - S_i\,(R/\mathrm{yr}) \tag{15}$$

where $AOMC_i$ is the annualized operation and maintenance cost, $ARC_i$ is the annualized replacement cost and $S_i$ is the salvage value.

### 4.4. *Annualized operation and maintenance cost*

The O&M costs are annual administrative, operation and maintenance costs that related to the operation of renewable energy projects. They can be utilized by the utilities as one of the indicators to minimize the cost of energy and increase the performance of a microgrid system under varying conditions. The AOMC is the cost that is associated with the operation and maintenance of a microgrid system.

$$AOMC = \sum_{i=1}^{n} AOMC_{c,i} \cdot (R/\mathrm{yr}) \tag{16}$$

where $AOMC_{c,i}$ is the annualized operation and maintenance cost of each component that constitutes a microgrid system.

### 4.5. *Annualized cost of replacement*

The annualized replacement cost is the cost of replacing the component that constitutes a microgrid system at the end of its lifetime by considering the lifetime parameters in the component model. The annualized cost of replacement for each component that constitutes the microgrid system can be expressed as (Homer 2017):

$$ARC = \sum_{i=1}^{n} ARC_{c,i} \cdot (R/\mathrm{yr}) \tag{17}$$

where $ARC_{c,i}$ is the annualized replacement cost of each component that constitutes the microgrid system.

### 4.6. *Salvage value*

The salvage value is defined as the residual worth of each component that constitutes a microgrid system toward the end of the lifetime of the project (Bhattacharjee and Dey 2014). This indicates that the salvage value of a microgrid system component is specifically corresponding to its residual life. The salvage value of a microgrid system can be calculated as follows (Homer 2017):

$$S = C_{repl} \frac{R_{rl}}{R_{cl}} \tag{18}$$

$C_{repl}$ is the replacement cost (R), $R_{rl}$ is the remaining life of the component and $R_{cl}$ is the component lifetime (yr).

### 4.7. *Cost of energy*

The COE produced by the utilities or consumers is the cost per kWh of electrical energy generated by a microgrid system (Sinha and Chandel 2016). It can also be defined as the ratio of the annualized cost of the system to the electric load served. This permits the economics of various configurations of renewable energy technologies to be compared. It is presented in Equation (19) as (Esan et al. 2018):

$$COE = \frac{ACS}{Energy_{served}} \cdot (R/kWh) \tag{19}$$

where ACS is the annualized cost of the system (R/yr) and $Energy_{served}$ is the energy served (kWh/yr).

### 4.8. *Net present cost*

The NPC is defined as the sum of the present value of the costs that incurs through the lifetime of a microgrid project, minus the present value of the considerable number of revenues that it makes through the project lifetime. The NPC of each component that constitutes a microgrid system can be expressed as (Adefarati and Bansal 2017a):

$$NPC = \frac{ACS}{CRF(i, \mathrm{Proj})} \cdot (\mathrm{R}) \tag{20}$$

### 4.9. *Internal rate of return*

The internal rate of return (IRR) is the discount rate at which the power systems under financial, environmental and technical assessment and existing case study have the same NPC (Adefarati and Bansal 2017a).

$$IRR = \frac{\sum B_n - \sum C_n}{(1+i)^n} = 0 \tag{21}$$

where $B_n$ is the benefits at year *n*, $C_n$ is costs at year *n*, *n* is the number of years and *i* is the discount rate.

### 4.10. *Simple payback*

Simple payback (SPB) is the number of years that require to recuperate all the costs spent on renewable energy projects to generate thermal energy and electricity. The SPB is where the nominal cash flow difference line crosses zero and numbers of years required to reach the breakeven point (Adefarati and Bansal 2017b).

$$SPB = \sum \frac{I_C}{Y_b - Y_c} \tag{22}$$

where *Ic* is the investment costs, *Yb* is the yearly benefits and *Yc* is the yearly costs.

### 4.11. *Discounted payback*

The discounted payback (DPD) is the number of years requires for the investment on the renewable energy project to be equal to the discounted value of expected cash flows. It is the number of years that capital expenditure on a project will break even from the initial investment by discounting impending cash flows and be acquainted with the time worth of money. It is also the period at which the cumulative net present value (NPV) of a project equals to zeros. The DPB can be used by the utilities or IPPs to determine the profitability of any investment on a project.

$$DPB = In\left(\frac{1}{1-\frac{Cap_{inv}}{CF}}\right) \Big/ In(i+1) \tag{23}$$

where *i* is the discounted rate, $Cap_{inv}$ is the capital investment and *CF* is the periodic cash flow.

## 5. Modeling of the proposed microgrid system

The power generated from the microgrid system is location-dependent and varies from one place to another based on the availability of the solar resources. This shows that the availability of local renewable energy sources coupled with their different locations is a paramount factor that determines the optimal operation of the proposed connected microgrid system as presented in Figure 6. The aim of the work is achieved by using the solar resources of different locations in South Africa to minimize the net energy purchased and maximize the revenue from obtained from selling electricity in the grid.

The aim of this research work can be accomplished by using the same load profile to carry out the feasibility study of renewable energy investment in South Africa. The proposed grid microgrid system has two load profiles for selected towns and cities as presented in Figure 7 (a-b).

## 6. The microgrid optimization technique

The HOMER is an application tool produced by the National Renewable Energy Laboratory for optimization of renewable and nonrenewable energy resources in the off and grid-connected power systems (Hafez and Bhattacharya 2017). The software can as well be used for optimal sizing, planning, and design of the standalone microgrid systems for remote areas. The HOMER streamlines the task of assessing and design of the microgrid systems for a variety of applications based on a large number of technologies, the disparity in technology expenses and accessibility of local renewable energy resources. The optimization and sensitivity analysis algorithms adopted by the HOMER make it simpler to assess numerous possible configurations in the power system (Elaziz, Elsadd, and Farrag 2017). The HOMER is developed to surmount the difficult tasks of assessing and design of

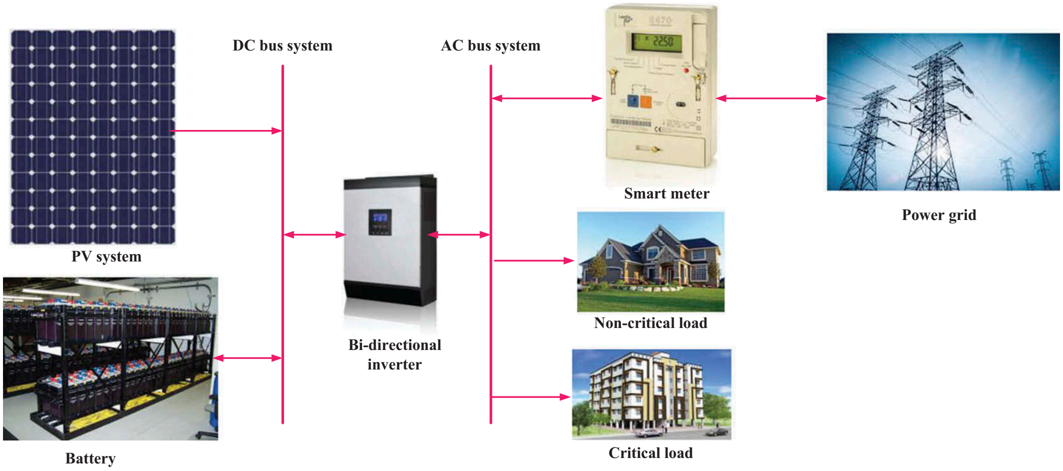
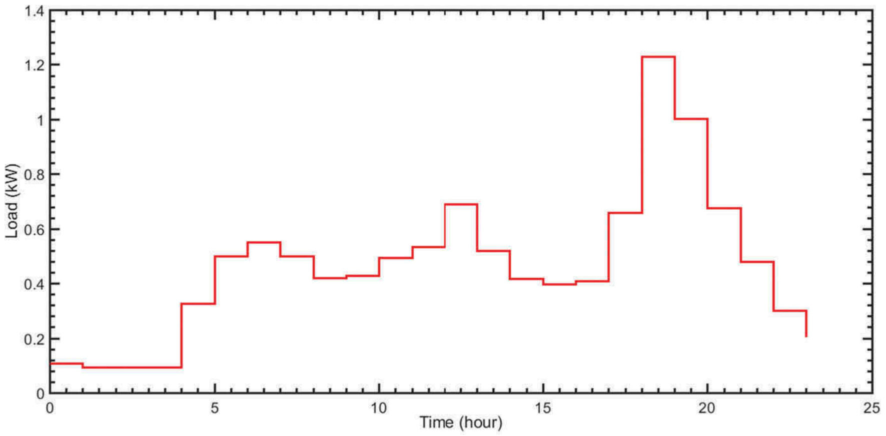
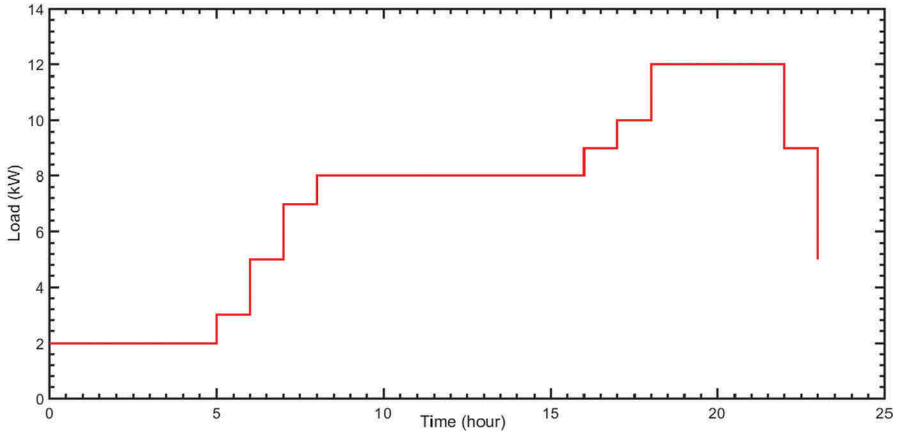


**Figure 6.** Proposed grid-connected microgrid system.



(a)



(b)

**Figure 7.** (a) Non-critical load. (b) Critical load.

standalone and grid-connected power systems that arise from the complex nature of the system configuration and uncertainty of some parameters such as future fuel price and load growth.

### *6.1. Simulation*

The operation of a microgrid system is simulated with the utilization of the HOMER package by making energy balance estimations on an hourly basis for each year. The operational strategy of each component of the microgrid is examined with the application of the aforementioned software to test their performances over a giving period of time. This is achieved by calculating the load flows based on each component of the proposed microgrid system. Then, HOMER determines the technical and economic feasibility of the microgrid configuration having considered the operation costs of the power system over the lifetime of the project (Lymberopoulos and Zoulias 2008). The microgrid assessment can be carried out by considering the following factors: operation and maintenance costs, capital cost, interest rate, inflation rate, replacement cost, etc. The sensitivity and optimization analysis with the application of the HOMER simulation tool depends on the operation of a microgrid system (Homer 2017).

### *6.2. Optimization*

The HOMER displays a list of feasible configurations based on the search space specified by the users. It utilizes an exclusive derivative-free algorithm to explore for the minimum cost of the system, sorted by minimum NPC or lifecycle cost (Homer 2017). After the optimization tool has carried out the simulation of the microgrid configuration based on the input data supplied by the users, the optimization is calculated and displays the optimal results based on the microgrid configuration. The HOMER characterizes the optimal configurations of a microgrid system with the NPC and capability to meet the users' constraints (Hafez and Bhattacharya 2017).

### *6.3. Sensitivity analysis*

The HOMER can be used to determine the optimal sizes and the number of components that are associated with a microgrid system. The sensitivity variables are the inputs defined by the users for the optimization of a microgrid system. The HOMER repeats the optimization procedure for every sensitivity variable to show the characteristics of the results is based on the values of the specified input data (Sinha and Chandel 2015). The sensitivity analysis of the HOMER depends on the type and values of input parameters. This shows that the HOMER will simulate the system configurations in view of the scope of operating parameters that the users specified. The users can analyze the impacts of input parameters vary with time (Homer 2017).

## 7. The configuration of the grid-connected microgrid system

This research work is aimed to study the economic impacts of the PV penetration in the grid by using different locations in South Africa as shown in Figure 8. The technique applied in this work is to facilitate investment in the PV technologies by allowing the power generated by the consumers to be compensated by the power feedback from the grid. This shows that the electricity is drawn from the utility grid and the surplus power produced by the consumers is fed back to the grid. The net metering facilities allow electricity consumption and electricity generated by the individual to be priced on a monthly or yearly basis. A microgrid system in the grid-connected mode as presented in Figure 6 is used for the technical and economic assessment of the PV system in 10 locations in South Africa. This research work backs the government and international organizations policies that encourage utilization of green technologies for power generation in the grid-connected microgrid and supports customer loads in some locations in South Africa. The geographical details of Pretoria and Cape Town are presented in Figure 9(a–b). The 10 locations selected in this work consists of a number of commercial centers, schools, banks, industries and residential loads for approximately millions of people during the Winter, Summer, Spring, and Autumn/Fall. The technical details of each component that constitutes the proposed microgrid system are presented in Table 2 (Adefarati and Bansal 2019; Homer 2017).

The following assumptions were taken into consideration when estimating the KPIs of the proposed microgrid system based on the selected locations in South Africa:

(i) The lifetime of the proposed microgrid system is assumed to be 25 years.
(ii) The interest rate is assumed to be 6%.
(iii) The inflation rate is assumed to be 4%.
(iv) The same load profiles are used for all the locations.
(v) The average solar resources of the selected locations are based on the NASA meteorology and solar energy databank.
(vi) The power generated by the PV system is a function of the solar resources of the selected locations.
(vii) The same components of the microgrid system are used for all the locations.

## 8. Results and discussions

The microgrid design for each case study is obtained with the application of the HOMER package, using the operating parameters of each component that constitute the proposed microgrid system as presented in Table 2. As explained earlier, the aim of this work is to maximize the economic benefits by determining the location with the least cost of

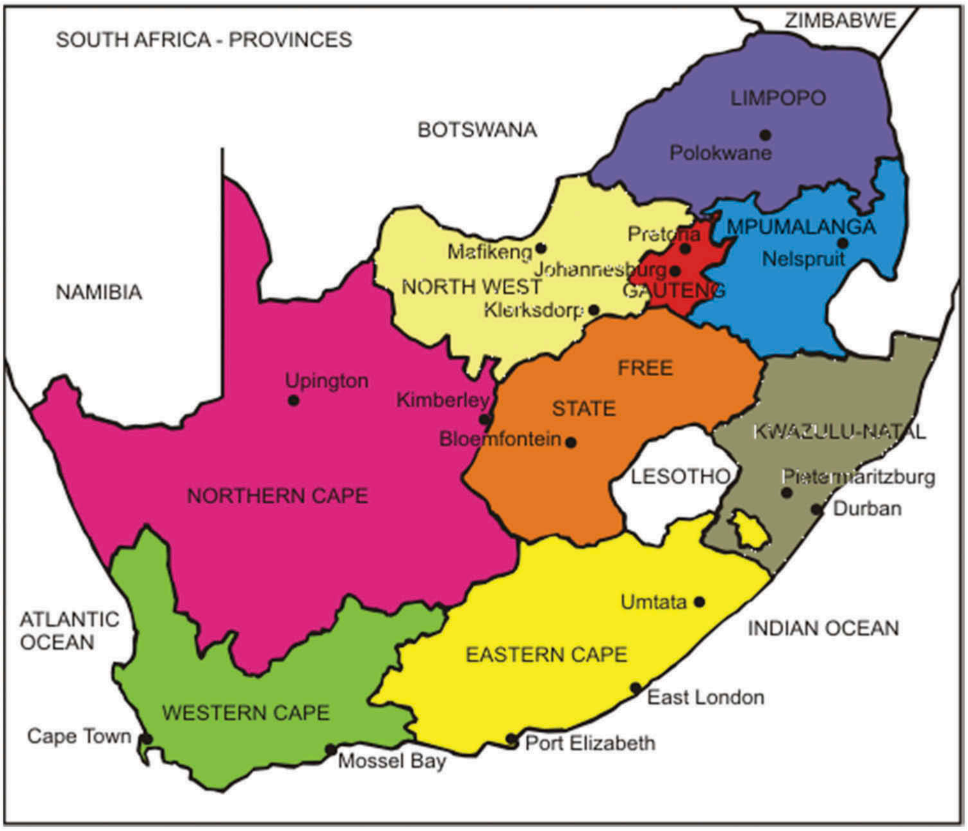
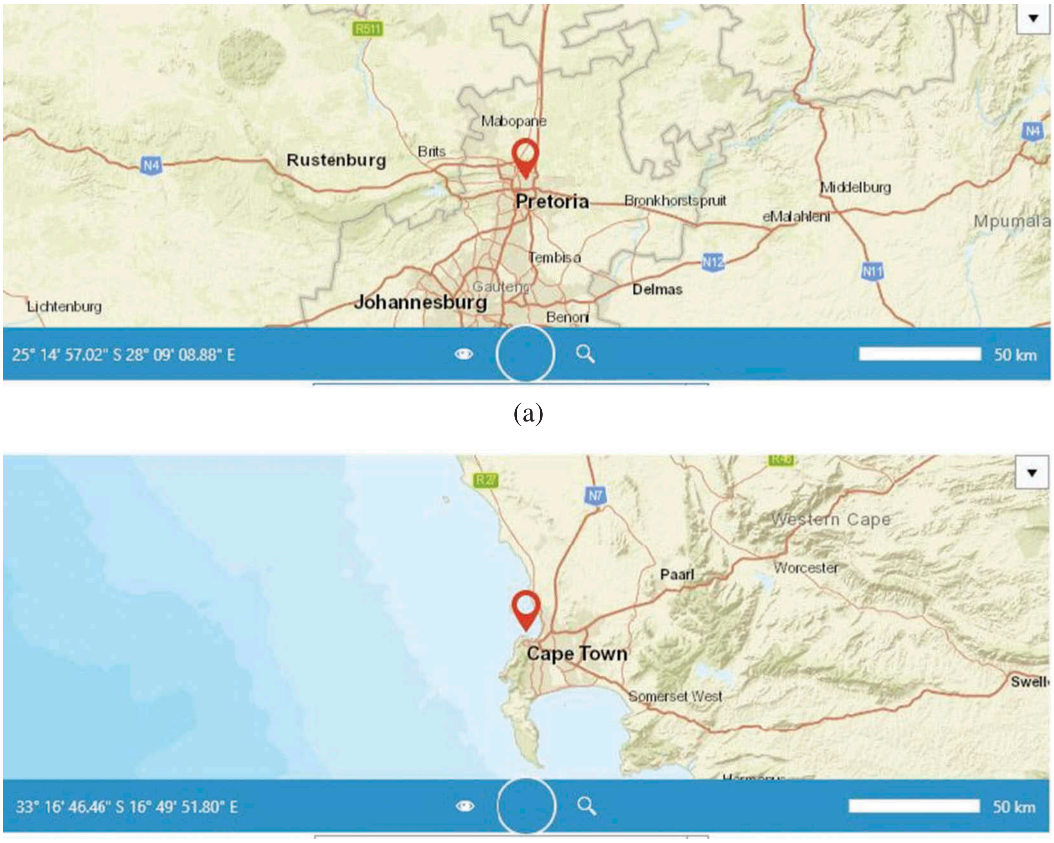


**Figure 8.** Locations of the cities and town for the case study (Sataxguide 2017).



(a)

(b)

**Figure 9.** (a) Geographical details of Pretoria on the map. (b) Geographical details of Map Cape Town on the map.

**Table 2.** Operating parameters of the microgrid system components.

| Characteristics of PV | | Characteristics of battery | | Characteristics of inverter | |
|---|---|---|---|---|---|
| Description | PV | Description | Battery | Description | Inverter |
| Model number | Fronius Symo 20.0-3-M with Generic PV | Model number | Generic 1kWh Lead Acid [ASM] | Model Number | System converter |
| Rated Capacity | 40 kW | Nominal capacity | 1.03 kWh | Rated power | 50 kW |
| | | Maximum capacity | 513 Ah | | |
| Other technical details of PV | | Other technical details of battery | | Other technical details of inverter | |
| Temperature coefficient | −0.4100 | Initial SOC | 90% | Rectifier input | |
| Operating temperature | 45 °C | Minimum SOC | 40% | Relative capacity | 100% |
| Efficiency | 17.30% | Degradation limit | 20% | Efficiency | 95% |
| Manufacturer | Fronius | Minimum operating temperature | −20°C | Inverter input | |
| | | Maximum operating temperature | 55 °C | Efficiency | 95% |
| Operating lifetime | 25 years | Operating lifetime | 5 years | Operating lifetime | 15 years |
| | | Capacity ratio | 0.611 | | |
| | | Maximum charge current | 167A | | |
| | | Maximum discharge current | 500A | | |
| Capital cost (R) | 250,000 | | 16,000 | | 30,000 |
| Replacement cost (R) | 250,000 | | 16,000 | | 30,000 |
| O&M cost (R/yr) | 2500 | | 160 | | 300 |

energy, NPC, energy purchased, net energy purchased, energy charge and highest revenue from the sale of electricity and annual utility bill savings. The microgrid system proposed in this study considered the technical specifications of each component to obtain the optimal configuration of the system.

### *8.1. Comparison of various case studies*

In this section, 10 case studies are selected as a measure to determine the feasibility of the PV investment and most favorable locations in South Africa. The case studies are utilized for performance assessment and economic analysis of a medium scale PV system for 10 towns and cities based on renewable energy planning and project in South Africa. The operating parameters of the components of the proposed microgrid are shown in Table 2. The factors that influenced the power generated by the PV system at the selected sites such as daily solar radiation and daily temperature are taken into consideration during the related time of period. The power output of the PV system together with any related performance indicators of the microgrid is computed with the equations presented in Sections 2 and 3. It is observed that the annual utility savings ranges from R50, 760.1657 in Durban to R62, 473.0109 in De Aar with the same load profile as shown in Table 3 and Figure 10. This indicates that De Aar is the most suitable site for installation of the PV system among the 10 towns and cities selected for the research work based on the least value of COE, NPC, energy charge, energy purchased and net energy purchased as shown in Table 3 and Figures 11–13. The power generated by the PV system depends on the availability and strength of solar resources at a particular site and the operating parameters of the PV units adopted in the microgrid system. It can be validated from Table 3 and Figure 11 that the microgrid system operates with the maximum revenue and annual utility bill savings in De Aar.

This research work is designed to minimize the values of COE, NPC and other key performance indicators. The variation in NPC and COE for each case study is presented in Figures 10 and 11. It is well established that the COE recorded in De Aar is the least based on the availability of solar resources while Durban is the highest based on the results of the simulation. Similarly, the value of NPC for De Aar is the least while Durban has the highest value of NPC in the simulation. Hence, the results presented in Figure 12 and 13 show that the microgrid system with the incorporation of the PV and BSS units in case study 10 have the lowest values of COE and NPC when compared with other case studies. Hence, Fronius Symo 20.0-3-M Generic PV with the operating parameters presented in Table 2 is suitable for the sites based on its power outputs from different locations. The monthly summary of the energy sold, energy purchased, net energy purchased, energy charge, and revenue for the 10 selected sites in South Africa are presented in Appendix A–J. Among the 10 sites considered in this work, De Aar is the most feasible economic location based on the optimal KPIs obtained from the microgrid system by utilizing its solar resources. It is observed that case study 10 is the most economically favorable option because of the presence of good solar resources that meet the specification of the PV unit. Apart from this, it results in most economic savings. It can be deduced from the results presented in Table 4 that Durban has the highest values of operating cost that is estimated to be equal to R 259 246 while De Aar has the least operating cost with the value of R 107 812 with reduction of 57.26% when compared with the results obtained in Durban.

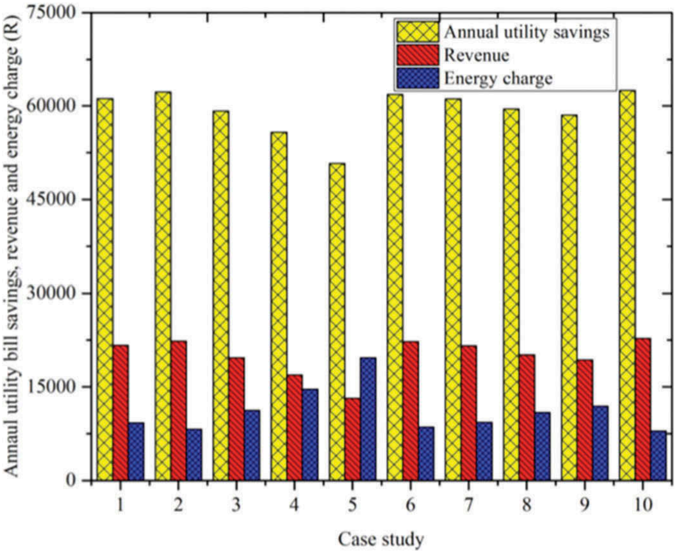


**Figure 10.** Annual utility bill savings, revenue, and energy charge for each case study.

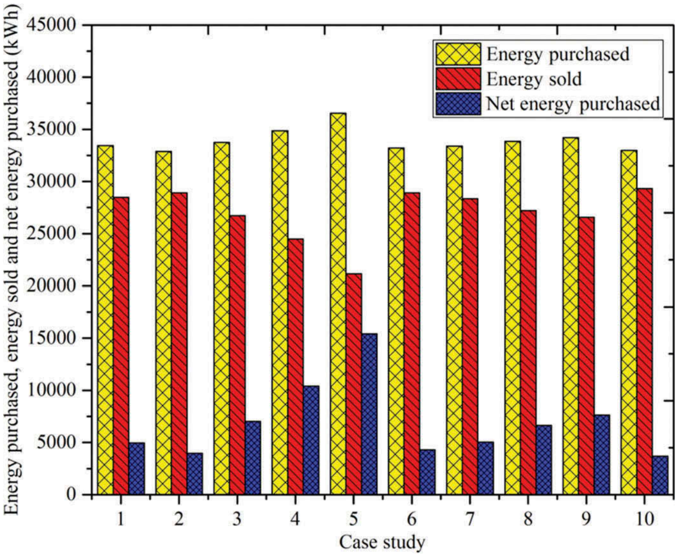


**Figure 11.** Annual energy purchased and energy sold utility for each case study.

**Table 3.** Overall optimization results for the selected locations in South Africa.

| Case study | City/Town | COE (R/kWh) | NPC (R) | Annual utility bill savings (R) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|---|
| 1 | Pretoria | 0.196 | 236, 068.00 | 61,174.9346 | 9241.0658 | 21687.1224 |
| 2 | Upington | 0.185 | 222, 796.50 | 62,202.9417 | 8213.0583 | 22336.4389 |
| 3 | Cape Town | 0.222 | 261, 976.10 | 59,170.6146 | 11245.3854 | 19663.7896 |
| 4 | Port Elizabeth | 0.266 | 305, 793.50 | 55,780.1402 | 14635.8598 | 16930.0492 |
| 5 | Durban | 0.335 | 370, 679.10 | 50,760.1657 | 19655.8343 | 13162.0099 |
| 6 | Bloemfontein | 0.188 | 227, 482.20 | 61,840.1769 | 8575.8231 | 22245.0997 |
| 7 | Klerksdorp | 0.197 | 236, 920.60 | 61,109.9648 | 9306.0352 | 21568.8878 |
| 8 | Polokwane | 0.217 | 257, 594.50 | 59,509.8103 | 10906.1897 | 20155.1877 |
| 9 | Nelspruit | 0.230 | 270, 523.50 | 58,510.251 | 11905.749 | 19336.4444 |
| 10 | De Aar | 0.181 | 219, 244.90 | 62,473.0109 | 7942.9891 | 22759.6401 |

### 8.2. Comparison of electrical generation and power consumption

The general comparison of electrical generation and power consumption from each case study are presented in Table 5 and Figure 14. The results shown in Table 5 demonstrate that case study 10 has the largest production of electricity from the

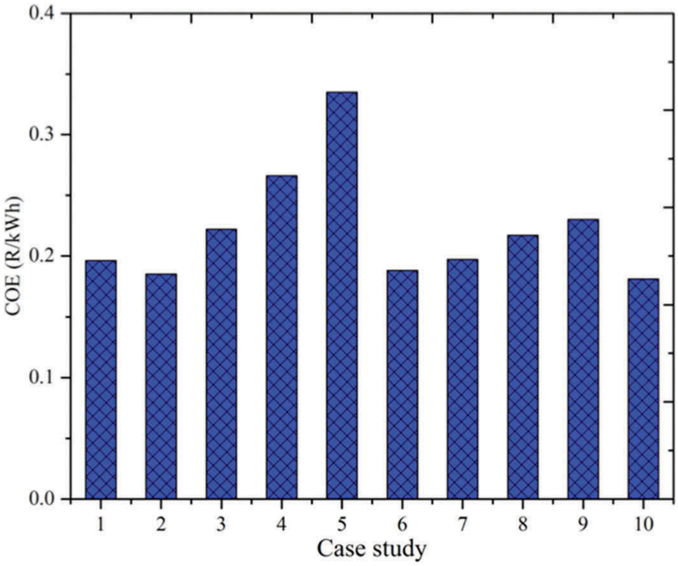


**Figure 12.** COE for each case study of the microgrid system.

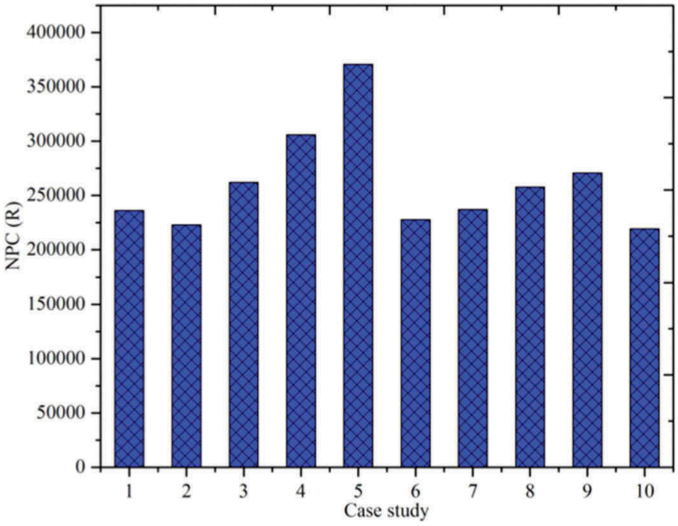


**Figure 13.** NPC for each case study of the microgrid system.

**Table 4.** Cost summary of the selected configuration.

| Case study | City/Town | Capital (R) | Operating (R) | Replacement (R) | Salvage (R) | Total (R) |
|---|---|---|---|---|---|---|
| 1 | Pretoria | 61321 | 124 635 | 50352 | −239,56 | 236 068 |
| 2 | Upington | 61321 | 111 363 | 50352 | −239,56 | 222 797 |
| 3 | Cape Town | 61321 | 150 543 | 50352 | −239,56 | 261 976 |
| 4 | Port Elizabeth | 61321 | 194 360 | 50352 | −239,56 | 305 794 |
| 5 | Durban | 61321 | 259 246 | 50352 | −239,56 | 370 679 |
| 6 | Bloemfontein | 61321 | 116 049 | 50352 | −239,56 | 227 482 |
| 7 | Klerksdorp | 61321 | 125 487 | 50352 | −239,56 | 236 921 |
| 8 | Polokwane | 61321 | 146 161 | 50352 | −239,56 | 257 594 |
| 9 | Nelspruit | 61321 | 159 090 | 50352 | −239,56 | 270 523 |
| 10 | De Aar | 61321 | 107 812 | 50352 | −239,56 | 219 245 |

**Table 5.** Comparison of energy production from PV and grid for the selected locations.

| | | Energy generated from PV system | | Energy obtained from the grid | |
|---|---|---|---|---|---|
| Case study | City/Town | kWh/yr | (%) | kWh/yr | (%) |
| 1 | Pretoria | 62661 | 65.2 | 33440 | 34.8 |
| 2 | Upington | 63707 | 66.0 | 32880 | 34.0 |
| 3 | Cape Town | 60503 | 64.2 | 33744 | 35.8 |
| 4 | Port Elizabeth | 56944 | 62 | 34874 | 38.0 |
| 5 | Durban | 51674 | 58.6 | 36543 | 41.4 |
| 6 | Bloemfontein | 63357 | 65.5 | 33208 | 34.4 |
| 7 | Klerksdorp | 62583 | 65.2 | 33394 | 34.8 |
| 8 | Polokwane | 60893 | 64.3 | 33858 | 35.7 |
| 9 | Nelspruit | 59846 | 63.6 | 34213 | 36.4 |
| 10 | De Aar | 64023 | 66 | 32977 | 34 |

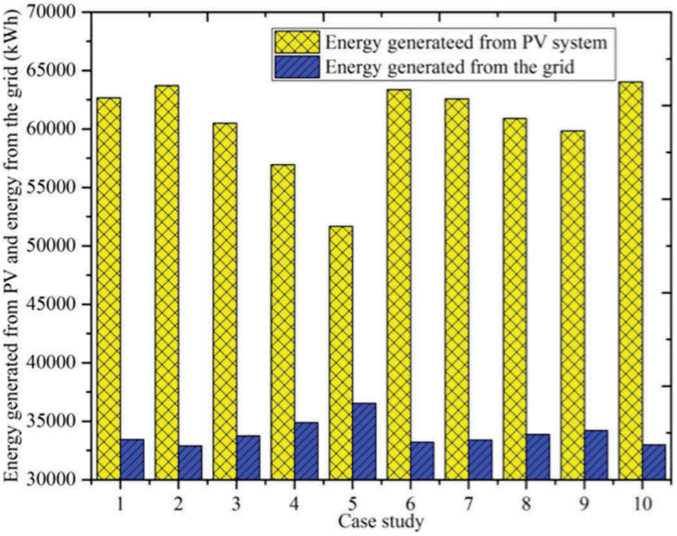


**Figure 14.** Energy production from PV and grid from each case study.

PV system with 64,023 kWh/yr which is about 66% and 32, 977 kWh/yr that translates to 44% unmet energy demand is obtained from the grid. The average daily solar radiation of De Aar in a year is 5.749617 kWh/m$^2$/day. The optimum operation of a microgrid system relies on the availability of this source of power. The energy generated from the PV system in case study 5 is 51,674 kWh/yr, this means 58.6% of the energy demand is obtained from the renewable energy source. While 36,545 kWh/yr that translates to 41.4% of the total electricity demand is sourced from the grid. The reduction in electricity production in case study 5 is attributed to variation in the local solar resources. This is because the output of the PV system is intermittent and location dependent. The average daily radiation of Durban in a year is 4.3 kWh/m$^2$/day. The energy produced by the PV system and energy sold in the grid has a significant difference when compared to case studies 1–9. It is well established from Table 6 that De Aar has the highest values of PV Penetration, capacity factor, hours of operation, mean output and total production among the selected locations owing to the presence of the adequate solar resources. On the basis other economic indicators that are presented in Table 7, it can be deduced that De Aar has the most economic feasible values of internal rate of return (IRR), discounted payback and simple payback when compared with other case studies. From the above-mentioned explanation, it shows that the optimal operation of the grid-connected microgrid system

**Table 6.** Fronius Symo 20.0-3-M with generic PV statistics.

| Case study | City/Town | PV Penetration (%) | Capacity Factor | Hours of Operation (hrs/yr) | Mean Output (kW) | Mean output (kWh/d) | Total Production (kWh/yr) |
|---|---|---|---|---|---|---|---|
| 1 | Pretoria | 97.2 | 17.9 | 4 384 | 7.15 | 172 | 62 661 |
| 2 | Upington | 98.8 | 18.2 | 4 369 | 7.27 | 175 | 63 707 |
| 3 | Cape Town | 93.8 | 17.3 | 4 370 | 6.91 | 166 | 60 503 |
| 4 | Port Elizabeth | 88.3 | 16.3 | 4 379 | 6.50 | 156 | 56 944 |
| 5 | Durban | 80.1 | 14.7 | 4 375 | 5.90 | 142 | 51 674 |
| 6 | Bloemfontein | 98.2 | 18.1 | 4 381 | 7.23 | 174 | 63 357 |
| 7 | Klerksdorp | 97.0 | 17.9 | 4 383 | 7.14 | 171 | 62 582 |
| 8 | Polokwane | 94.4 | 17.4 | 4 387 | 6.95 | 167 | 60 893 |
| 9 | Nelspruit | 92.8 | 17.1 | 4 380 | 6.83 | 164 | 59 846 |
| 10 | De Aar | 99.3 | 18.3 | 4 388 | 7.31 | 175 | 64 023 |

**Table 7.** Comparison of a grid-connected microgrid by using some economic indicators.

| Case study | City/Town | Locations | IRR (%) | Discounted payback (yr) | Simple payback (yr) |
|---|---|---|---|---|---|
| 1 | Pretoria | 25°44,4′S, 28°13,4′E | 56.7 | 1.92 | 1.76 |
| 2 | Upington | 28°23,4′S, 21°14,9′E | 57.7 | 1.88 | 1.73 |
| 3 | Cape Town | 33°55,5′S, 18°29,4′E | 54.9 | 1.98 | 1.82 |
| 4 | Port Elizabeth | 33°57,6′S, 25°37,2′E | 51.7 | 2.12 | 1.93 |
| 5 | Durban | 29°51,9′S, 31°1,4′E | 47.0 | 2.34 | 2.13 |
| 6 | Bloemfontein | 29°5,8′S, 26° 9,5′E | 57.4 | 1.90 | 1.74 |
| 7 | Klerksdorp | 26°51,9′S, 26°37,2′E | 56.7 | 1.92 | 1.76 |
| 8 | Polokwane | 23°53,3′S, 29°26,6′E | 55.2 | 1.97 | 1.81 |
| 9 | Nelspruit | 25°28,1′S, 30°58,6′E | 54.2 | 2.01 | 1.84 |
| 10 | De Aar | 30°40,2′S, 24°0,6′E | 58.0 | 1.87 | 1.72 |

depends on the availability of solar resources and other economic parameters.

## 9. Conclusion

The economic impacts and performance analysis of the PV systems are carried out in 10 locations in South Africa in line with the solar resources obtained from NASA databank. The power generated by the PV system is location-dependent and varies from one place to another based on the availability of solar resources. This shows that the availability of local renewable energy sources coupled with their different locations is a paramount factor that determines the optimal operation of the PV technologies in a grid-connected power system. This demonstrates that the key performance indicators of a microgrid system are affected by the availability of local renewable resources. This paper presents an approach to enhance South Africa energy security and also addresses the economic impacts of utilizing the PV units in the utility grid-connected power system. The results obtained from the research work can be utilized as standards to make managerial decisions in renewable energy project and can be used by the government agency and many international renewable energy organizations as benchmarks for renewable energy sustainability projects in South Africa.

The outcomes of the research works are summarized as follows:

(i) The annual utility bill savings range from R50, 760.1657 in Durban to R 62,473.0109 in De Aar. The best location for the installation of the PV unit is De Aar based on the availability of solar resources.
(ii) The least COE in the research work is R 0.181/kWh at De Aar while R0.335/kWh is the highest value of COE that is obtained in Durban.
(iii) The highest values of revenue that is found to be R 22,759.6401 is obtained in De Aar with the same load profile.
(iv) Among the 10 locations, the least energy purchased, net energy purchased and energy charge is De Aar with the following values: 32979 kWh, 3676 kWh and R 7942.9891.
(v) The best option to improve energy security in South Africa is to introduce some policies that will encourage the integration of PV technologies into the conventional power system.
(vi) The highest value of internal rate of return is obtained in De Aar with the value of 58% while the lowest is obtained in Durban with the value of 47%.
(vii) The integration of the PV system into the South Africa grid will reduce the GHG emissions and the effects of COE hikes as well as the provision of a reliable power supply at the load centers.

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## Appendix

## Appendix A. Utility monthly summary for Pretoria

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2801 | 2301 | 500 | 854.4641 | 1752.6717 |
| February | 2446 | 2118 | 328 | 642.1342 | 1613.2806 |
| March | 2923 | 2202 | 721 | 1082.476 | 1677.2634 |
| April | 2800 | 2300 | 500 | 854.33 | 1751.91 |
| May | 2944 | 2570 | 374 | 752.9702 | 1957.569 |
| June | 2912 | 2358 | 554 | 921.065 | 1796.0886 |
| July | 2904 | 2682 | 222 | 602.0358 | 2042.8794 |
| August | 2897 | 2504 | 393 | 764.8638 | 1907.2968 |
| September | 2689 | 2458 | 231 | 581.8236 | 1872.2586 |
| October | 2692 | 2474 | 218 | 569.7758 | 1884.4458 |
| November | 2724 | 2194 | 530 | 872.8694 | 1671.1698 |
| December | 2707 | 2311 | 396 | 742.2579 | 1760.2887 |
| Annual | 33439 | 28472 | 4967 | 9241.0658 | 21687.1224 |

## Appendix B. Utility monthly summary for Upington

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2607 | 2641 | −34 | 317.0369 | 2040.7007 |
| February | 2348 | 2295 | 53 | 365.6249 | 1773.3465 |
| March | 2845 | 2271 | 574 | 931.2343 | 1754.8017 |
| April | 2833 | 2216 | 617 | 970.8062 | 1712.3032 |
| May | 2921 | 2299 | 622 | 987.3955 | 1776.4373 |
| June | 2974 | 2140 | 834 | 1197.5352 | 1653.578 |
| July | 2974 | 2382 | 592 | 965.7718 | 1840.5714 |
| August | 2902 | 2392 | 510 | 877.5852 | 1848.2984 |
| September | 2719 | 2370 | 349 | 698.8552 | 1831.299 |
| October | 2606 | 2668 | −62 | 290.0872 | 2061.5636 |
| November | 2560 | 2575 | −15 | 328.9305 | 1989.7025 |
| December | 2590 | 2658 | −68 | 282.1954 | 2053.8366 |
| Annual | 32879 | 28907 | 3972 | 8213.0583 | 22336.4389 |

## Appendix C. Utility monthly summary for Cape Town

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2512 | 2697 | −185 | 159.6847 | 1984.1829 |
| February | 2272 | 2424 | −152 | 159.1048 | 1783.3368 |
| March | 2800 | 2345 | 455 | 811.2335 | 1725.2165 |
| April | 2864 | 2122 | 742 | 1094.6758 | 1561.1554 |
| May | 3194 | 1888 | 1306 | 1679.0716 | 1389.0016 |
| June | 3262 | 1688 | 1574 | 1944.854 | 1241.8616 |
| July | 3166 | 1817 | 1349 | 1716.4979 | 1336.7669 |
| August | 3213 | 1880 | 1333 | 1707.4774 | 1383.116 |
| September | 2798 | 2036 | 762 | 1104.9792 | 1497.8852 |
| October | 2605 | 2607 | −2 | 347.4151 | 1917.9699 |
| November | 2531 | 2583 | −52 | 289.6067 | 1900.3131 |
| December | 2528 | 2641 | −113 | 230.7847 | 1942.9837 |
| Annual | 33745 | 26728 | 7017 | 11245.3854 | 19663.7896 |

## Appendix D. Utility monthly summary for Port Elizabeth

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy Charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2774 | 2256 | 518 | 868.082 | 1560.4752 |
| February | 2463 | 1983 | 480 | 789.9843 | 1371.6411 |
| March | 3028 | 1946 | 1082 | 1442.2862 | 1346.0482 |
| April | 2981 | 1940 | 1041 | 1396.7178 | 1341.898 |
| May | 3153 | 2006 | 1147 | 1521.2992 | 1387.5502 |
| June | 3205 | 1787 | 1418 | 1787.8091 | 1236.0679 |
| July | 3149 | 2017 | 1132 | 1506.3973 | 1395.1589 |
| August | 3140 | 1969 | 1171 | 1542.5407 | 1361.9573 |
| September | 2889 | 1920 | 969 | 1315.4262 | 1328.064 |
| October | 2742 | 2211 | 531 | 876.2409 | 1529.3487 |
| November | 2701 | 2124 | 577 | 914.797 | 1469.1708 |
| December | 2650 | 2317 | 333 | 674.2791 | 1602.6689 |
| Annual | 34875 | 24476 | 10399 | 14635.8598 | 16930.0492 |

## Appendix E. Utility monthly summary for Durban

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 3023 | 1818 | 1205 | 1559.4128 | 1132.0686 |
| February | 2592 | 1678 | 914 | 1222.925 | 1044.8906 |
| March | 3115 | 1803 | 1312 | 1674.2239 | 1122.7281 |
| April | 2995 | 1860 | 1135 | 1488.619 | 1158.222 |
| May | 3172 | 1903 | 1269 | 1640.6865 | 1184.9981 |
| June | 3220 | 1683 | 1537 | 1903.7869 | 1048.0041 |
| July | 3190 | 1809 | 1381 | 1750.3627 | 1126.4643 |
| August | 3289 | 1786 | 1503 | 1880.478 | 1112.1422 |
| September | 3048 | 1700 | 1348 | 1699.7164 | 1058.59 |
| October | 2966 | 1727 | 1239 | 1584.3309 | 1075.4029 |
| November | 3022 | 1588 | 1434 | 1778.592 | 988.8476 |
| December | 2912 | 1782 | 1130 | 1472.7002 | 1109.6514 |
| Annual | 36544 | 21137 | 15407 | 19655.8343 | 13162.0099 |

## Appendix F. Utility monthly summary for Bloemfontein

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2701 | 2531 | 170 | 525.0131 | 1948.1107 |
| February | 2408 | 2219 | 189 | 503.9181 | 1707.9643 |
| March | 2905 | 2216 | 689 | 1049.4158 | 1705.6552 |
| April | 2851 | 2258 | 593 | 950.2352 | 1737.9826 |
| May | 2968 | 2431 | 537 | 912.2937 | 1871.1407 |
| June | 2968 | 2221 | 747 | 1113.4107 | 1709.5037 |
| July | 2938 | 2515 | 423 | 799.0929 | 1935.7955 |
| August | 2919 | 2474 | 445 | 817.6144 | 1904.2378 |
| September | 2695 | 2403 | 292 | 641.0479 | 1849.5891 |
| October | 2642 | 2614 | 28 | 381.1078 | 2011.9958 |
| November | 2602 | 2452 | 150 | 492.5832 | 1887.3044 |
| December | 2609 | 2567 | 42 | 390.0903 | 1975.8199 |
| Annual | 33206 | 28901 | 4305 | 8575.8231 | 22245.0997 |

## Appendix G. Utility monthly summary for Klerksdorp

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2788 | 2320 | 468 | 822.0744 | 1764.824 |
| February | 2448 | 2097 | 351 | 664.4295 | 1595.1879 |
| March | 2937 | 2150 | 787 | 1147.5616 | 1635.505 |
| April | 2853 | 2229 | 624 | 980.1921 | 1695.6003 |
| May | 2935 | 2502 | 433 | 808.2676 | 1903.2714 |
| June | 2922 | 2337 | 585 | 952.0947 | 1777.7559 |
| July | 2885 | 2646 | 239 | 615.7688 | 2012.8122 |
| August | 2913 | 2488 | 425 | 797.6558 | 1892.6216 |
| September | 2680 | 2463 | 217 | 567.2089 | 1873.6041 |
| October | 2687 | 2457 | 230 | 580.5977 | 1869.0399 |
| November | 2664 | 2307 | 357 | 699.1413 | 1754.9349 |
| December | 2683 | 2358 | 325 | 671.0428 | 1793.7306 |
| Annual | 33395 | 28354 | 5041 | 9306.0352 | 21568.8878 |

## Appendix H. Utility monthly summary for Polokwane

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2844 | 2227 | 617 | 972.2813 | 1649.5389 |
| February | 2471 | 2054 | 417 | 730.722 | 1521.3978 |
| March | 2986 | 2075 | 911 | 1272.8873 | 1536.9525 |
| April | 2822 | 2227 | 595 | 948.2617 | 1649.5389 |
| May | 2941 | 2462 | 479 | 853.1264 | 1823.6034 |
| June | 2954 | 2229 | 725 | 1090.4639 | 1651.0203 |
| July | 2941 | 2540 | 401 | 778.4258 | 1881.378 |
| August | 2919 | 2356 | 563 | 930.623 | 1745.0892 |
| September | 2723 | 2357 | 366 | 715.6725 | 1745.8299 |
| October | 2728 | 2383 | 345 | 696.2313 | 1765.0881 |
| November | 2773 | 2106 | 667 | 1010.6452 | 1559.9142 |
| December | 2756 | 2195 | 561 | 906.8493 | 1625.8365 |
| Annual | 33858 | 27211 | 6647 | 10906.1897 | 20155.1877 |

## Appendix I. Utility monthly summary for Nelspruit

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2878 | 2156 | 722 | 1077.3992 | 1568.9212 |
| February | 2494 | 1985 | 509 | 821.9147 | 1444.4845 |
| March | 3005 | 2047 | 958 | 1320.4471 | 1489.6019 |
| April | 2856 | 2196 | 660 | 1015.0716 | 1598.0292 |
| May | 2952 | 2455 | 497 | 871.8401 | 1786.5035 |
| June | 2935 | 2290 | 645 | 1011.3 | 1666.433 |
| July | 2968 | 2550 | 418 | 798.3274 | 1855.635 |
| August | 2933 | 2374 | 559 | 928.6696 | 1727.5598 |
| September | 2788 | 2179 | 609 | 957.1101 | 1585.6583 |
| October | 2774 | 2270 | 504 | 854.6742 | 1651.879 |
| November | 2837 | 1991 | 846 | 1190.6559 | 1448.8507 |
| December | 2793 | 2079 | 714 | 1058.3391 | 1512.8883 |
| Annual | 34213 | 26572 | 7641 | 11905.749 | 19336.4444 |

## Appendix J. Utility monthly summary for De Aar

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) | Revenue (R) |
|---|---|---|---|---|---|
| January | 2648 | 2665 | −17 | 338.8159 | 2069.9055 |
| February | 2366 | 2295 | 71 | 385.2773 | 1782.5265 |
| March | 2865 | 2302 | 563 | 923.3816 | 1787.9634 |
| April | 2831 | 2277 | 554 | 910.2029 | 1768.5459 |
| May | 2949 | 2385 | 564 | 935.6037 | 1852.4295 |
| June | 3026 | 2150 | 876 | 1244.7318 | 1669.905 |
| July | 2941 | 2453 | 488 | 861.7457 | 1905.2451 |
| August | 2913 | 2460 | 453 | 824.4714 | 1910.682 |
| September | 2702 | 2406 | 296 | 645.8174 | 1868.7402 |
| October | 2606 | 2699 | −93 | 260.3985 | 2096.3133 |
| November | 2555 | 2559 | −4 | 338.7947 | 1987.5753 |
| December | 2577 | 2652 | −75 | 273.7482 | 2059.8084 |
| Annual | 32979 | 29303 | 3676 | 7942.9891 | 22759.6401 |