Chapter 16

Techno-Economic Feasibility Study of Autonomous Hybrid AC/DC Microgrid System

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Additional information is available at the end of the chapter

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Abstract

Distributed generation technology based on diesel generators often has been considered as a viable solution to providing power to remote areas, but the sky-rocketing of diesel fuel price and the increasing cost of delivery to such remote sites have called for providing a sustainable solution that is environmentally friendly, economical, affordable, and easily accessible. To this end, the use of locally available energy resources is accepted as a sustainable solution in providing electricity for rural and remote settlements. The system cost of wind and solar energy systems is continuously decreasing because of the increase in the acceptance and deployment of the energy systems based on these renewable energy resources. A standalone hybrid AC/DC electric power system is designed, modeled, simulated, and optimized in HOMER Pro. HOMER is a Hybrid Optimization Model of Electric Renewable that enables the comparison of electric and thermal power production technologies across an extensive variety of applications. Both cycle-charging and load-following dispatched strategies are investigated. Plausible selected system components ratings are chosen for the simulation to ensure that there is enough search space for HOMER Pro to obtain an optimal system configuration. Net present cost (NPC) is used as an economic metric to assess the optimal configuration that is technically feasible.

Keywords: HOMER, wind, solar PV, renewable energy system, electrochemical devices, net present cost, economics analysis, Sub-Sahara Africa

1. Introduction

Energy access and affordability is a very big concern for the majority of the Africa populace. With over 620 million people without access to modern electricity in the Sub-Saharan Africa alone [1], different innovative solutions are being considered. Grid extension is definitely not an option because of the sparse population distribution, which makes the economic viability of such action infeasible. Distributed generation technology based on diesel generators has often been considered as a viable solution but the sky-rocketing of diesel fuel price and the increasing cost of delivery to remote sites have called for providing a sustainable solution that is environmentally friendly, economical, affordable, and easily accessible. To this end, the use of locally available energy resource has been accepted as a sustainable solution in providing electricity for rural and remote settlements. Matching the consumer demand profile and renewable energy production always has been perceived as enormous problem but can be mitigated by incorporating adequate sized energy storage systems [2, 3].

An autonomous electric power system is one that is not connected to the utility for one or all of the reasons given in the last paragraph. Wind and solar resources are local energy resources that can be efficiently and economically harnessed to provide electric power to remote site electricity consumers. While the cost of such renewable resources are cost-free, but the system required for harnessing and processing the energy plus the balance of system (BOS) is expensive. However, the system cost of wind and solar energy systems have been continuously decreasing because of the increase in the acceptance and deployment of the energy systems based on renewable resources. For the many Africa people who do not have access to modern energy system, it has been proven that high-quality electric power can be delivered to remote areas using local energy resources such as wind, solar, biomass, and so on [4–6].

Many of the historical technological advantages that resulted in AC power system to dominate over DC power systems are not valid any longer. For example, in the electric power generation sector, many distributed energy resources, such as electrochemical storage systems, fuel cells system, and photovoltaic systems, produce efficient and economical DC power. Many of the modern electrical and electronic loads, as well as energy storage systems, are either internally DC power operated or worked equally well with DC power sources and connect to the AC systems through power electronic converters [7]. Overall improved system efficiency, reduced system cost, increased reliability, and reduced system footprint are attained when multiple conversion stages are eliminated in externally operated AC power system for internally operated DC power devices. Also, many power quality issues, such as harmonics and unbalances, are not present in DC power systems [8, 9]. Advancements in power electronic technology continue unabated, leading to more applications in modern systems such as VSC-HVDC, electric vehicles, wireless power transfer, fuel cells vehicles, and so on [10, 11].

The design of hybrid renewable energy systems has been extensively studied, and numerous optimization techniques, such as genetic algorithm (GA), linear programming, etc., have been implemented for optimum economic and technical feasibility [12–16]. Many software packages, such as HOMER Pro [9], RETScreen [17], and Hybrid2 [18], have been developed for the proper selection of appropriate generation technologies and capacity sizing. This software makes a multi-objective optimization process easy to carry out to arrive at a robust and reliable decision. HOMER Pro is user-friendly software produced by the national

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renewable energy laboratory by the department of energy in the USA. It uses hourly data for the assessment of hybrid renewable energy systems and performs optimization based on net present cost (NPC). HOMER Pro is used in this study because of its proven ability to design, model, simulate, and perform sensitivity analysis of complex mix of different energy technologies, thermal and electrical load, and storage devices. Both cycle-charging and load-following dispatch strategies are available to choose from or use simultaneously as utilized in this study [19, 20].

The rest of the chapter is organized as follows. A brief discussion of two different dispatch strategies used in hybrid energy systems is provided in Section 2 of this chapter. All the energy system components of the studied autonomous hybrid AC/DC microgrid system are briefly discussed in Section 3. Section 4 explains the capability and functionalities of Hybrid Optimization Model of Electric Renewable (HOMER) as powerful software that is designed and optimized for modeling, simulating, optimizing, and performing sensitivity analysis of micropower systems. The system model and simulation process of the studied hybrid system is comprehensively detailed in Section 5 of this chapter. The system simulation results and discussion and conclusion are given in the penultimate and Section 7 of this chapter, respectively.

2. Cycle-charging and load-following dispatch strategy

Two system dispatch strategies are employed in HOMER Pro namely: cycle-charging and load-following dispatch strategy. Under the load-following dispatch strategy, a power generator produces only enough to serve the load and does not charge the battery bank. For the cycle-charging dispatch strategy, the generator run at full power to serve the load and any excess is used to charge the battery [7].

Tuglie and Torelli [21] developed a new load following dispatch algorithm that correlates system imbalances with unbalanced transaction in a bilateral transaction-based market. The developed algorithm is implemented on the IEEE 30-bus test system under a variety of operating conditions. In Bizon [22], a hybrid power source comprising wind energy conversion system, solar Photovoltaic system, and fuel cell system with energy storage system is designed and optimized for load-following dispatch strategy. The battery/supercapacitor hybrid energy storage system operates as an auxiliary source for supplying the power deficit based on dynamic balance strategy. An optimal energy management system for a stand-alone wind turbine/photovoltaic/hydrogen/battery hybrid system with supervisory control based on fuzzy logic is presented in Pablo et al [23]. The energy management system in Ref. [23] uses a fuzzy logic control to satisfy the energy demanded by the load and maintain the state-of-charge of the battery and the hydrogen tank level between desired target margins, while trying to optimize the utilization cost and lifetime of the energy storage system. A new method to model and control the aggregated power demand from a population of thermostatically controlled load, with the goal of delivering ancillary services such as frequency regulation and load following, is developed by Callaway [24]. It is shown in the paper that identified models perform only marginally better than the theoretical model. Subho and Sharma [25] developed a hybrid system with cycle charging dispatch strategy using swarm optimization algorithm for a remote area in India. A comparative study of particle swarm optimization (PSO), genetic algorithm, and HOMER is performed in Ref. [25]. PSO is judged to be better than GA and HOMER in terms of the minimum cost of electricity generation. In another paper by Subho and Sharma [26], different optimization algorithms and software packages are used to evaluate the economics of a hybrid renewable energy system. It is concluded that cycle charging strategy is most cost-effective compared to the load following and peak shaving dispatch strategies.

Both dispatch strategies are employed in this study to determine which is economically viable and technically feasible.

3. Energy system components

For the considered autonomous electric power system model in this study, all the components and energy resources involved are briefly discussed. The components related to this work are Solar PV, wind energy conversion system (WECS), electrochemical battery storage device, and bidirectional power electronics converter.

3.1. Solar PV energy system

Solar PV technology uses semiconductor material, such as silicon, to convert solar radiation energy to direct current (DC) electrical power. The generated DC power is regulated by charge regulator to charge electrochemical battery storage device. The electrochemical storage device supplies power directly to the electrical load if it is a DC load. If not, an inverter is used to convert the DC power supplied by the electrochemical storage device into an AC power for the AC load.

PV cell is usually modeled using a single diode or double diodes, but a single-diode model is shown in **Figure 1**. Series and shunt resistances represented in the figure are used to represent the leakage current and the inherent loss due to internal electrical connection, respectively [27–29].

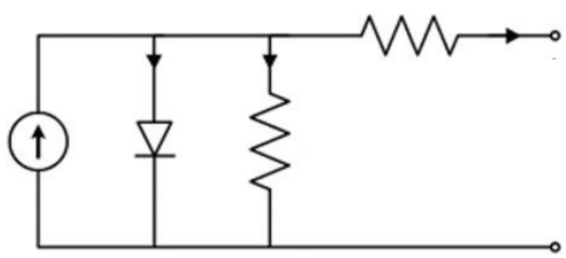

Figure 1. Single-diode model of solar cell.

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The insolation intensity is strongly related to the solar cell current, and the cell operating temperature is inversely proportional to the output voltage across the solar cell. These factors basically limit the maximum power that can be generated by the solar cell [30].

Homer Pro calculates the power output of the PV array using equation 1 below.

$$P_{PV} = f_{PV}\, Y_{PV} \frac{I_T}{I_S} \tag{1}$$

Where f_{PV} is the PV derating factor, Y_{PV} is the rated capacity of the PV array (kW), I_T is the global solar radiation (beam plus diffuse) incident on the surface of the PV array (kW/m^2), and I_S is the standard amount of radiation used to rate the capacity of the PV array given as 1 kW/m^2.

A generic flat plate PV system is selected for the modeled hybrid microgrid from the HOMER Pro components library with a rated capacity of 40 kW. The capital cost of the PV is \$3000/kW$_p$, replacement cost of \$2000, and operation and maintenance cost of \$10.00/year.

3.2. Wind energy conversion system

A blowing wind consists of kinetic energy carried by the atmospheric air. The moving air is converted to rotational kinetic energy by the rotor blade of the wind turbine system. The rotating rotor is coupled via a solid shaft to an electrical generator to generate AC electric power. The extraction of the power contained in the moving is limited by the aerodynamic efficiency of the rotor blade as illustrated in **Figure 2**.

The theoretically generated turbine power limit of which is 59% is known as the Betz limit. Most of the modern wind turbines are practically in the 30–40% range. Equation 1 below gives the relationship between the extracted power and other parameters and variable of a wind

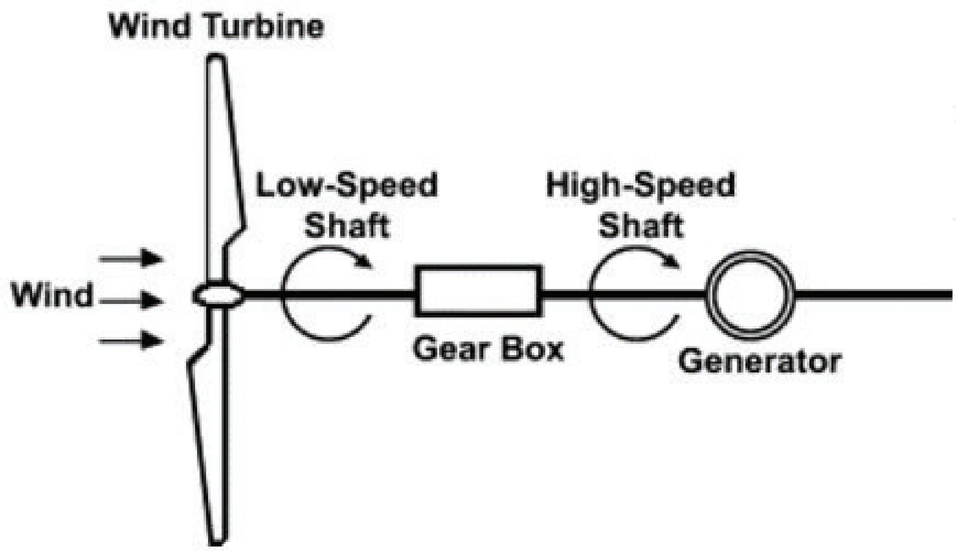

Figure 2. Wind energy conversion system (WECS) adopted from Ref. [31].

energy conversion system. The wind speed is strongly coupled to the available power, whereas the power coefficient depends on the tip speed ration (TSR) and the blade pitch angle [10, 16].

$$P = \frac{1}{2} A \rho C_p V^3 \tag{2}$$

A is the rotor swept area, ρ is the air density, C_p is the power coefficient that is dependent on the rotor blade pitch angle and tip speed ratio, and V is the average wind speed.

HOMER Pro determines the output power of the wind turbine in a four-step process. In the first step, it determines the average wind speed for the hour at the anemometer height by referring to the wind resource data. In the second step of the process, it determines the corresponding wind speed at the turbine's height using either the logarithmic law or the power law (the logarithmic law is used in this study). Thirdly, it refers to the turbine's power curve to calculate its output power value at that hourly wind speed assuming standard air density. Finally, it multiplies that output power value by the air density ratio, which is the ratio of the actual air density to the standard air density. HOMER Pro also assumes that air density ratio is constant throughout the year.

A generic wind turbine model of 10 kW rated power is selected in HOMER Pro for the study. The capital cost is $5000/kW, replacement cost of $5000/kW, operation, and maintenance cost of $500/year, operational lifetime of 20 years. The hub height of the generic wind turbine model is 24 m above sea level. The power curve of the selected turbine is shown in **Figure 3**.

3.3. Electrochemical battery energy storage system

A common electrochemical energy storage used in autonomous and emergency standby is Lead-Acid battery that has proven to be robust, cost-efficient, and cost-effective. However, many new battery technologies are being developed and utilized for practical applications with improved operational characteristics but are currently more expensive than the traditionally used battery technology [7]. With the interest in electric vehicle, lithium-ion battery technology is in the pole position to be the mainstream electrochemical technology

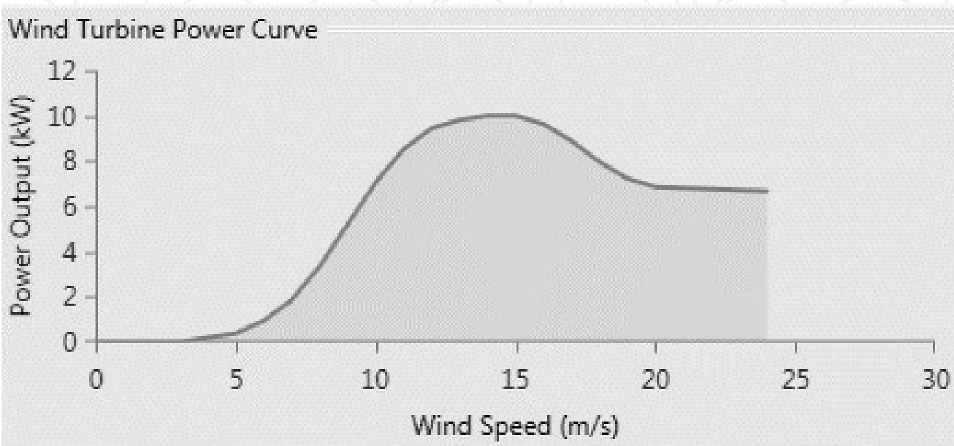

Figure 3. 10 kW generic wind turbine power curve (HOMER Pro).

for various applications. Among the operational parameters of Lead-Acid battery, maximum state of discharge (DOD), minimum state of charge (SOC), cycle times, round trip efficiency, maximum charge rate, maximum discharge rate are the most important. This battery technology also needs regular maintenance and should be well ventilated especially if it is not the sealed type [7].

A generic 1 kWh lead-acid battery is selected from the Homer Pro library for the hybrid microgrid presented in this study. The nominal voltage of the battery is 12 V configured in a string of 20 batteries (240 Vdc) to conform to the bidirectional rectifier rated input voltage. The maximum capacity and round trip efficiency of the battery are 83.4 Ah and 80% respectively. The capital cost is $300/kWh, replacement cost of $200/kWh, operation and maintenance cost of $20/unit/year.

3.4. Static power converters

Power electronics converters are needed for various power conversions and conditioning to optimally match electrical power source with electrical and electronic loads. Four main types of such converters are available: AC-AC, AC-DC, DC-DC, and DC-AC power converter [7]. A bidirectional power electronic converter is considered in this study because the wind energy conversion system is modeled as an AC power source, whereas the energy storage and solar PV are modeled as DC power source. Such power electronic converter allows power to flow bidirectionally between the AC and DC bus. Such functionality is possible by adequately

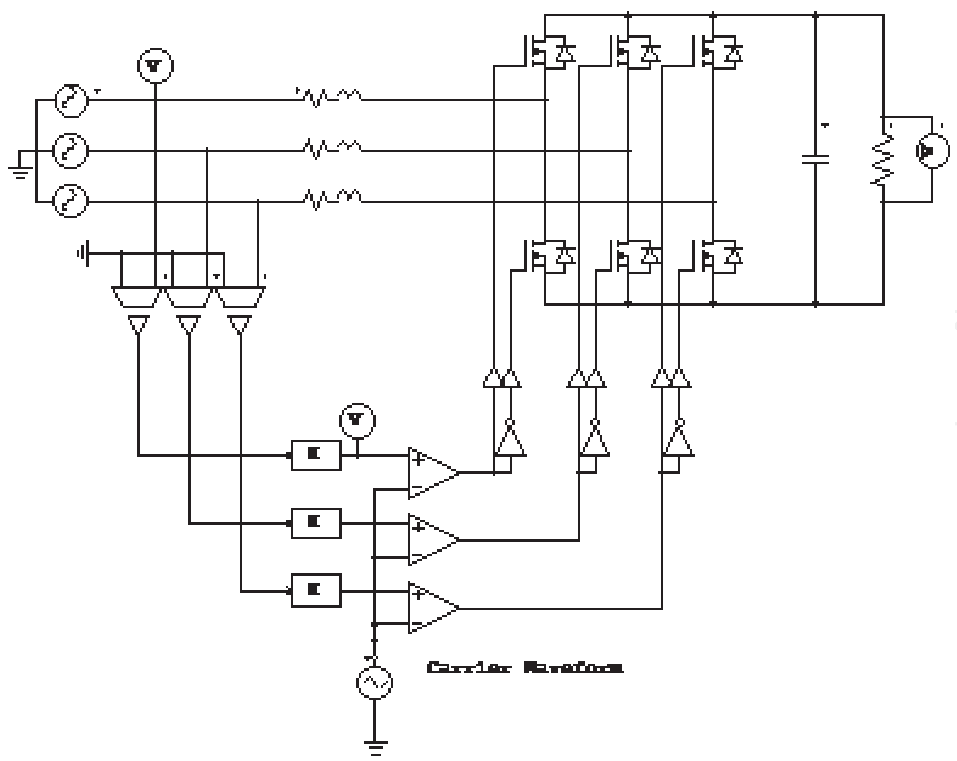

Figure 4. Three-phase pulse-width modulation (PWM) rectifier.

modulating the semiconductor switches that are embedded in the power converter topology [7, 32]. Such configuration that operates as an active end rectifier is shown in **Figure 4**.

HOMER Pro assumes that the inverter and rectifier capacities are not surge capacities that the device can tolerate for only short periods of time, but rather, constant capacities that the device can withstand for as long as needed [7].

A Leonics MTP41FP 25 kW 240V DC bidirectional power converter is selected for the studied hybrid AC/DC microgrid to interconnect the DC and AC bus. The capital cost of the bidirectional converter is $600/kW, replacement cost of $600, operation and maintenance cost of $0/year. The lifetime of the selected converter is 10 years and its inverter efficiency is 96% while the rectifier relative capacity is chosen to be 80% and its efficiency is 94%.

Table 1 shows the associated costs of all the system model components. These costs are used in Section 4 to perform the system simulation in HOMER Pro software.

System component	Capital cost per unit of rated value	Replacement cost per unit	Operating and maintenance cost per unit per year
PV panels	$3000	$2000	$10
Wind turbine	$5000	$5000	$500
Bidirectional power converter	$600	$600	$0
Electrochemical battery storage system	$300	$200	$20

Table 1. Costs of system model components [33].

4. HOMER pro simulation environment

HOMER Pro software is able to evaluate off-grid or grid connected power system design, choose the best system based on cost, technical requirements, or environmental considerations. It can also simulate many design configurations under market uncertainty and evaluate risk plus the ability of the modeler to choose the best addition or retrofit for an existing system [7].

HOMER Pro software is used in this research investigation. Wind energy conversion system, solar PV system, bidirectional converter, electrochemical batteries, AC primary load, and renewable resources are modeled and analyzed. Energy resources data, system components data, typical community load profile, and system components costs are some of the important parameters that are used as inputs in the HOMER Pro model. AC and DC bus are created in the HOMER Pro model to facilitate the connection of different types of locally available resources. HOMER Pro is able to optimize feasible electric power system configurations that are technically possible [7]. Sensitivity analysis of feasible configurations

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is performed to give an indication of the system robustness which is reported in Section 4 that follows.

5. System modeling and simulation

The investigated hybrid AC/DC microgrid system model architecture is shown in **Figure 5**. The system consists of two electrical buses: AC and DC bus. To ensure improved overall system efficiency, 25% of total electrical load is the DC load that is connected to the DC bus. The wind turbine and solar energy system are connected to the AC and DC bus, respectively. In modeling the battery, HOMER Pro includes in the battery model, a charge regulator to ensure that the specified operating condition is not violated via the SOC and DOD characteristic curves. The interlinking power converter connects the two buses together by acting as a rectifier or inverter depending on the power state of the hybrid system. In the rectifier mode, it transfers power from the AC bus to the DC bus whenever there is excess power in the AC bus and there is instant demand of power from the DC bus. Alternatively, in the inverter mode of operation, power is transferred from the DC bus to the AC bus whenever there is excess power on the DC and there is instant demand of power from the AC bus. In both modes of operation, the SOC of the energy storage system is to be taken into consideration. The dispatch strategy can be set in HOMER Pro. Load-following and cycle-charging dispatch strategies are available for selection in HOMER Pro. Under the load-following strategy, generators produce only enough power to serve the load, and do not charge the energy storage device. For the cycle-charging, the excess energy available after serving the load is used to charge the battery [2, 7, 34].

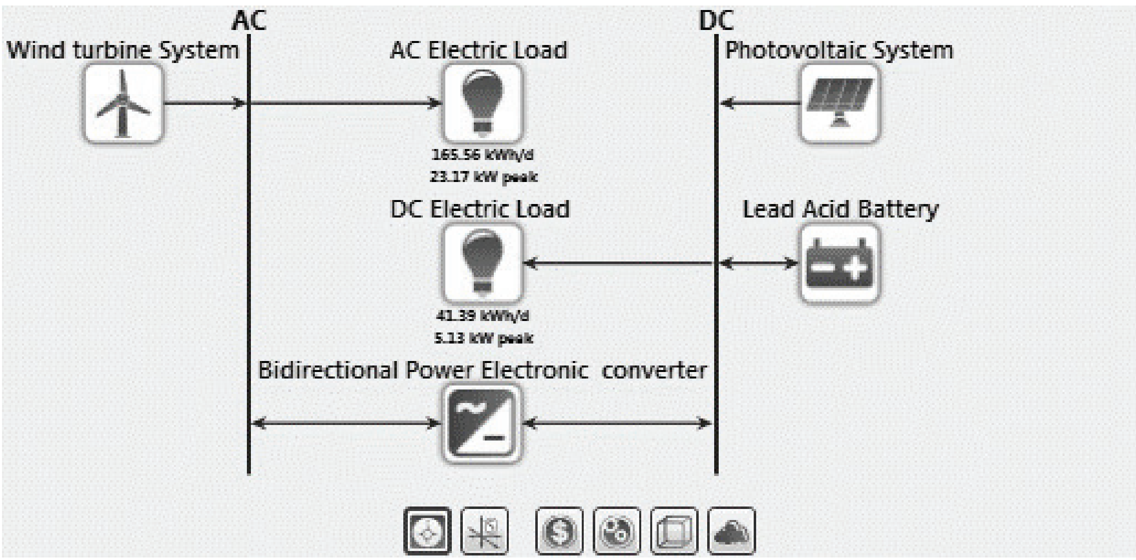

Figure 5. Autonomous AC/DC hybrid microgrid system.

The simulation process models the micropower system under investigation, and the optimization process determines the optimal system configuration that satisfies the modeler-specific constraints at the lowest total net present cost. The sensitivity analysis functionality of HOMER Pro allows energy planner, which energy technology combinations are optimal under different conditions [7, 9].

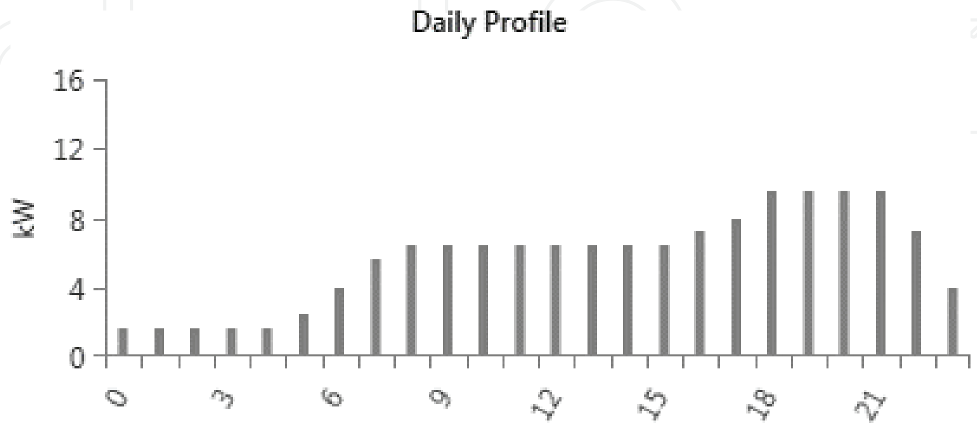

Figure 6. Community daily AC load profile.

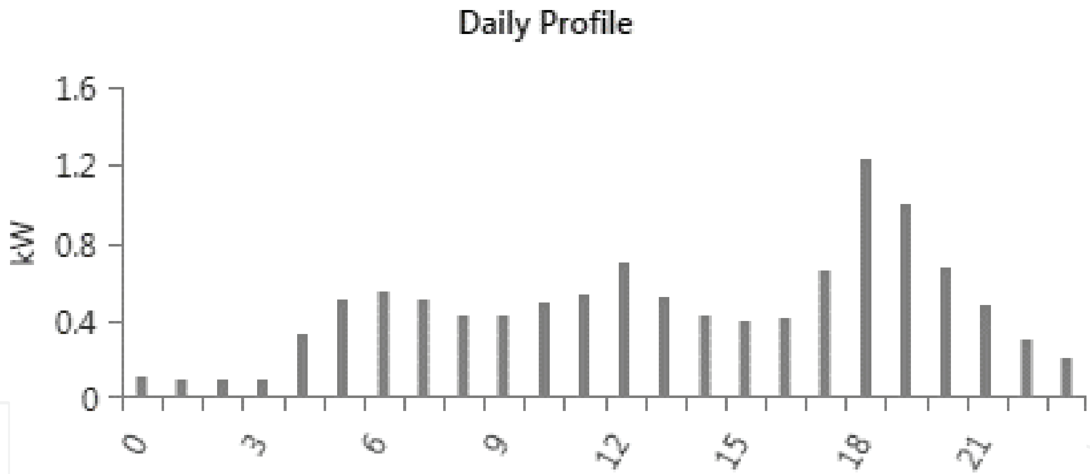

Figure 7. Community daily DC load profile.

Electrical loads		
	AC load	**DC load**
Average consumed energy	165.56	14.39
Average power (kW)	6.9	0.6
Peak power (kW)	23.17	2.67
Load factor	0.3	0.22

Table 2. Community load profile data.

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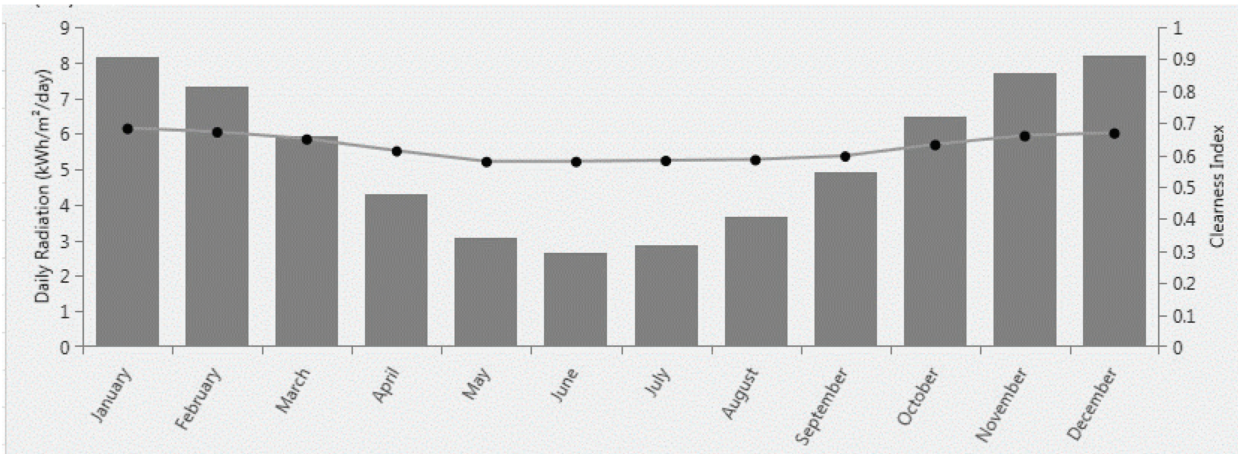

Figure 8. Monthly average solar global horizontal irradiance of Cape Town South Africa.

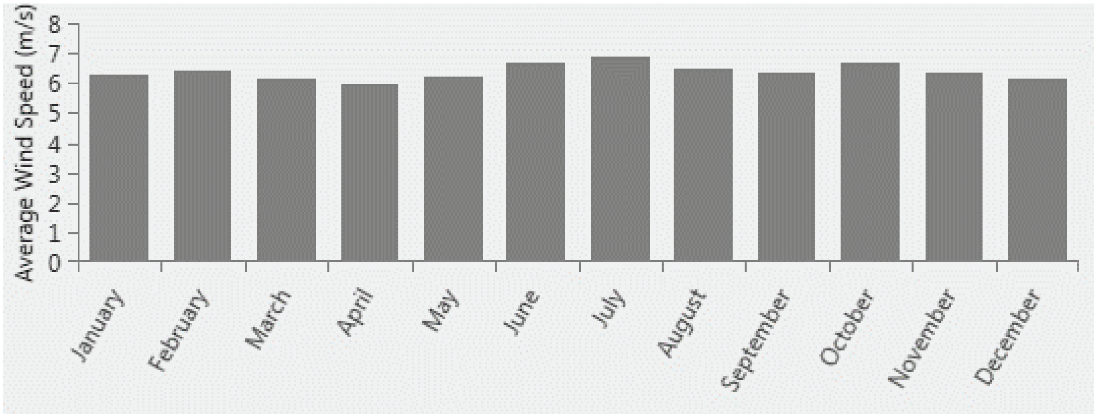

Figure 9. Average wind speed of Cape Town South Africa.

The AC load daily and DC load profiles are shown in **Figures 6** and **7**, respectively. The data used for this plot are shown in **Table 2**. The community load profile used in this study is the reference load date available in the HOMER Pro library [9].

The wind and solar resource data are obtained from the NASA Surface Metrological and Solar Energy database website. **Figure 8** depicts the monthly average solar global horizontal irradiance data. These monthly average data are averaged over 22-year period (July 1983–June 2005) [35]. The solar irradiance of Cape Town is low during the winter months of April, May, June, and July as shown in **Figure 8**. The wind speed data are also obtained from NASA Surface Metrological and Solar Energy database website. Wind speed at 50 m above the surface of the earth for terrain similar to airport, and monthly averaged values over 10 years period (July 1983–June 1993) are used in this work. These data are displayed in **Figure 9** (NASA Surface Meteorology and Solar Energy).

The Cape Town average wind speed as reported by the NASA database is nearly constant throughout the year, with average speed hovering around 6 m/s.

6. Results and discussions

The hybrid microgrid system consisting of PV system, wind turbine, bidirectional converter, lead-acid battery, and DC and AC load shown in **Figure 4** is simulated in HOMER Pro software environment. Both cycle-charging and load-following dispatched strategies are investigated. Plausible selected system component ratings are chosen for the simulation to ensure that there is enough search space for HOMER Pro to obtain an optimal system configuration. Net present cost is used as an economic metric to assess the optimal feasible configuration.

The optimal system configuration with load-following dispatch strategy consists of a 50-kW generic flat plate PV system, 20 kW wind turbine, 15 kW bidirectional power electronic converter, and 160 kWh lead-acid battery consisting of eight string. The initial capital cost of this optimal configuration is $307 000. The total present cost is $558,717, with levelized cost of energy (COE) being $0.3652, and the operational cost is of $11 363 throughout the project lifetime. The number of autonomy is 11 days. For more simulation results, see **Figure 10**.

The optimal system configuration with cycle-charging dispatch strategy consists of a 30-kW generic flat plate PV system, 20 kW wind turbine, 15 kW bidirectional power electronic converter and 140 kWh lead-acid battery consisting of seven strings. The initial capital cost of this optimal configuration is $241,000. The total present cost is $453,517, with levelized cost of energy (COE) being $0.2973, and the operation cost is of $9 593 throughout the project lifetime. The number of autonomy is 10 days. For more simulation results, see **Figure 11**.

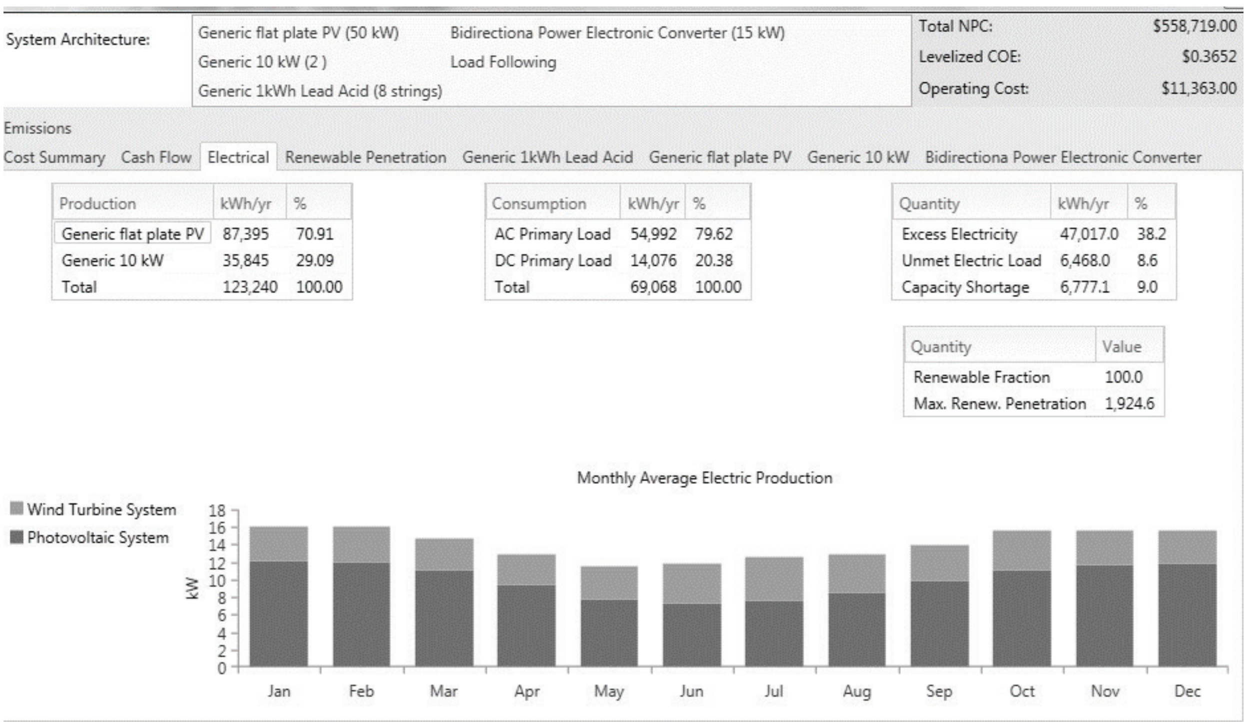

Figure 10. Simulation results of the optimal architecture with load-following dispatch strategy.

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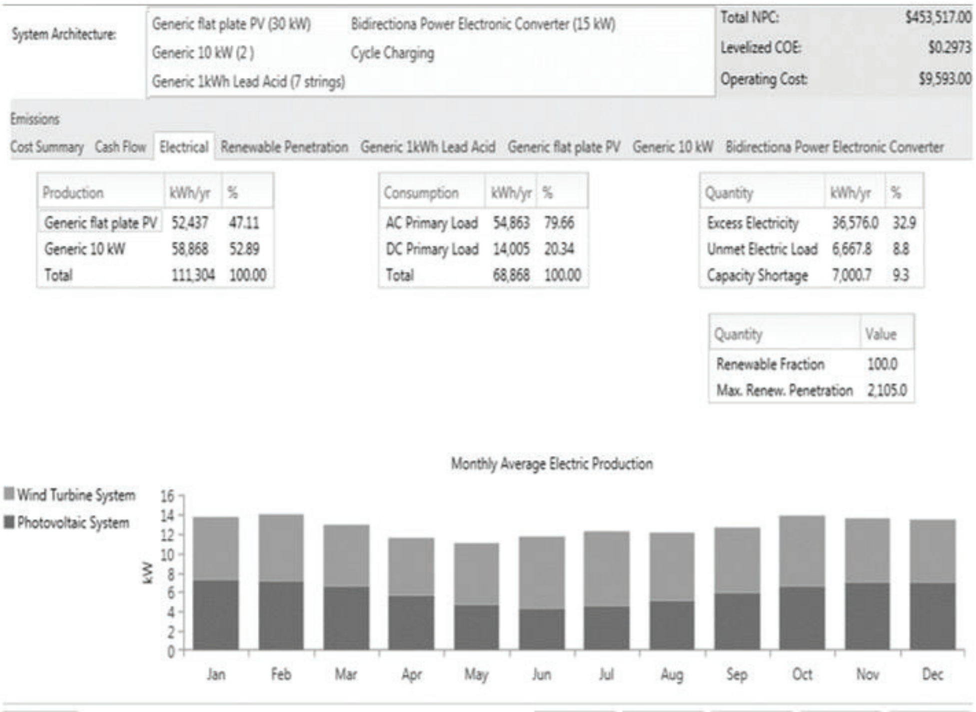

Figure 11. Simulation results of the optimal architecture with cycle-charging dispatch strategy.

For the same technically feasible configuration, the total net present cost and the initial capital cost of the load-following dispatch strategy are more expensive than the cycle-charging dispatch strategy. The levelized cost of energy of optimal configuration with load-following strategy is higher compared to the one with cycle-charging dispatch strategy. In the periods of extended cloudy season and low solar insolation, the configuration with load-following dispatch strategy offers a marginally extended period of autonomy.

7. Conclusion

The use of renewable energy as local energy resources enhances the accessibility and affordability of energy to unconnected areas around the world. Renewable energies, such as wind, solar, and biomass, have the potential to reduce the energy poverty of rural areas and sites very far from the grid. Being local resources, they also provide higher energy security to the populace.

The technical and economic analysis of the designed hybrid AC/DC micropower system studied in this work reveals the optimal electric power system configuration that is technically and economically viable using the net present cost as the econometric index. It is concluded that it is marginally better to dispatch load-following strategy for higher net present cost and autonomy compared to cycle-charging strategy dispatch. For lower levelized cost of energy (COE) and initial capital cost, it is marginally better to consider a cycle-charging dispatch strategy compared to a load-following dispatch strategy.

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