Article

A Review of Microgrid-based Approach to Rural Electrification in South Africa: Architecture and Policy Framework

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Abstract: Access to electricity for every South African citizen, including rural dwellers, is a human right issue guaranteed by the government's laws and policies. However, many remote rural areas still suffer from lack of the very important amenity, due to the expensive prospect of connecting them to the central national grid. The feasible approach to connecting the rural communities to electricity supply is suggestively through the use of microgrid solutions. The microgrid technology is a very recent and viable option to the energy revolution. Microgrids result from the incorporation of energy storage systems, distributed generators, and localized loads. The application of this technology requires a deliberate and extensive work on the operational architecture and the policy framework to be adopted. The energy storage devices form an integral part of the microgrid configuration or architecture to make sure more maintainable and constant operation is attained. This paper presents a review of the architectures of the existing microgrid systems, as well as the policy framework for implementable solutions. The various architectures display the peculiarity of the systems based on the increased grid performance, stability, quality of electricity, and other comparative advantages. The microgrid architectures are fundamentally recognized according to their AC, DC or hybrid distribution buses, and the complexity inherent to them. In the policy and development section, the problems are treated as 'a search for the truth' — a truth being revealed by close and objective examination. The core of the problem to be solved is revealed clearly, thereby giving the basis for simplifying and solving it. The policies encourage the accomplishment of a zero-carbon dioxide (CO_2) emissions, energy security attainment, the meeting of the electricity demand, and lastly, the promotion of access to electricity in rural areas. It is established that the returns through charges of the consumers are very insignificant. Although returns on investment always come in conflict with the human right demands of the local indigenes, the policy framework would be explicit on the mode of returns for the government, private partners and the communities — a return that can be short-term, medium-term or long-term. The policymakers would be keen on the exhaustive analysis of issues, leading to optimal decision making.

Keywords: Microgrids; energy demand; policy framework; grid architecture; distributed generation; energy storage systems.

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0. Introduction

Most remote rural communities in South Africa (SA) do not have access to electricity. The South African Government (SAG) provides energy to her citizens and inhabitants as a fundamental right, through power supply from a central national grid. All the main cities and the remote rural areas have a common right of access to electricity. However, the rural communities are located at distances apart and far away from the central grid. Hence, the provision of energy for the various communities via the connection to the grid becomes economically unviable, both in terms of energy quality, cost, security and loss. Meanwhile, the immediate returns on investment in these areas are insignificant and almost nothing because charges through electricity tariffs from the consumers are extremely low. The main purpose of electricity for the rural dwellers is domestic use, electricity affordability remains a challenge. The SAG must intervene in making access to electricity possible in a customized form to meet the consumers' needs and their capacity to pay [1]. The conventional centralized grids continue to experience struggles with issues like reliability, stability, sustainability, power quality, and efficiency [2], [3]. The conventional energy distribution mode in South Africa significantly consist of coal and nuclear plants which are located far away from the remote rural communities thereby making power distribution cost very high [4]. However, grid extension is not sustainable in providing electricity to remote rural communities.

A decentralized approach of microgrid solutions is the viable alternative for providing the required energy demand with the right policy framework for support. The high cost of extending grid to remote SA communities and other developing nations with little or no economic activity has increasingly made a researched microgrid approach the attractive measure to solve the problem of energy provision [2], [3]. The brand of energy technology provides improvement for the living standard of the rural dwellers. Also, it positively impacts the social strata of the communities through local content harmonization and encouragement of feasible and efficient energy systems. According to Akinbulire et al. [5], the envisaged decentralized approach is researched and established to be economically viable for remote communities. In 2008, the World Bank reiterated that grid extension is mainly viable as an alternative for urban electrification and about 28% for the remote communities. The further focus is the system viability for power supply to the majority (72%) of the remaining rural communities. Therefore, the use of stand-alone grids or microgrids is regarded as an alternative solution with the need for appropriate architecture and policy formation relating to funding models. With the right models and policy frameworks, renewable energy-powered microgrids will provide electricity for a larger rural population at a very low cost in comparison to the required cost for the conventional generators [6], [7].

Microgrids are interconnections of power generators, storage devices and the distribution equipment to make power available to selected isolated consumers. The number of target consumers differentiates the sizes of the grids, whether to be referred to as "micro or mini" grids. The microgrids rate at about 160 to 700 kW while the mini-grids have power generation ranging from 5 to 12 kW. The microgrids are designed for isolated operation, or rarely through connections to the national utility facilities [8]–[11]. Microgrids have been considered as preferred alternatives to the weakening conventional energy distribution structure, especially in supplying modular consumers. Microgrids can operate as well-adjusted electricity cells in the current supply grids or as standalone electricity systems for few populations. A microgrid has the capacity of providing platforms for easily-adaptable power system networks within the existing centralized grid during planning programmes for the network expansion. Microgrids provide distinctive competitive benefits to consumers and advance considerable advantages within the entire energy chain. The utility grid has presented an opportunity to unearth microgrid as a way out to upcoming electrical network problems namely forever growing electrical demand, collecting energy from renewable energy sources, make certain the consistency and power quality. The system provides intervention which includes increased energy utilization, enhanced energy proficiency, reduced environmental impression (reduction in the CO_2 emissions), improved power supply reliability, increased grid capacity, clog support, improved grid safety and better cost-effective energy configuration substitution [12], [13].

The majority of the power projects in the country are composed of either coal or nuclear generation plants and is built and managed by SAG institutions. Renewable energy (RE) based microgrids are becoming more popular and adaptable with the incorporation of distributed generations. Across many nations, investors are leveraging on the decreasing cost of RE technologies, along with the discouraging very high cost of fuel-powered plants to focus investments in the area of microgrids [14]. Some countries have made remarkable progress in the establishment of microgrids and mini-grids. China has approximately 22,000 microgrid projects. Also, each of Vietnam, India, Nepal, and Sri-Lanka has between 50 to 700 microgrids projects [15]. Despite the benefits of microgrids and the improvement they provide for electricity access, the rate of adoption is still low in many developing countries. The causes of the low adoption and implementation could be attributed to economic, socio-political and technical issues. Access to the required funds is a major barrier in the implementation of the result-oriented systems in rural communities [6], [16]. A very huge upfront investment cost is predictably incurred in implementing microgrids for the remote areas, and the returns on such investment are expectedly very low from the target market. The initial capital for setting up such systems is predictably greater than the required capital for commensurate diesel-powered generators [14].

Access to electricity in South Africa by both modern cities and rural dwellers is a common human right issue. However, the absence of economic activity in remote rural communities makes returns on investment through charges of the consumers very insignificant. A robust government policy framework is needed and influential to ensuring the required attraction for future investment in microgrids for rural dwellers in South Africa. A framework to facilitate the most suitable business model for developing the best schemes for providing electricity for the communities. In addition, it enables small-scale and localized architecture that will make the management of the equipment easier and consequently minimizes the possible technical and non-technical losses of the existing network. The improved reliability will lower the total cost when considered as a long-term facility, aided by the partnership of government, private investors and the communities [13].

This paper reviews the details of the existing architectures of microgrid systems, and the policy framework for implementing feasible power supply solutions to SA remote rural communities. It provides an extensive discussion of the various microgrid architectures and highlights the peculiarity of the systems based on the increased grid performance, stability, quality of electricity, and other comparative advantages. The paper also discusses the needed policy framework that meets the electricity demand and quality. A framework that ensures a balance between the human right demand for access to electricity by the consumers and the possibility of returns on investments in energy provision by the government, private partners and the communities – a return that can be short-term, medium-term or long-term. The remaining part of the paper is structured as follows: Section 2 reviews the existing electricity supply in South Africa, section 3 reviews the various architectures of microgrid systems, section 4 discusses the policy framework for the implementable microgrid systems, and section 5 concludes the paper.

1. Existing Electricity Supply Chain in South Africa

South African energy is mainly generated from coal with about 59% of its total primary energy capacity. The other local sources of energy in South Africa include natural gas, hydropower, biomass, nuclear, solar and wind power. This is indicated in Figure 1. The country has an abundance of coal in the eastern region, known as Mpumalanga province, which thus explains why most of the power plants are located in the area [17]. The energy outputs from the various plants are harnessed into a centralized grid from which every part of the country is being supplied with electricity [18]. The SA coal are plenty and cheap, thereby enabling energy costs in the country to be very low. However, the present dependence on coal-fired power plants makes SA one of the countries with the highest CO_2 emissions, which contibute to climate changes. The increasing population in the South African cities and the energy demands in the rural communities continuously dictate the need for expansion in the supply capacity of the energy sector. Also, it is imperative to ensure optimal use of resources, energy security, and common access across the board [17], [19], [20].

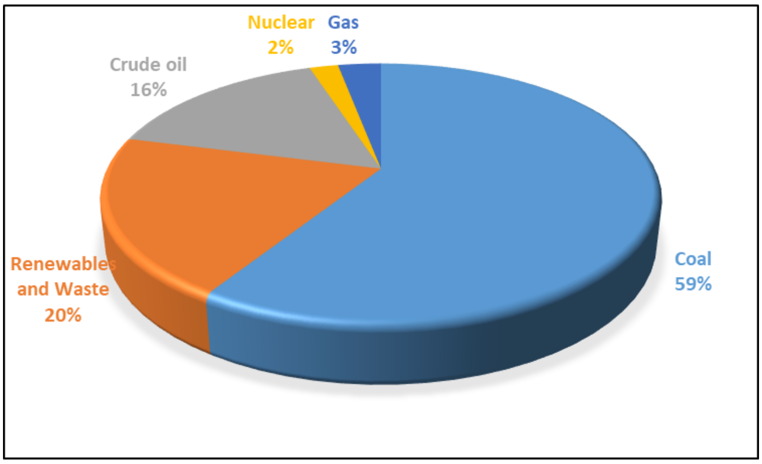

Figure 1. Primary Energy Supply in South Africa.

Electricity supply in SA is vertically integrated with Eskom, the only power transmission licensed company. The power distribution responsibility is shared among Eskom, the municipalities and some other licensed distributors. The SA electricity end-users are categorized as agriculture (2.6%), industrial (37.7%), domestic (17.2%), mining (15%), transport (2.6%), commercial (12.6%), and general (12.3%). In the SAG gazette No 31741 of 2008, the major objectives in the electricity sector include non-discriminatory and open access to the transmission system, increased social equity to cater for the low-income earners, improved competitiveness and efficiency for the provision of high-quality and low-income inputs in all sectors, sustainable and environmentally friendly short and long-term exploration of the natural resources, private sector partnership and participation in the energy industry, and the right of choice for electricity supply [17], [18], [21].
Demand for electricity is being influenced by different factors, among which are: output or economic production growth, electricity tariff, weather pattern, population growth, and changes in technology. Price and income remain the fundamental drivers for electricity demand at the macroeconomic level [22]. Eskom generates about 95% of the consumed electricity in South Africa. Therefore, as indicated in Figure 2, Eskom can transpose the national electricity demand in SA from the historical trend in the annual sales. The data represent the annual financial period of Eskom, with a change in the financial year in 2004 thereby making FY2005 to present 15 months data. Meanwhile, the overview of maximum demand data can help to identify possible risks. Whenever there is a small margin between the measured and the notified maximum demand, there is a risk of a consumer exceeding the notified maximum demand. On the contrary, prospective opportunities can be harnessed in reducing the cost of the notified maximum demand whenever the margin of difference is relatively large. The maximum demand margin can be calculated using equation 1 [23]:

$$MD_{margin} = \left[1 - \frac{\sum_{i=1}^{12} MD_i}{\sum_{i=1}^{12} NMD_i}\right] \times 100 \tag{1}$$

Where: MD_i is the measured demand (maximum) for month i in kVA and NMD_i is the notified demand (maximum) for month i in kVA.

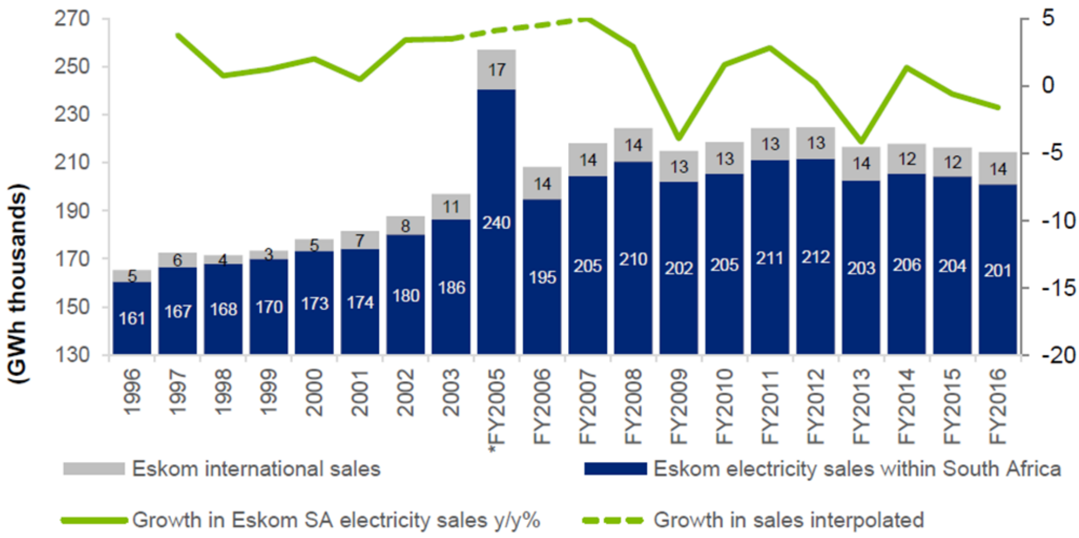

Figure 2. Historical trend of South Africa's electricity sales by Eskom between 1996 and 2016 [22].

A major electricity objective of the SAG before 2025 is to increase the energy end-use for the residential sector to 97% of official households. In South Africa, 31% of the inhabitants reside in remote rural areas. About 95% of rural dwellers are minimum wage earners with a lack of accessibility to reliable electricity. The SAG's commitment towards rural electrification is being impeded by the centralized nature of the electricity grid, the capital-intensive means of extending the existing power infrastructure, and the near-zero returns on investment due to no economic activities in the areas. Eskom states that usage of electricity in remote rural communities is minimal and subsequently impossible to recover operation and capital cost from charges alone from those areas. Therefore, the SAG (through Eskom) faces a complex problem of increased electricity demand and difficult diversification of energy production capability; resulting in considerable blackouts, load-shedding, power unreliability, instability, and low power quality in many parts of the country for both rural and urban areas [22]–[24].

Presently, the SAG is utilizing both grid and off-grid connected alternatives for rural area electrification. The off-grid alternative (50 W Solar Home Systems (SHS)), a cheaper and easier electricity generation, is supplied per household where the centralized grid connection is isolated. However, the off-grid electricity supply is limited to domestic applications. It does not provide scope for job creation, boosting of economic activities in the communities, or promotes rural development for future economic planning. The solar energy alternative has the greatest potential to address the need for access to electricity in remote rural communities with adequate increased localization. The electricity has several forms of supply, which can meet or surpass the electrical energy needs of remote rural communities with reasonable reliability [27]. Also, various studies have suggested other alternative approaches to providing electricity access such as hybrid and stand-alone photovoltaic (PV) system, wind turbines, diesel generators and microgrids. The electricity supply alternatives are utilized with energy storage, excluding main grid connections [28], [29]. Meanwhile, researchers have established a grid decentralization solution as a very reliable approach to providing electricity access to remotely scattered rural communities. The approach is well harnessed and implementable in an efficient microgrid system for alternative power solutions to the different rural locations in South Africa. By taking the advantage of the renewable energy regime of SAG, a preferred PV solar microgrid system architecture can be adopted, with a suitable policy framework formulated, to expand electricity access to the rural communities of South Africa.

2. Architecture and Control Strategies of Microgrid Systems

Microgrids consist of a generalized collection of interrelated electrical loads and distributed energy resources which are operative in both grid-connected or island mode [30]. Microgrid being defined according to U.S Department of Energy (DOE) is determined as a set of intertwined loads and integrated or distributed electricity resources (DERs) within explicitly characterized system-controlled electrical boundaries [31]. Microgrids are limited, modernized, small scale grids, in contrary to the normal centralized power network (macrogrids) [27], [32]. Microgrids are playing a key role in expanding access to electricity to remote rural communities. The limitations and insufficiencies of the utility grid are overpowered by microgrid application and control. The microgrid systems have been applied and used in remote rural communities of countries like US, UK, Canada, Kenya and South Africa [33]. Currently, there is an increase of awareness for clean, consistent and inexpensive energy generation, which is shifting the existent energy predicament for reliance. The current ageing utility grid infrastructure is at risk due to high accumulative energy demand, it requires cost-effective and integrated solutions [12]. Meanwhile, microgrids could be powered conveniently by clean renewable energy sources. Also, microgrids have the ability for detachment from the utility grid and function alone, sustain system adaptability or resilience, and help with mitigating system instability [28]. Various studies have stated that few profitable microgrid connections have enhanced energy access and further socioeconomic results [30], [34]. In addition, some research works have observed the combination of hybrid energy storage with stand-alone photovoltaic (PV) system to solve electrification problems in rural areas. Globally, rural electrification is best considered to be achievable through microgrids built on renewable energy (RE) sources. When such microgrids are based on variable RE sources, it is not feasible to deliver quality high power service to the consumer of interest. In such cases pertaining to Africa, it is reasonable to explore multi-scale time-based variability presented by the available local solar resource, and its implications [35]. The expansion of utility grid to remote rural communities is verified as uneconomical for implementation in South African remote communities. Hence, the stand-alone solar PV microgrid. The operations of stand-alone PV systems have substantial dependence on batteries for satisfactory power demands. However, the performance, maintenance cost and operational life of batteries also depend on the charging/discharging phases which the frequent fluctuation in weather conditions aids [36]. As a stand-alone and self-sustaining system, the microgrid provides aggregate benefits to the community and increases supply redundancy factor with likely lower cost of over-sizing system modules. Meanwhile, the intermittent renewable generation results in some advert effects that need to be minimized. The energy storage unit help to keep the excess produced power from the renewables, dispatch some during poor distributed energy resources conditions [37]. A detailed modelling and analysis is therefore necessary to standardize the DC voltage level and establish the overall efficiency of the selected microgrid system regardless of the loads [38], [39]. The design requires unique criteria-based modelling with factors such as batteries sizing, battery type, daily load, discharge limit, number and autonomy of required days, system voltage and operating conditions. However, beside meeting the battery type and storage capacity required, the final selection takes into consideration of the comparative battery cycle performance to failure at the specified discharge depth. Also, the resulting design must critically observe the cabling cost for any 10 km radius transmission and distribution across the villages [37].

2.1. Microgrid Power Architecture

In adopting the microgrid technology, the architectures and the control strategies used are very important. Grid strategy must have the capacity for convenience in both grid-connected and insulated mode to function. Hayden and Ceh [31] recognized several significant categories of microgrids to include Campus Environment or Institutional Microgrids; Community Microgrids, Remote off-grid Microgrids, Military Base Microgrids, Commercial and Industrial Microgrid. A microgrid can also be classified based on the structure of transmitting and distributing the microgrid power including DC, AC (high frequency and line frequency), and hybrid (DC-AC) microgrids. Also, the microgrids can be identified based on the interfaces as either power electronically coupled or rotating generator based [40]. Other categorized microgrids include single or three-phase, low or medium voltage connected, and grid or islanded operation connected [40]−[42]. The distinct types have different operational requirements and control schemes. The different architectures and the control strategies of microgrids have been discussed in many literatures [12], [24]–[26], [43]–[50]. Microgrids are more than capable of connecting and disconnecting from the utility grid if need be it can independently function efficiently to support the local loads. A typical architecture of a microgrid is illustrated in Figure 3, showing the versatility in the concept as it accommodates micro-generators, local storage units and the loads. The connected loads continuously influence the reliability of stand-alone microgrids. However, it is imperatively fundamental to strategically design suitable and flexible architecture of microgrid system which is proficiently operational in both grid-connected and isolated methods, and is presently essential [51], [54]. Therefore, it is critical to explore and review different topologies, designs, architectures and expansions of microgrid networks. More importantly, the application architecture and control strategies should indicate the significant contribution and integrated collaboration of basic microgrids components with the utility grid as we transition into a clean distributed energy future [55], [56].

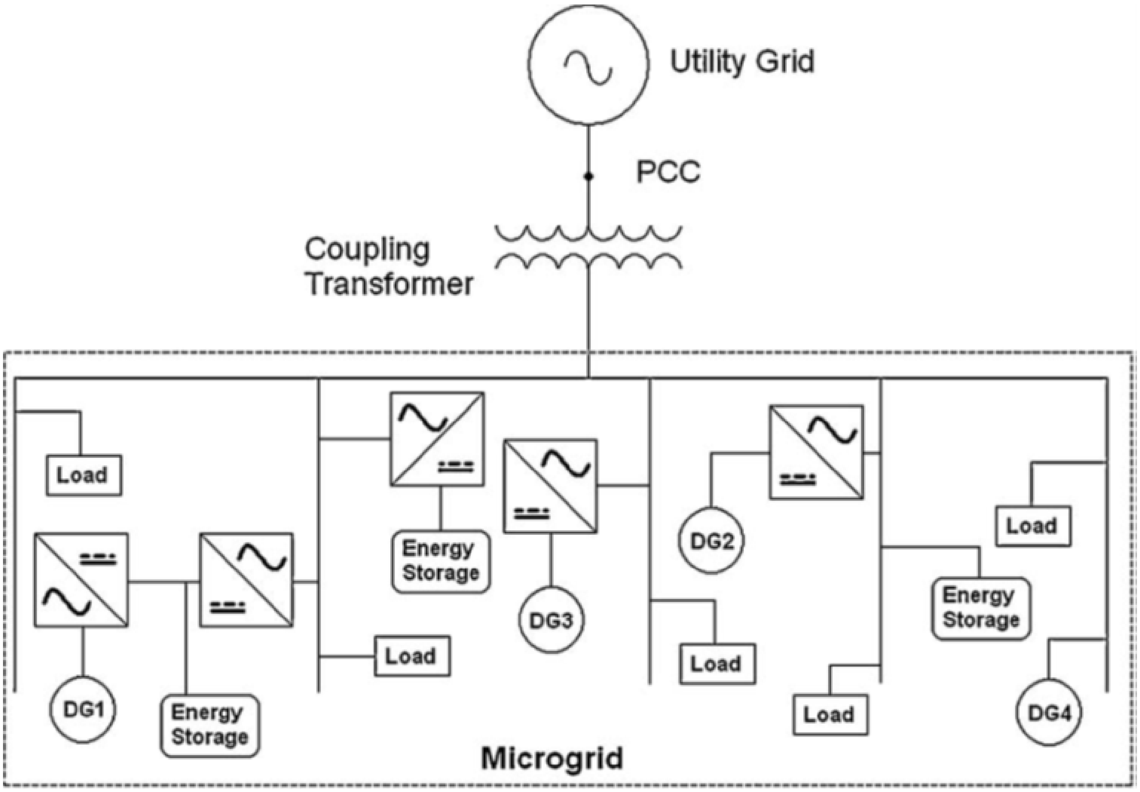

Figure 3. A typical architecture of a microgrid.

2.1.1. DC microgrid architecture

DC Microgrid is defined as an electrical servicing unit to efficiently transmit, consume, ultimately supply and maintain DC power to a wide variety of electrical equipment across households when connected to an electrical grid or as an islander [46], [53]. Nowadays, in the renewable energy culture, DC Microgrid is assuming a new level, and attractively becoming a growing fashionable integrated solution for different kinds of industrial, residential and DC powered household functions [45], [58]. Hence, DC microgrids are an attractive choice for application to solving rural electrification in South African remote communities. The architecture of DC microgrids is relatively studied in this paper in comparison with the AC microgrid complement. The energy sources and electrical loads can be completely distributed in a more efficient and proficient DC network scheme, by electing an applied voltage level and therefore escaping a few makeover phases. However, energy storage devices could usually be directly interconnected primarily to DC bus via a high efficient DC/DC converter [54], [59], [60]. AC grids interface with DC microgrids through AC-DC converters with a step-down transformer being connected to a medium voltage AC network on the AC side. The application requirement of the microgrid determines the AC-DC converter topology to be adopted, whether bidirectional power flow (active front end) or unidirectional based topology [53]. During any power outages, DC microgrid battery storage uninterruptedly provides energy to the electrical loads in the AC main network. Most generators, which are distributed, consist of an electrical DC/DC converter or an AC/DC switch to connect to the bus. From time to time DC loads can be directly interrelated to the DC bus or a DC/DC converter may be required, probably depending on the bus voltage. However, DC microgrids have tremendous advantages over AC microgrids, which include the enhancement of effectiveness, stability, dependability, and lastly lack of reactive power. The DC microgrid architecture central limitation is the associated bidirectional AC/DC arrangement which manages complete energy flow from or to the utility network as it results in reliability reduction [54]. Subsequently, the most significant AC/DC converter maintains and controls the voltage of DC bus of which is of higher quality even when distribution grids are of low quality [61].

2.1.2. AC microgrid architecture

This AC microgrid architecture is operational in grid-connected approach, whereby energy is flowing directly from the utility grid. The supply avoids any kind of series related converter thereby ensuring prominent dependability or high reliability [52]. AC interfaces are utilized to connect any device to the microgrid framework and comprise of one or more AC buses, and many distributed generators using DC/AC power electrical interfaces. The architectural technique of transmission has been utilized to supply more effective and sustainable power conversion for efficiency, compared to the different architectures utilized in data centres [62], [63]. The AC architecture is as shown in Figure 4(a) in comparison to a DC microgrid illustrated in Figure 4(b).

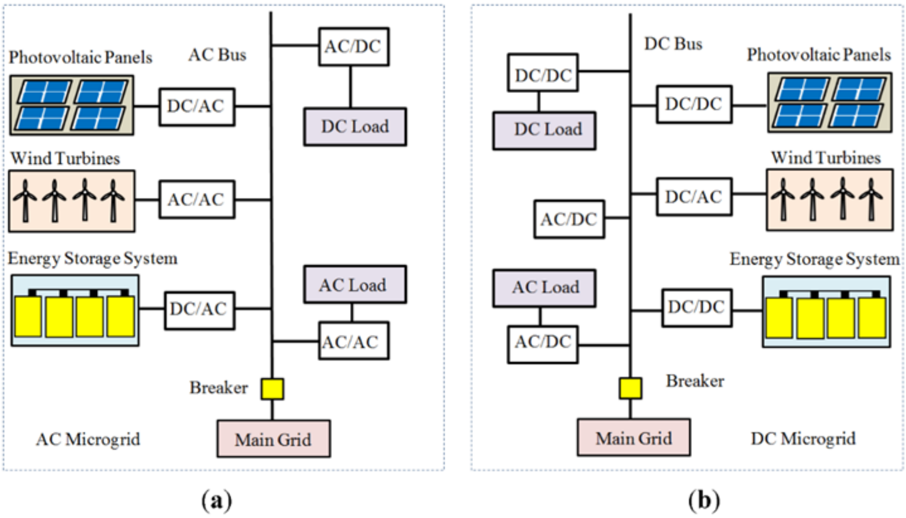

Figure 4. Architecture comparison, (a) AC microgrid, and (b) DC microgrid.

The AC power is converted to DC via the AC-DC converters to supply DC loads, while AC loads are connected directly through the AC bus. AC microgrid provides the possibility of voltage step-up for long-distance distribution. In the grid mode, abnormal conditions in grid result in the AC microgrid isolating itself and protecting the load within the microgrid network. Therefore, AC loads in the microgrid are protected from the main grid disturbances. The loads are capable of direct interconnection within the microgrid circuit without prior conversion. However, the conversion of AC to DC for DC loads supply reduces the efficiency in the architecture and increases the main grid's harmonics. Also, the possibility of integrating renewable energy sources is hampered because both the sources and the PV output are DC which require conversion the AC with the use of an inverter [29].

2.1.3. Hybrid DC/AC Architecture

Hybrid AC/DC microgrids have developed into a much more noticeable conventional power distribution network. This system is stimulated for effective incorporation of small distributed generation units into an existing distribution network [40], [64]. Hybrid AC/DC Microgrid is the application that incorporates both architectures and advantages of AC and DC microgrids [11], [59], [65]. Bidirectional AC/DC (interlinking) converters combine AC and DC microgrids from side to side. Distributed generators (DG) can directly be associated with the AC or DC feeders, whereby AC loads can connect directly to AC feeder and DC loads to DC feeder [66]. The hybrid microgrid uses the DC section to connect the distributed energy storage system through bi-directional converters, while the PV systems and other DC energy sources are connected to the DC-DC converters, and the small gas and wind turbines are connected via the rectifiers. Power converters are used to execute the decoupled control of AC and DC microgrid parts [67]− [70]. Summarily, the features of the DC, AC, and hybrid microgrid architectures are indicated in Table 1.

Table 1. Features of the microgrid architectures.

	Advantages	Disadvantages
DC Microgrids	High system efficiency, Power reliability, Safety, Control simplicity	More converters required; High initial cost; Efficiency metrics issue, Inverters required for AC loads
AC Microgrids	No inverter required for AC loads; Integration through AC bus, Good synchronization for both grid-connected and isolated mode	Operation and control difficulties; Reliability issues
Hybrid Microgrids	Integration synchronization merit, Voltage transformation, Economic feasibility	Protection and control complexity

2.2. Microgrid Control Architecture

Microgrids are designed to adapt to the operational requirements of the operating modes: either grid-connected mode or islanded mode. Hence, the necessity for distinguishing control schemes. In grid-connected mode, micro-resources operationally inject power into the grid, the present model. Meanwhile, in the islanded mode, microgrids have to switch to a voltage control mode to ensure that local loads are fed with constant voltage. The control strategies for microgrids take into account these modes of operation when switching from grid-connected mode to islanded operation, and the different microgrid components in each of the modes [71]. The hierarchical control strategies of microgrids are considered in four levels. Converter output control level accounts for regulating energy flow and shaping current output. Power-sharing control level is responsible for the distribution of power between numerous equivalent converters and influenced by communication associations. The supervisory control level is the secondary control, which caters for controlling parameters internal to the microgrids and low-level controllers. Also, the grid supervisory control level provides the tertiary control responsible for managing current flow between the utility grid and microgrid [71], [72]. Based on communication mode, control strategies in DC microgrids could be categorized into decentralized, centralized and distributed control, with their corresponding peculiar structures [44], [45], [65]. The reviewed control strategies for developing microgrid power quality, reliability and power allocation methods are categorized as shown in Table 2.

Table 2. Categorization of the control strategies.

Basis	Control Strategies
Communication mode	Decentralized, Centralized and Distributed approach
Hierarchical control	Converter output, Power-sharing, Supervisory control, and Tertiary control
System-level control	Peer-to-peer control or Master-slave control
Device-level control	Droop control, Voltage/Frequency control, P/Q control, Virtual flux control, Adaptive derivation
Grid-connected operational mode	micro-resources operationally inject power into the grid
Islanding operational mode	microgrids switches to a voltage control mode to ensure that local loads are fed with constant voltage

The control strategies adopted for AC microgrids are more complex than those in their DC counterparts. In minimizing the circulating reactive current and mitigating the necessity for reactive power compensation, DC microgrids adopt P-V droop while AC microgrids employ reactive (Q-V) and real (P-f) droop. The simplified control strategies for DC microgrids contribute to the microgrids higher resilience [73]–[75]. DC microgrids use a set of control strategies for soft-start control, restoring of the DC system voltage deviation through an external controller, and current/power flow regulation in or out of the stiff DC source or a connected power converter to a possible AC grid [76]-[78]. Algorithms for the control strategies in DC microgrids are designed requirement for transitioning from grid-connected to islanded mode. However, the power-sharing among the DG units in the islanded system vary between the decentralized and centralized control approaches [76], [79]–[82]. Considering the droop-characteristics as shown in Figure 5, the sharing of the active power within the DG units of a DC microgrid can be obtained using the following equation [62]:

$$V_{dci} = V_{dc}^{'} - \alpha_{vi} \cdot P_i \tag{2}$$

Where: α_{vi} is the droop gradient coefficient, V_{dci} and $V_{dc}^{'}$ are respectively the measured DC voltage, and the reference voltage value, P represents the active power difference between the active power set-point and the corresponding instantaneous shared value, and i = 1, 2, 3...n as the number count of the DG units. Meanwhile, the DG unit ratings and operating conditions, as well as minimal voltage variations must be considered when tuning the droop gradient coefficient [62], [83]–[85].

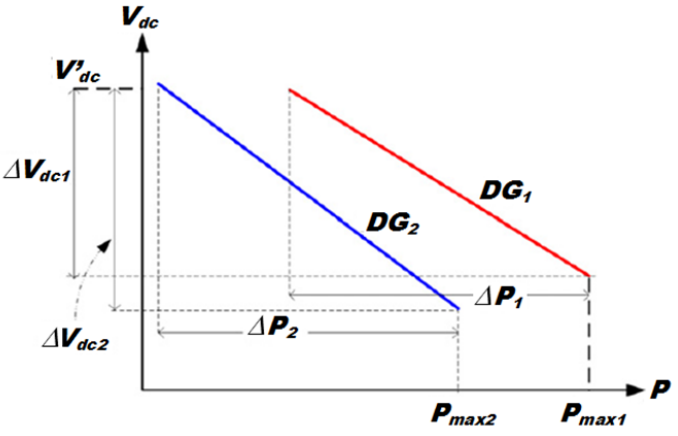

Figure 5. Control strategy for DC microgrid system using droop-characteristics.

In addition to the various alternative projects being executed by the SAG, it recently embarked on supporting the implementation of some microgrid projects with innovative solutions with relative achieved success. An integrated solar diesel microgrid architecture was commissioned by ABB in 2016 at the long-meadow vicinity in Johannesburg. Also, Robben Island solar PV microgrid and Singita Kruger National Park microgrid projects were implemented as predominantly combining solar PV and lithium-ion storage microgrid framework. In order to ensure seamless power supply, the launched projects combine distributed control systems (DCSs), intelligent power controllers, and integrated multiple controllers (IMCs) of solar PV, energy storage and generators. The microgrid controllers are considered as the microgrid brain for ensuring both on-site and off-site supply. Other projects include the Wilhelmina farm solar microgrid and Touwsrivier concentrated photovoltaics (CPV) solar power projects, and few others implemented and commissioned in the Northern Cape and Eastern Cape provinces of South Africa. A total of about 30 solar PV plants with power capacity of 5 to 75 MW each were implemented by the SAG under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), as illustrated in Table 3, and are situated in different locations within the country [86], [87].

Table 3. Some Solar Photovoltaic Facilities Approved by SAG in REIPPPP.

Project details	Rated Output (MW)
SlimSun Swartland Solar Park	5.0
Vredendal Solar Park	8.8
Upington Solar PV	8.9
Aurora Solar Park	9.0
Mulilo Renewable Energy Solar PV De Aar	9.7
Greefspan PV Power Plant	10.0
Mulilo Renewable Energy Solar PV Prieska	19.9
Soutpan Solar Park	28.0
Touwsrivier Project (CPV)	36.3
SA Mainstream Renewable Power Droogfontein	48.3
Boshoff Solar Park	60.0
Lesedi Power Company	64.0
Dreunberg Solar PV	69.6
Sishen Solar Facility	74.0
Jasper Power Company	75.0

Meanwhile, the analysis and comparison of the feasible sustainability of the microgrid types are based on varying economic parameters. The rural electrification strategies can be compared based on performance, efficiency, cost, equipment utilization, power quality, excess of energy produced, and even the environmental impacts. Using cost factor as parameter of interest, the cost of constituent components like Solar PV array, converters, inverters, and battery storage systems should be accurately estimated for correct determination of the system energy efficiency. This forms the basis for harmonizing cost optimization method and the robust design of the systems. DC or AC microgrid has its particular efficiency reliant on the quantity of conversion phases within the system. The perception of sustainability is about the utilization of energy resources in an approach considered to be adequate. Other long-term projects were also targeted for sub-urban centres with relatively greater capacities and costs. Some of these projects are shown in Table 4 [88]–[91].

Table 4. Some of SA renewable energy projects with capacities and estimated costs in South African Rands (ZAR):

Project names	Capacities (MW)	Estimated Cost (ZAR)
Khathu Solar Park	100	12 billion
Jasper Solar Power	96	2.3 billion
Solar Capital De Aar Project 1 and 2	175	7.2 billion
Mulilo Prieska PV	86	1.3 billion
Kalkbult solar power	75	–
Robben Island solar PV microgrid	1	25 million

The SAG previously pursued sustainable policies to legally regulate the possible implementation of cumulative RE-based power projects with capacity greater than 5 MW. It contributed a tax incentive through the South African Revenue Service for the installation and commission of photovoltaic solar energy production systems. The target of the policy was remote rural communities with no access to the utility grid. Most of the configurations were hybrid microgrid architectures made up of solar PV, diesel and wind. This system infrastructures were considered as innovative solutions to resolve the country energy crisis at a larger landscape but the sources require a review and improvement. The government eventually realized the necessity of allowing public-private partnership in the process of guaranteeing energy security. A policy has thus been promulgated to accommodate the various interests at achieving success over the energy limitations. The policy model has two parts: mid-term plan for the REIPPPP and the long-term standard containing the Integrated Resource Plan (IRP 2010) of 2010 to 2030 [86].

3. Policy Framework for Microgrid Systems in South Africa

The right regulation and policy framework for microgrid implementation in South African remote areas is vital and required. Microgrids encounter global regulation challenges concerning policies, protection issues, consumers and power suppliers engagements, legalities, operation limitations, renewable sources integration, and microgrid interconnection with utility grid containing higher connectivity costs as a result of high policies association fee. Hence, amongst microgrids and utility grids are interconnection guidelines which are formulated for the regulation purpose of the development and management of DG integration impacts without disturbance of the utility grid safety and functionality [85]. Access to electricity for rural remote areas is one of the most important issues in Africa, with success depending on governments, investors and energy policymakers [90]. South Africa has the biggest developing economy with great potential for microgrid systems. The potential of microgrids and its investments is threatened by skewed and limited policies in the country. The SAG as well as some other African countries are supporting and promoting the attention of microgrid investment by developing healthy policies and incentive structure [63]. The existing policy frameworks in SA are fully designed for grid electrification, which is skew and against the possibility of microgrid application. The energy sectors in South Africa, just like some African economies are primarily managed by competitive policies, rules, regulations and monopolistic laws which unfortunately supports grid electrification and ultimately limits rural electrification. The countries are beginning to review these policies and laws so that they could in-house private sector participation and other energy key players [19], [91]-[93]. The limited policy framework of microgrid systems could reduce their desirable potential and success since governing support and distribution opportunities will be inadequate. The SAG is the fundamental player in formulating microgrid policy framework and providing funding for microgrid projects taking place in the country. Microgrids advocates and policymakers need to formulate and execute policies which could mitigate any associated issues to microgrids and produce a continuously perfect microgrid environment [30]. Various studies have highlighted the microgrid technologies with shortage on policies, barriers and incentives on microgrid deployment and promotion. Microgrid policies should be related to policies on distributed and renewable energy. The policy framework of the system should indicate an essential need to evaluate the functionality of microgrid policies and regulations which are considered issues influencing adoption of the microgrid as an innovative distribution framework [49]. The issues, barriers and challenges of the regulations and policies are knotted as highlighted in Figure 6.

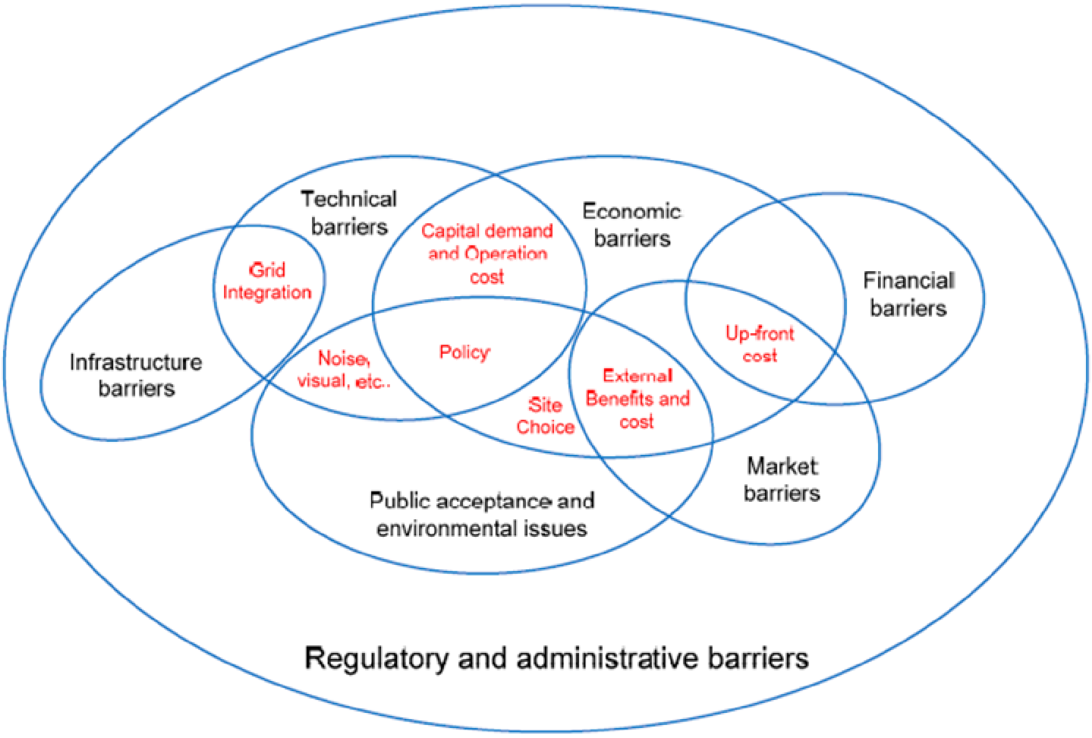

Figure 6. Development barriers for microgrid renewable energy [50].

Sustainable microgrid operation in remotely situated rural areas can quickly progress forward if the policies and regulations of microgrid systems are successfully formulated and addressed. However, to support distribution and operation in microgrid systems, there is a necessity to articulate regulations and policies which encourages the integration of renewable energy sources (RES) and DG into the traditional grid, to subsequently increase energy source security and competitive cost-effective advantage [68]. RE and innovative networks are presenting a new opportunity for a meaningful contribution to global energy access. The new emerging innovation is the combination of RE and mini or microgrids for grid-quality power to remote communities [94].

3.1. Existing Energy Policy Charter

The SAG stands good stead to produce an effective policy framework which would enable successful implementation and operation of RE-microgrids systems [64],[95],[96]. South Africa is affiliated with International Renewable Energy Agency (IRENA), an international institution which supports and upholds the utilization of renewable energy policies, with major objectives in policy-making aids and sustainable energy technology supply to its member countries [97], [98]. Presently, the three energy policy framework hitherto developed by SAG as illustrated in are the White Paper on Energy Policy in 1998, the White Paper on Renewable Energy Policy in 2003, and National Climate Change Response Policy White Paper in 2011. The specific objectives of the policy documents are summarized to include improved access to low-cost energy services, enabling effective energy governance, securing energy source diversity, ensuring and managing the consequences of environmental impacts, encouraging cost-effective growth [11], [95], [96], [99], [100].
The Integrated Energy Plan (IEP) and Integrated Resources Plan (IRP) are the other strategic policy documents by the SAG as interventions for shaping and outlining essential future of renewable energy

sources in South Africa [90], [95], [100]. These charters focused on the secondary level of energy application and operations. The IEP was a gazette in 2016 to provide an imperative framework for South Africa's sustainable energy environment and support future investment in the energy infrastructure and policies improvement [95]. The SAG failed to IRP 2010 and subsequently in a policy framework limbo because IRP 2013, IRP 2016, and IRP 2018 were never approved. The last of the pack is the IRP 2019, which is not yet approved. Consequently, there is a negative outlook for the SA renewable energy policy, resulting in substantial holdback of investment in the sector to guarantee system flexibility and efficiency [61]-[63]. An effective IRP implementation is necessary for accomplishing the overall energy sector transformation to meet the demand across SA cities and rural communities in the next 20 to 40 years [61], [97], [98].

3.2. Policy Options for RE-Microgrid Implementations

The prime recurring factors of consideration in formulating policy for investing in RE-microgrid systems include the required cost, lack of existing supporting systems for implementation and the non-financial effects on social and psychological factors. The decision-making process requires a multi-lateral appraisal of the factors for selection, as discussed in the subsection here. The significance attached to each category of factors for evaluating RE systems varies from one literature to the other. In few cases, relevance are given to the economic, technical, social and environmental categories with which the importance of deriving conclusions from quantifying valuation criteria are highlighted to support the categories. However, studies that attach relative importance to assessing socio-political effect in evaluating RE systems are deemed non-suitable for South Africa scenario [92]. The SAG should explore various policy options in promoting the integration of RE with microgrids systems to support effective and sustainable power provision for the remote rural communities. The experience with some industrialized nations and economies will guide the choice of policy options, and make available insights into implementing them. The component integration and improvement on the existing policy papers would enable a speedy and robust framework as depicted in Figure 7 to adequately address the need for affordable and quality energy access in the dispersed rural areas.

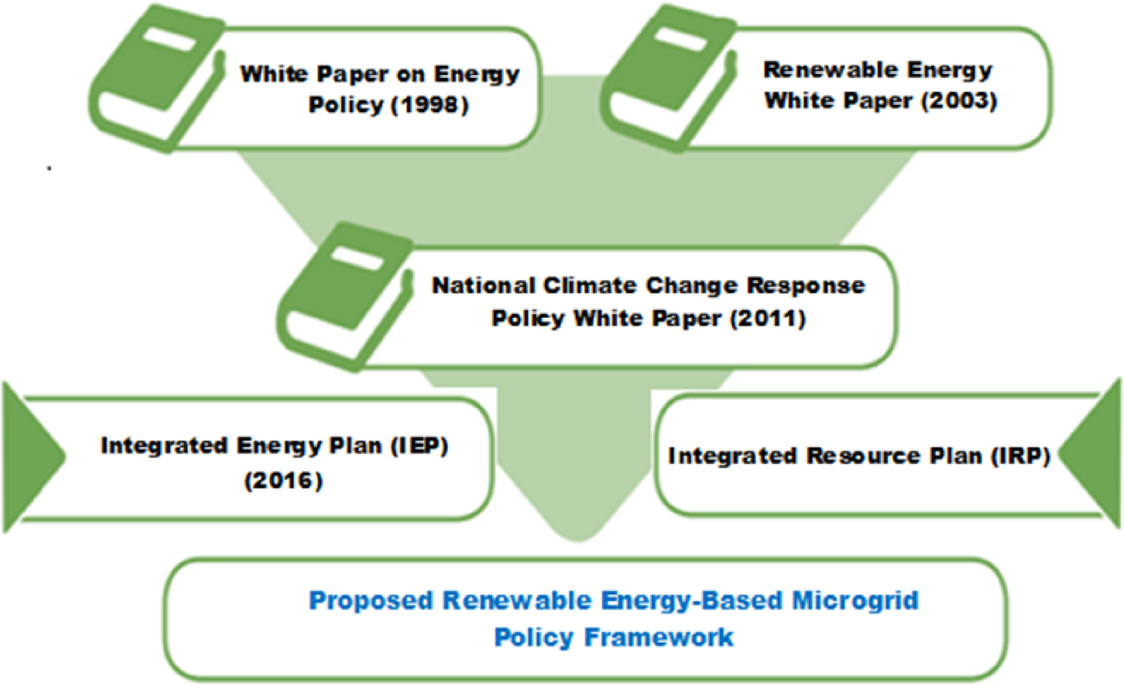

Figure 7. Energy policy framework in South Africa.

3.2.1. Private-sector partnership

Across the world, there is significant focus on policy mechanism that encourage increase in renewable energy supplies. The nexus and most agreeable model in RE-microgrid policy making is by ensuring less funding by the government on new investment, benefits for private partners from installing and handling new technologies, and public benefitting through social, economic and sustainable environment. The model allows government to directly regulate the cost incurred by the consumers or indirectly through empowered regulators. Basically, the policy framework incorporates four major classes to include the feed laws that obligate fixed-rate tariffs within the energy networks; the quotas that define the proportion or renewable portfolio standard indebted to the electricity suppliers; the financial incentives that cater for the grants and/or exempted taxes; and lastly, competitive tendering on behalf of government contracts for energy generation which oblige the suppliers to buy the RE at a first-rate price to be recovered from consumers' levies [87], [99]. A viable policy framework for RE-microgrid systems to ensure rural electrification in South Africa will require the SAG to introduce different measures to promote private-partnership investment in the energy sector. The investment cycle in the sector is comparatively long. Therefore, the private sector partnership should be ensured as soon as possible. The government recognized this importance in the advent of renewable energy and other clean technologies and taken steps to support them while imitating successful case studies in other economies. The supporting measures for adoption include feed-in tariffs [101], quota models, tax incentives or subsidies for the enabling technologies such as photovoltaic (PVC) and clean energy technologies, cap-and-trade system [102]. Currently, SA has emulated China and India in introducing tax exemption for clean development mechanism (CDM), intending to attract substantial investments to the projects. The global overview of the distribution of the CDM projects is as shown in Table 5.

Table 5. Distribution of global clean development mechanism projects.

Country	% **CDM** Projects
China	36
India	26
Brasil	7
Mexico	4
South Africa	1
Others	26

South Africa is providing a favourable atmosphere for CDM project investment and development. The SAG can employ the various incentives in the enhanced policy actionable plan to reflect cater to climate change issues, energy security and profitable returns on private investments. As electricity access remains a human right issue in SA and the economic activities in the target areas for electrification are low, the government is faced with fashioning a policy plan that will clearly outline the short-term or long-term basis of private investment returns. The relativity of pricing to capacity for returns in investment as explained in details in 3.2.3 is illustrated in Figure 8. The current capacity of the energy is represented by Q1, while the next installed new plant capacity is represented by Q2. Relative to the capital investment at Q1, demand is much lower than the available supply. As the demand increases with the addition of new users, a point of equality will be reached between the two.

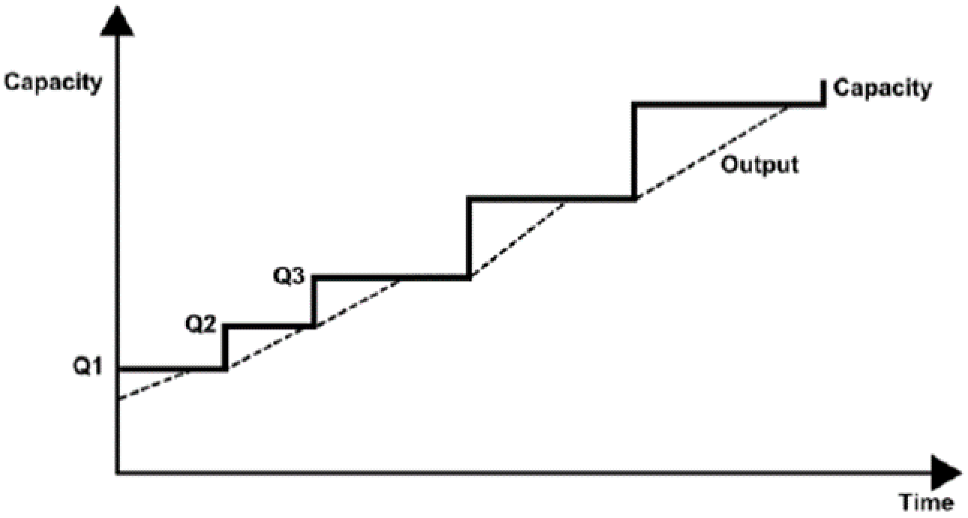

Figure 8. Indication of lumpy investment on SMC-based pricing.

3.2.2. Power generation target

The SAG can set the target of the power generation level expected from the RE-based microgrid platform, by parameterizing a substantial amount of energy demand of the target areas to be acquired from it. This will form a key mechanism for evaluating the value addition of the platform without depending on the market assessment of the social and environmental benefits. Government has always involved such targets in its previous policy efforts. In the RE paper of 2003, a target of annual additional 10000 GWh to the final energy capacity was set to be achieved by 2013 [103]. Also, the SA power utility company Eskom has targeted the power generating capacity of the country at 4000 MW from renewable sources by this year 2020, about 8.3% of the total output. This supports a projection of about 15% renewable generation by a research study at the University of Cape Town. The SAG should be committed to the development of RE-microgrid strategy to translate the set-out objectives, goals and deliverables into a policy and implementation plan [11], [65], [101], [102].

3.2.3. Electricity pricing

Another policy instrument to achieve the desired framework in the implementation of RE-microgrid systems is price-fixing through tariff regulation. A major feature of the existing energy regime in South Africa is the low-cost of electricity sales, one of the lowest globally. The two enabling factors for the low price are the use of the largely available low-grade coal and the pricing policy in practice. Designing a policy framework, an efficient and cost-reflective tariff which also satisfies a range of economic, social and political objectives can be incorporated. The policy needs to guarantee that set-targets of electrification are met, and ensure low-cost electricity provision, improved quality and security of power supply, enhanced price equality, proper operation and coordination of investments, protection of the existing competent workforce, and financial viability [64], [104], [105]. In arriving at the best pricing policy, both short-run marginal cost (SMC) and long-run marginal cost (LMC) approaches should be considered. While SRC is often an efficient pricing technique for goods and services, LMC is consistent with efficient economic resources allocation and relatively stable tariff path. The SMC can deal with incremental cost on an additional power unit provided generation capacity remains fixed, while LMC will cover such costs when all inputs vary. Therefore, the generation capacity installed over a period and variation of the different parameters will influence pricing method adopted. Importantly, the pricing policy needs to anticipate the incremental cost of supplying additional power unit with a continuous maintaining an optimal level capacity to supply projected demand for many years to come. Also, it will ensure price stability, fair cost allocation based on burdens obligatory on the system, provision of minimum basic service to those unable to afford the cost, ensuring financial sustainability of the utility and administratively efficient tariff structure [106]–[109]. According to documents by National Energy Regulator of South Africa (NERSA) [110]–[112], a multi-year price determination (MYPD) methodology was employed by Eskom to determine its allowable revenue as illustrated by equations (3) and (4):

$$A_r = (R_{AB}W_{ACC}) + P_C + T \pm R_{CA} \tag{3}$$

$$P_C = E + P_E + D + T_{NC} + R_C + I_{DM} + S_{QI} \tag{4}$$

Where: A_r is the allowable revenue, R_{AB} is the regulatory asset base, W_{ACC} is the weighted average cost of capital, P_C is the pass through cost, T is government levies and taxes, R_{CA} is the regulatory clearing account, E is the expenses (operating and maintenance), P_E is the primary energy, D is depreciation, T_{NC} – transmission and network cost, R_C – research and development costs, I_{DM} – integrated demand management, and S_{QI} – service quality incentive.

4. Conclusions

Access to electricity is an important benefit to be guaranteed by the South Africa Government for all citizens and dwellers in the country. However, the different rural communities still lack electricity, despite being a right supported by the country's laws. The feasible, affordable and sustainable approach to connecting the rural communities to electricity supply is suggestively through the use of microgrid solutions. Microgrids are undoubtedly beginning to fundamentally undertake a strategic function in the expansion of smart-grids. There are several discrepancies in the implementation of microgrid architectures and designs. Whereas most literature study focused predominantly on the AC and DC microgrids, hybrid AC/DC networks are phenomenal alternatives, which are imperatively combining the benefits of the two aforementioned configurations. Energy storage devices in the application of microgrid are fundamental segments, which make microgrid systems to be proficient, stable and efficient in their operations. The review of the various architectures of microgrids shows that AC microgrids could be observed as one of the most stable and reliable microgrids because their current AC installations can be simply redesigned for architectural implementation with only minimal adjustment of their components, allowing the current AC loads to be reused. Meanwhile, DC microgrid configurations are proposed to be suitable solutions for providing reliable electricity access to rural remote communities due to their higher efficiency, reliability, stability, load-sharing performance, and capable of being connected to DC renewable and storage sources. These beneficial advantages of the proposed system make it outstanding and gain a competitive advantage over other microgrids systems. The system presents benefits such as a reduction of operating and maintenance cost. The DC Microgrids can entirely function while is disconnected from the utility grid which is called an isolated operation approach. DC microgrids are a cost-effective option with a capacity of supplying electricity for areas in developing countries Both AC and DC MG configuration requires be modernizing and modifying to meet the respective target customer demands. DC microgrid is currently in the expansion phase due to the improvement of sustainable renewable energy sources and energy storage systems. The expansion of DC microgrid encounters imperative limitation in the current power framework, which is having a smaller quantity of DC loads. The DC microgrids, just like other types require a set of hierarchical control strategies for its operation and applications. The DC microgrids use the control strategies for soft-start control, restoring of the DC system voltage deviation through an external controller, and current/power flow regulation in or out of the stiff DC source or a connected power converter to a possible AC grid. Algorithms for the control strategies in DC microgrids are designed requirement for transitioning from grid-connected to islanded mode. However, the power-sharing among the DG units in the islanded system vary between the decentralized and centralized control approaches. It is extremely significant for policymakers and governments to formulate and implement policies that stimulate efficient, dependable and competitive policy framework for microgrids. Policies are considering changing to in-house dissimilar forms of microgrid systems and designed to diversify combination of distributed and renewable energy resources. A well-structured policy framework of governments is the dynamic driving force towards successful implementation of renewable energy systems. Also, sustainable microgrid operation in remotely situated rural areas can quickly progress if the policies and regulations of microgrid systems are successfully formulated and addressed. However, the gap between microgrid architecture, renewable energy policy framework and also the actual application is relatively extensive. The component integration and improvement on the existing policy papers would enable a speedy and robust framework that can guarantee private-sector partnership on investment, meeting power generation target and ensuring the right electricity pricing to ensure attractive returns on investment both in the short-term and long-term basis.

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Sample Availability: Samples of the compounds ...... are available from the authors.

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