A REVIEW OF GRID CONNECTED DISTRIBUTED GENERATION USING RENEWABLE ENERGY SOURCES IN SOUTH AFRICA

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Abstract – The energy model in South Africa for electricity generation has been evolving at a rapid rate during recent times. The country has taken initiatives to incorporate more renewable sourced power into its coal-dominated electricity generation programme. The introduction of small to medium scale distributed generators closer to the load centres and powered by renewable energy sources will be a step forward for the country. Grid integration of these distributed generators will cause a bidirectional flow of electricity through the utility grid, which will lead to various technical issues such as voltage profile deviation and harmonic distortion. However, it will also allow the grid to act as a back-up electricity source when the distributed generators fall under and allow any excess electricity generated by the distributed generators to be absorbed by the grid. The use of optimisation techniques has been reviewed to be a feasible method to mitigate the undesirable technical concerns that arise during grid integration. The optimal location, size and design of distributed generators can be determined so that objectives such as minimising voltage deviation, power losses and net costs can be achieved.

Keywords – Distributed power generation, Optimisation, Power systems, Renewable energy sources.

I. INTRODUCTION

South Africa’s long established relationship with coal goes as far back as 1870 when it was first used for diamond mining [1]. Abundant reserves of coal in the country and the dated electricity generation design that calls for using low grade coal made it possible to supply electricity at very low electricity tariff rates [2]. In the year 1990, the country had a stable, energy dependent economy and a reliable, high quality state owned electric utility named Eskom, with a significant surplus capacity [3]. Since then, while the electrification strategy has slowly adapted to the needs and demands of modern South Africa, the country is still heavily dependent on coal as its primary source of electricity. This paper explores the scope for renewable sources of energy to supplement the existing coal based generation practices of South Africa, while also reviewing the various technical factors to be considered before integrating the grid with such renewable based generators. In order to give a clearer context to the current energy situation of the country, this section of the paper focuses on the different policy initiatives adopted over the years and the evolving role played by Eskom, in establishing the current energy model of South Africa.

In the late 1980’s, Eskom’s objective had shifted from “supply quality driven optimisation” to “cost driven optimisation” by introducing changes in design specifications which led to load drop, relaxing the voltage regulation specifications on low voltage systems which led to lower investment costs, introducing single phase lines which led to reduction in construction costs, and establishing more prepaid meters while improving its standards to make it more compatible. After 1995, Eskom decided to supply electricity to an area (blanket electrification) instead of only supplying to customers (selective electrification). This led to an even larger number of households being able to access electricity, but also led to low average power consumption and increase in operating costs.

In December 1998, a new white paper was published on energy policy which focused on the active promotion of utilising renewable energy sources for electricity generation [4]. It also highlighted the role that can be played by independent power providers, which included independent power distributors, and transmission and generation companies. In 2001, the state decided to fund the electrification programme, coinciding with the conversion of Eskom into a private corporation that needed to pay tax. The tariff costs gradually began to rise again as a result of costs incurred while setting up of new transmission systems in remote areas. Free Basic Electricity was introduced by the Department of Energy from July 2003, through which free electricity to cover basic needs in a household (50 kWh) is supplied every month to the poorer sections of the society, while charging higher tariff rates to high income households to compensate for the free power distributed [5].

In the year 2003, the Renewable Energy Policy White Paper was published by the Department of Minerals and Energy in South Africa. The target, as outlined by the paper, was to reach 10 000 GWh of renewable energy generation by the year 2013 [6]. How this should be brought about was not mentioned specifically, and needless to say – the target was not met. The annual production of coal had risen by a factor of 119% in 2007 compared to its number in 1980 [7]. In the same year, the National Energy Regulator of South Africa (NERSA) approved Eskom’s application to build two new coal fired power plants, Medupi and Kusile, to accommodate the growing consumer demand [8].

In the year 2009, South Africa voluntarily vowed to reduce its CO_2 emissions by 34% by 2020, and then a further 8% drop by 2025, at the Copenhagen Conference of Parties. This promise paved way for the introduction of Renewable Energy Feed in Tariff (REFIT) [9]. The REFIT was revised in 2011 in order to bring down the feed in tariff rates. However, in August of the very same year, Department of Energy announced another programme titled- Renewable Energy Independent Power Provider Procurement Programme (REIPPPP), which led to the termination of REFIT [9]. The REIPPPP initiative defined its target as the introduction of 17.8 GW of power through renewable sources by the year 2030 [10]. The main policy drivers for this programme were a reduction of CO_2 emissions, additional generational capacity for the utility and economic development in terms of job opportunities [11].

All Independent Power Producers (IPP) who wish to place a bid through REIPPPP must satisfy the minimum requirements. This is checked through a screening process, after which the bids are evaluated based on measurement criteria by legal, technical and financial evaluation teams and independent reviewers [12]. Up until the introduction of REIPPPP, electricity in South Africa was solely generated by Eskom. IPP often find it immensely difficult to enter the electricity sector in South Africa, one of the reasons being that it is impossible to match the profit obtained by Eskom through electricity generation. Another factor that prevents new investors from establishing control is that Eskom holds the right to vital information and data that would help them, but instead use confidentiality clauses to prevent third parties from accessing reliable data for professional use [2].

The REIPPPP initiative had 4 bidding windows behind it. The first bid window introduced a total renewable energy capacity of 1436 MW into the energy mix [13]. The second and third bid window introduced a total renewable energy capacity of 1054 MW and 1656 MW respectively [13]. The results of the fourth window, as of 2017, indicate a total of 1084.2 MW renewable energy allocation [13]. A vast majority of capacity allocation has been provided for solar photovoltaic (PV) and onshore wind energy technologies, and a lower but fair share has been allocated for concentrated solar power technology.

As of 2017, there are 59 fully operational renewable energy based power plants that have been established in South Africa as a part of the REIPPP programme [14]. There are 22 fully operational wind based power plants with a total capacity of 1876.6 MW, 33 fully operational solar (PV) plants with a total capacity of 1501.55 MW, 2 fully operational small hydro power plants with a total capacity of 14.3 MW and 4 fully operational concentrated solar power plants with a total capacity of 300 MW [14]. It can be stated without a doubt that the development and renewal of policy programmes have paved the way towards a greener energy model in South Africa. Similarly, studies to understand the impacts of grid integrated distributed generators can provide indispensable information to policymakers, thus helping to set new and improved standards and paving the way to a more sustainable electricity model for the country.

With the release of standards and codes for distributed generation [15], [16], the study of technical issues that arise as a result of integration and possible mitigation methods has become a matter of great significance. The number of DG units that are connected to the utility grid is only expected to increase, and with this increase comes the possibility of erratic penetration and eventual power system instability. Proper planning in terms of allocation and sizing of DG units will help overcome many technical (which eventually translates to economic) issues. Researching mitigation strategies in this field will also help the country improve on its released set of guidelines and make it more accommodating [17].

There are 29 power stations under operation by Eskom as of the year 2017. The total nominal capacity of these stations is of the order of 44 134 MW, out of which 82.6 % is contributed by coal plants [18]. Most of Eskom's coal based power plants are over 20 years old and hence less efficient and will soon reach their 40-50 year lifespan limit [19]. This means that there will soon be seen a need to build more and more power plants to replace the ones too old to perform; the funding of which will be acquired partially through increase in electricity tariff rates [20]. In order to mitigate this, there must be an intensive drive to adopt a modern energy model for the country.

Studies in the field of renewable energy for distributed generation can offer policy-makers information on how to diversify the energy mix of the country, while meeting its renewable energy and greenhouse gas emission targets; and provide consumers with a reliable and low cost alternative to the current centralised electricity generation and supply system. However, the integration of such a large network of grid connected DG system on the distribution network without prior research and studies may lead to undesirable changes in the existing voltage and power profile of the network.

In the subsequent sections, the changing status of renewable energy in the energy model of South Africa is discussed, followed by a review of various studies performed regarding the integration of DG units to the utility grid, the resulting technical issues incurred and the use of optimisation techniques to find the ideal size and location of DG units to mitigate some of these issues such as power loss sustained during grid integration and cost of installing such DG units. The general structure of this paper is shown in Figure 1.

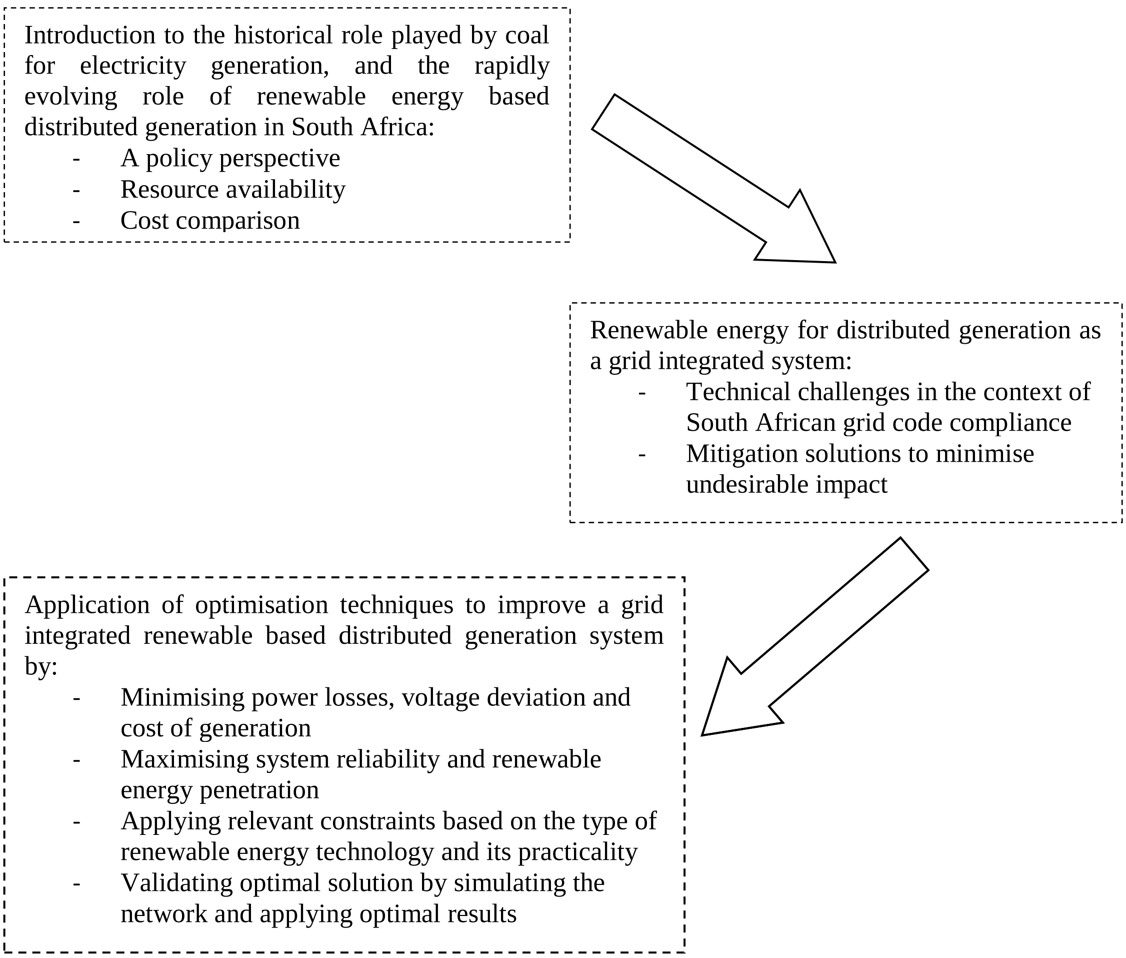

Figure 1: Block diagram representing overall structure of the paper

II. DYNAMICS OF RENEWABLE ENERGY TECHNOLOGY IN SOUTH AFRICA

A. The different roles played by coal and renewables for electricity generation in South Africa

In the year 2016/17, the total nominal capacity of Eskom's power stations amounted to 44 134 MW, with 36 441 MW contributed by coal power stations, including the recently inaugurated Unit 6 of the Medupi power station [18]. Renewable energy plants operated by Eskom have a total capacity of 700 MW through hydro stations (600 MW capacity) and the 100 MW capacity Sere Wind Farm [18]. Eskom generated 220 166 GWh of electricity (200 893 GWh contributed by coal, 579 GWh contributed by hydro stations, 3 294 GWh by pumped storage schemes, 345 GWh by wind power stations, 15 026 GWh contributed by nuclear and 29 GWh by open cycle gas turbines), and sold a total of 214 121 GWh [18].

The difference in numbers between power generated and power sold is attributed to transmission and distribution losses, and is an indicator of the efficiency of the power system. It must be noted that the figure of 220 166 GWh of electricity was generated solely by Eskom. Generation capacity refers to the total amount of power that can be generated, but not necessarily generated, by various power plants per hour. It is represented by the term capacity factor, which is the ratio of a power plant's actual output to the power plant's generation capacity over a year [21]. In the capacity factor analysis shown in Table 1, the contribution of Eskom towards electricity generated through coal and renewable power systems is used.

TABLE 1
CAPACITY FACTOR COMPARISON BASED ON VALUES FOR ELECTRICITY GENERATED BY POWER PLANT
9 TYPE AND ITS POWER CAPACITY FOR THE YEAR 2016-17 [18]

Power systems	Coal	Renewable
Electricity generated (GWh)	200 893	924
Power capacity (MW)	36 441	700
Capacity factor (%)	62.93	15.07

Higher the capacity factor of an energy source, the more reliable it is to produce and provide consistent electricity. Renewable energy sources have very low capacity factor, mainly due to the unreliable availability of energy resource [22]. Coal is steadily available and can be transported across locations in order to ensure a constant supply of power. Power plants that provide high capacity factor make good base-power plants, and those with low capacity factors can be used to provide power during peak load times. Base load power plants supply the minimum level of power demand to the consumers throughout the day, and are only shut down for maintenance and repairs. Peak load power plants cater to the consumers' needs only during peak load hours. They are built to supplement the power provided by base load plants [23]. In South Africa, base load power plants are coal based and operate for 24 hours and require at least 8 hours reaching full load status, whereas peak load plants are hydro powered or depend on gas turbines.

It can be concluded that, based on capacity factor alone, a hybrid energy model which uses coal as the base load power supplier and renewable energy sources as the peak load power supplier can provide a sustainable and reliable form of electricity generation. However, this also implies that, due to the non-dispatchable nature of renewable energy, renewable power plants such as a PV or wind farm must be designed with energy storage facilities in the form of pumped hydro storage or even a large battery bank of lead acid or lithium ion batteries. This will undoubtedly add to the cost of electricity generation from renewable sources.

B. Cost Analysis of Coal and Renewable Energy

A study on the power production costs of three electricity generation methods was performed which took into consideration the case of Matla coal power plant, Villiera wine farm (a medium scale PV system) and Kathu Solar Park (a large scale PV system) in South Africa [20]. The power production costs include cost of resources and initial investments and operating and maintenance costs for each of these generation systems. The electricity production cost of Matla power plant for a two year period from 2011 to 2013 is considered in this study. All prices are in United States Dollar Cent per kilo Watt Hour (USDc/kWh), and an assumption is made that PV systems will function for a 25 year period.

The results of this study summarised in Table 2 show that the medium and large scale PV plants had to incur higher initial investment cost than Matla coal power plant by a margin of 5.66 and 7.3 USDc/kWh respectively. Other significant observations from this study are that the operation and maintenance cost is considerably smaller for the medium scale PV plant (7.4% of that of large scale PV), and that as the nominal active power rating of PV plants increased from 0.131MW to 81 MW, the initial investment costs only increased by 1.64 USDc/kWh.

TABLE 2
TOTAL PRODUCTION COST COMPARISON OF COAL POWER PLANT, MEDIUM-SCALE PV PLANT AND A LARGE-SCALE PV PLANT [20]

Power systems	Matla (coal)	Villiera (medium scale PV)	Kathu (large scale PV)
Installed capacity	3600MW	0.131 MW (when solar radiation is at its peak)	81 MW (when solar radiation is at its peak)
Resources and initial investments (USDc/kWh)	2.39	8.05	9.69
Operation and maintenance costs (USDc/kWh)	2.3	0.227	3.05

It can be concluded that from an electricity generation perspective, it is still economical to use coal as a source of electricity. However, with PV semiconductor technology growing in leaps and bounds, and the prices of these materials steadily decreasing, the focus of future studies should be on identifying the correct nominal power rating of farms that requires minimal investment and operation costs, while also providing maximum sustainably sourced electricity to the energy mix.

Another subject that must be considered in the cost based analysis of coal and renewable technologies are externality studies. These studies reveal the true cost of production and consumption of energy sources by taking into account the extra price, apart from tariff rates, that consumers will have to pay due to negative impacts associated with the energy source that is the subject of the study. These negative impacts are related to public (consumers') and occupational (workers') health, and pollution of the environment.

South Africa had a CO_2 emission rate of 9.622 metric tonnes per person in the year 2011 [24]. Coal is responsible for 87.8 % of net CO_2 emissions [25]. This is classified as a greenhouse gas, along with CO and CH_4. Greenhouse gases are held responsible for climate change which is an urgent source of concern globally. The intensity of emission (expressed in kg/kWh) is higher for older power plants, with ranges extending from 1.11 to 0.84 [26].

South Africa is also one of the 30 driest countries in the world, and hence water is regarded as a limited resource in the country [27]. In the year 2010, Eskom used 1.35 m3 of water per MWh of electricity it produced [28]. Department of Water Affairs supplies water to Eskom at a lower rate based on long term contracts. Since this price does not indicate the true cost of water, it is considered as an externality. It has also been noticed that different power plants pay different rates for water supply [26]. Besides water being used up during production of coal, there is also contamination of drinking water that takes place as a result of coal mining.

The external costs associated with the impact of gas emissions from 10 base load coal power plants on the health of residents living within a 500 km radius of each of these power plants were analysed in South Africa using Externalities of Energy (ExternE) method [26] . The results of the study show that the total external costs of coal was found to be 1.08 USDc/kWh, with public impacts of coal contributing 9.2% and environmental impacts of coal contributing 87.4% to this total cost [26]. While there are no exclusive studies done on calculating the externality and impact of renewable energy in the country thus far, there have been many international studies on the same. In [29], the external cost of a concentrated solar power plant in Southern Spain that is also powered by natural gas inputs ranging from 0% to 30% is studied as a part of Full Environmental Life Cycle Costing technique. The total real external costs taking into account impact on human health, effect on biodiversity, climate change, damage to crops and damage to materials were observed to rise to 1.536 USDc/kWh for 30% natural gas incorporation, as opposed to 0.224 USDc/kWh when the concentrated solar power plant works on solar energy alone.

Therefore, from externality studies, it can be observed that while cost of coal for electricity generation may be cheaper than renewable energy, the overall impact on public health and environment is higher. There is also a need to conduct more studies to assess the exact externality cost contribution of renewables in South Africa. The findings of the three studies considered in this sub-section is summarised in Table 3. Since these studies were conducted in different years, the effects of inflation must be accounted for to draw a fair comparison between the results.

TABLE 3
SUMMARY OF TOTAL COST ANALYSIS STUDIES OF DIFFERENT ENERGY TECHNOLOGIES

Types of costing parameters	Cost in USDc/kWh for different technologies	Assumptions made
Resources and initial investment cost [20]	Coal: 2.39 Medium scale PV: 8.05 Large scale PV: 9.69	1. South African based study 2. Power plants have very different nominal capacities 3. A two year time period was considered
Operation and maintenance cost [20]	Coal: 2.3 Medium scale PV: 0.227 Large scale PV: 3.05	
Normalised externality cost for electricity generation [26]	Coal: 1.08	1. South African based study considering only coal as the source. 2. Health and environmental impacts during electricity generation using coal constitute the externality cost.
Total externality cost over a complete plant lifecycle [29]	Natural gas: 1.536 CSP: 0.224	1. Spanish study considering a CSP plant that can use up to 30% natural gas for electricity generation. 2. Health and environmental impacts for the complete lifecycle of the CSP plant constitute the externality cost

C. Resource Availability Overview

The consistent and widespread availability of energy resource is one of the challenges faced by renewable energy sources. However, there are many areas in South Africa where it is possible to generate a good quantity of power with readily available resources. The country receives an average solar radiation 7 kWh/m^2 and an average wind speed of over 7 m/s in coastal areas [9]. Some of the geographical locations suitable for wind power generation are listed in Table 4, and the average wind speeds for the country at a height of 100m above the ground level is shown in Figure 2.

TABLE 4

POTENTIAL GEOGRAPHICAL SITES FOR WIND POWER IN SOUTH AFRICA [30]

Wind speed	High wind speed (>4m/s)	Medium wind speed (3-4m/s)	Low wind speed (<3m/s)
Location	Coastal line of South Africa	Karoo, Drakensberg foothills, Eastern Highveld Plateau, Bushmanland	Western and Southern Highveld Plateau, Lowveld, Northern Plateau, Limpopo, Bushveld, and Kalahari basins, Cape Middleveld and KwaZulu-Natal

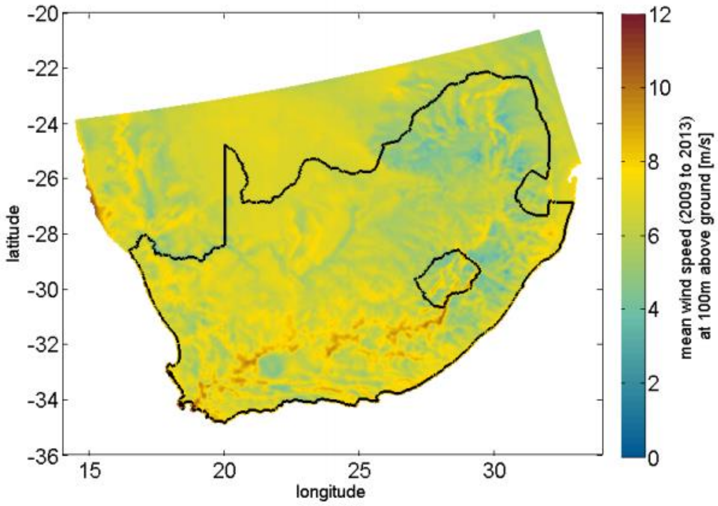

Figure 2: Average speeds recorded for the years 2009 to 2013 in South Africa at 100 m above ground, adapted from [31].

While the availability of vast areas that are sparsely populated can make South Africa an ideal candidate for wind power generation, there are some drawbacks that must be considered. The capital and production costs of a wind farm are higher than coal power plants. Wind energy can only provide 25 to 2000 kW of power per unit, which is negligible compared to the 200 to 600 MW of power generated by one unit of a coal power plant [32]. They are also highly intermittent in nature, and there is no guarantee that enough wind at high speeds will be available at all times to meet the generation capacity.

Solar power as an alternate source of energy is a more probable reality in South Africa. The country receives an average of 4.5 to 6.5 kWh/m^2 of solar radiation daily [30]. The annual solar radiation levels in kWh/m^2 for the whole of South Africa is shown in Figure 3. Since solar energy is only available during day time, and has varying power generation capacity during different times of the day depending on seasonal and weather conditions, it is best used in conjunction with a conventional source or with storage devices. Solar power can be used for photovoltaic and thermal power applications to generate electricity and for solar water heaters. There is a high initial cost of investment at the consumer's end, which is not experienced when the consumer is directly connected to a grid powered by coal.

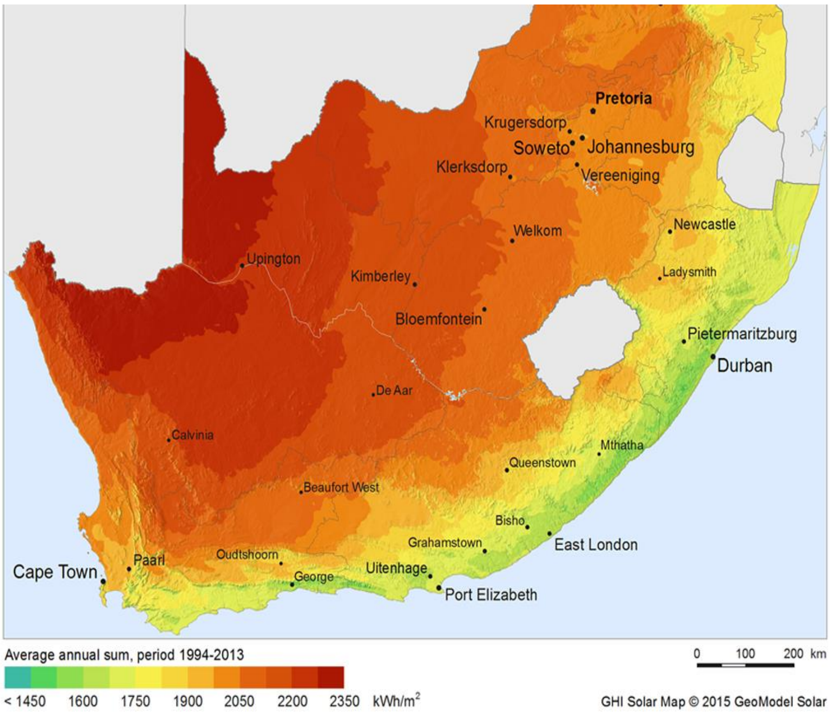

Figure 3: Average annual solar radiation in kWh/m^2 recorded for the years 1994 to 2013 in South Africa, adapted from [33].

Meanwhile, coal is readily available in South Africa and has abundant reserves that can last for 300 years [2]. In the year 2013, South Africa became the world's seventh largest producer of coal [34]. Therefore, depletion of conventional resources of energy, and hence facing an uncertain supply, is not a major concern as in other countries. It can even be transported to rural areas where it is not readily available. This works against any system that calls for urgent introduction of renewable power generation.

D. Summary

From the above discussion, it can be concluded that the main drawback of depending on coal as a source of energy is undoubtedly the increase in carbon emissions in the atmosphere, along with oxides of sulphur and nitrogen and particulate matter. This mix of gases is known to cause environmental and health impacts, thereby causing damages represented as external costs. Renewable energy on the other hand is a clean source of energy that does not leave a carbon footprint and does not cause danger to the public health. However, renewable energy sources are not available all the time and at all places. Coal can be transported to rural areas and islands, whereas renewable energy sources are linked to geographical locations and their climatic conditions.

While the country may not be ready to be powered by renewable energy alone, it is possible to take the first step towards such a future by slowly integrating renewable energy based distributed generators into the coal powered utility grid. This has also been more recently endorsed by Eskom and the Department of Energy as a part of their way to meet the REIPPP targets. As the electric energy model of the country gets deregulated and is expected to get more so in the coming years, it is important to have a deeper understanding about the grid. The reaction of the grid to the integration of distributed generators also plays a vital role, especially taking into consideration its sensitive nature.

III. GRID INTEGRATION OF RENEWABLE ENERGY POWERED DISTRIBUTED GENERATORS

Off-grid technologies have been providing power in South Africa's rural areas for the past couple of decades, but integration to the grid has various advantages such as eliminating the use of battery backup or diesel generators. Integration can help lower the impact of rising tariff rates for consumers and lower reliability on the utility grid. Small scale distributed generators can be used for domestic, commercial and industrial application, as long as the regulations provided by Eskom and the Department of Energy are followed and specifications met [35].

Studies conducted on embedded generation have cited various technical impacts that arise during the integration of DG onto the grid [36] [37] [38] [39] [40] [41] [42] [43]. The impact of these technical issues depends on the capacity of the DG being integrated; if the total number of DG capacity is a significantly small number as in the case of the DG that are in the process of being introduced to the South African utility grid by the REIPPP initiative, then there may not be an urgent need to address these issues [44]. However, as the number of bidding windows increase, and as the capacity allocated for renewable energy such as wind and solar energy increase, the study of grid integration along with studies targeted at improving the efficiency of such systems will become a necessary course of action as is being done in other countries worldwide [45] [46] [47] [48].

A. Technical Impact of DG Grid Integration

The technical impact of grid integration include rise in voltage levels due to the reverse flow of electricity into the distribution network, transient instability in cases of multiple generator installations, rapid increase and decrease in voltage levels due to intermittent nature of electricity generation by DG, increase in thermal ratings of the equipment, increase in fault levels of the distribution network near DG connection locations, inability to meet load requirements during power outages due to restrictions of working in islanding mode, incorporation of protection scheme to the DG in order to disconnect it from the grid during faulty conditions, and decrease in power quality when DG is connected to a weak distribution network [49], [50].

As discussed previously, the South African electricity generation model primarily depends on coal as the source of electricity. Coal power plants employ synchronous generators which maintain the inertia of the system. The integration of renewable based DG systems affects the network's ability to maintain this inertia, especially during moments of instability such as an increase in frequency due to a sudden loss of load. In [51], this impact is addressed by modelling the behaviour of synchronous machines on power electronic converters. The change in voltage and frequency levels were monitored at the POC using Matlab/Simulink software, and were found to be minimal during unstable conditions. A double synchronous control technique is proposed in [52] for the control of large scale renewable power plants. Using the South African grid connection code for renewable power plants [15] as a point of reference, some of the other different technical impacts are as follows.

1) Fluctuation in voltage levels of the system

The integration of DG into the distribution network can lead to a change in voltage level of the system due to large penetration of electricity from the DG. This effect is more pronounced in renewable DG systems due to the unpredictable nature of the fuel source and hence electricity generation, and in low load distribution systems. If there is an increase in voltage at the point of connection (POC) of the DG system to the utility, the network voltage may rise beyond the desired voltage regulation limit. Similarly, there must be a number on the minimum voltage supplied at the POC, so that the grid does not experience under voltage conditions [53].

For example, in the case of PV systems, high voltage is expected at POC during maximum generation at peak solar radiation hours (midday). The load profile in South Africa is such that maximum demand for electricity does not occur during midday when there is ample PV electricity being generated, thus leading to an increase in network voltage levels. In the case of urban areas of the country where the load demand is higher and comparatively consistent through the day, the penetration may not cause a significant rise in the voltage [54].

2) Impact on power quality

The use of power electronic inverter technology in DG systems that generate a DC output (such as PV inverters, capacitor banks, reactors) leads to the presence of harmonics that can alter the sinusoidal waveform of the network. Low frequency oscillations are introduced to the system due to the interaction of DGs and produce oscillations of the range of 0.7 to 2 Hz (few DGs placed close to each other- local oscillations) or 0.1 to 0.7 Hz (large number of DGs-inter-area mode oscillations). Passive filters that restrict the passage of harmonics to the grid [55], and active filters that supply a compensating current to the generated supply current in order to suppress the harmonics [56], [57] can be used to mitigate the effect of harmonics on power quality of the distribution network. As per the South African grid code [15], renewable plants are not allowed to cause a resonance more than three times at the POC at any frequency.

In [58] [59], the authors have developed a direct quadrature rotating frame dynamic model to improve the performance of single phase voltage source inverters (used for PV applications). For harmonic current compensation when the inverters are connected near nonlinear loads, the controller was modelled by calculating a highly accurate reference for the inverter currents, and the results show a total harmonic distortion value of

4.5% was obtained. In South Africa, a total harmonic distortion value of up to 6% is permitted for DGs connected to medium voltage (up to 33kV) points in the network.

3) Effect on reactive power compensation

A renewable plant connected to the grid should be able to export and import reactive power for unity, leading and lagging power factor conditions while it is generating active power. The plant should be able to produce 5% to 100% of its maximum power output, and correspondingly achieve its target reactive power, in order to be compliant [15]. However, during low network voltage conditions, generators can fail to supply enough reactive power to the grid. In order to resolve this, renewable plants are installed with a capacitor bank that can compensate for the lack of reactive power supply by the plant. This can also lead to harmonic current injection to the network, thus affecting the power quality. In [60] [61] [62], Direct Lyapunov Control technique is used for active and reactive power compensation for grid connected DG systems, and also helps in reducing the total harmonic distortion in the system as seen by simulation studies.

4) Increase in power losses in the system

In residential DG systems, there is a possibility of voltage instability as low voltage lines of the order of 11 kV cannot withstand the penetration of over 500 kW of generated electricity [63]. The effect of DG on power loss of the network was observed in [64], however the extent of power loss depends on the type of renewable energy technology used by the DG and the amount of penetration of electricity generated by the DG. The voltage level at each bus where the DG and loads are connected also affects the degree of power losses.

B. Minimising Technical Impact of DG Grid Integration using Optimisation Techniques

The use of optimisation techniques can help achieve the correct placement and sizing of DG on the distribution networks, while minimising power loss, and improving voltage stability and overall power quality. Studies have been done that confirm the impact of optimal location and sizing in the reduction of technical issues faced during the grid integration of DG, and to improve the general working efficiency of the DG [65] [66] [67] [68] [69] [70] [71] [72] [73] [74]. A general flowchart indicating the optimisation process is shown in Figure 4.

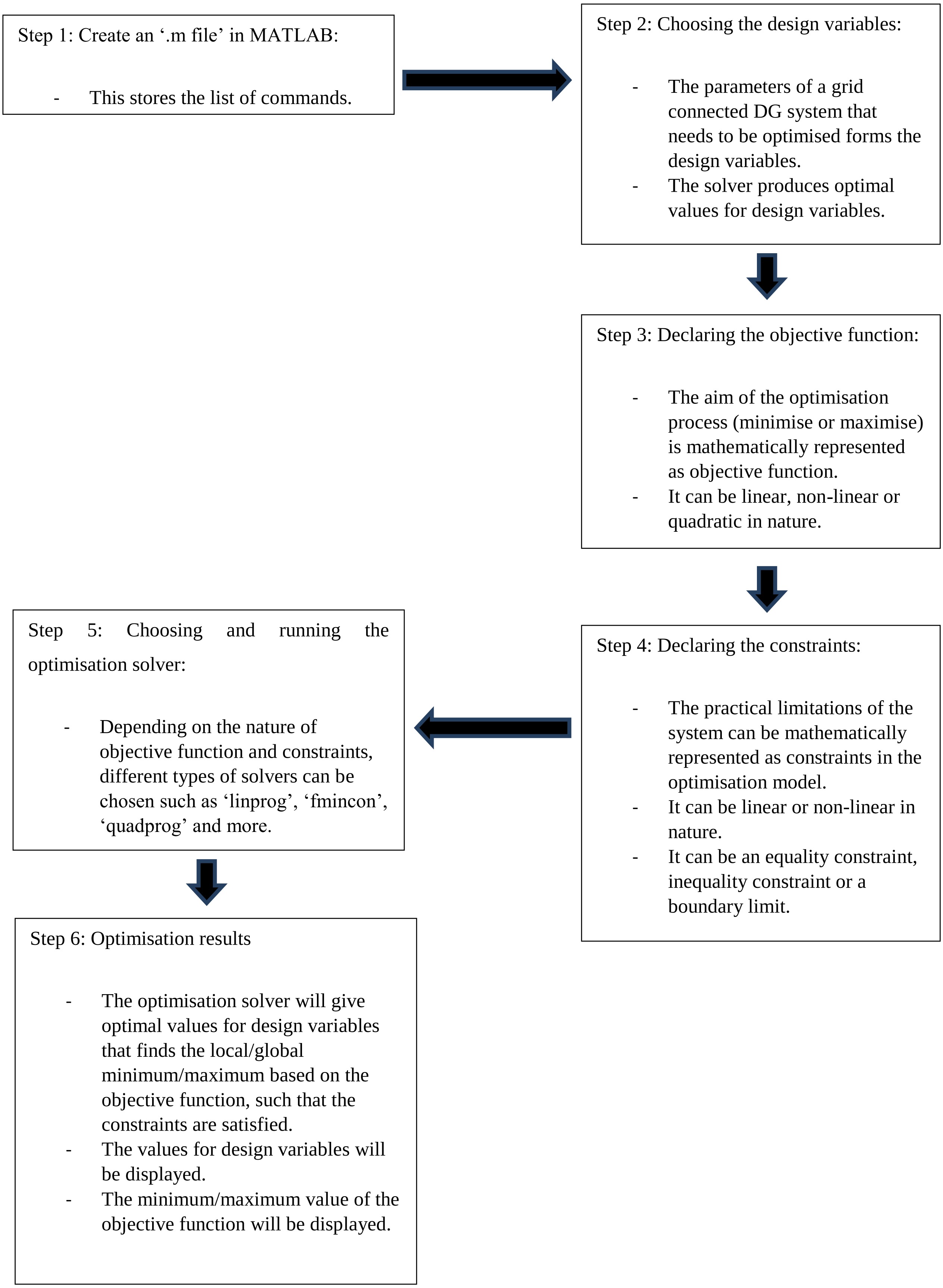

Figure 4: Block diagram representation of a general optimisation process using MATLAB.

However, there are certain challenges to the optimisation process. The most optimal location to introduce a DG into the distribution network in theory may not have enough solar or wind power to ensure enough generation capacity in practice. The optimal location of DG also varies year after year due to the increasing number of DGs being connected to the grid and changes in the availability of fuel sources. Dynamic modelling must be used to recreate the energy system due to the dynamic nature of the fuel source and hence electricity generation. Using a wide set of data collected during frequent intervals is essential to achieve an accurate dynamic model, as opposed to static modelling where data obtained at one point in time can be used to predict the optimal working conditions for a long time into the future [75]. Based on different objectives that are considered for optimisation of grid integrated renewable based distributed generator systems, the studies are classified as follows;

1) Maximising renewable energy penetration:

Since one of the main aims of introducing a grid connected DG energy model in South Africa is to reduce the country's dependence on coal as the primary source of energy and to meet the renewable energy targets that were set by various policies issued, it can be said that maximising the penetration of renewable energy into the grid should be a main objective function of a grid integration optimisation problem. In order to maximise renewable energy penetration, the amount of emissions caused by the whole system can be minimised to find the optimal size of the DG unit. Therefore, it is seen that in many studies, minimising pollution and/or greenhouse gas emission is taken as the objective function [76] [77] [78]. The minimisation of cost of energy generation (which includes investment and operational cost) in DG systems is also seen as an objective function in these studies.

2) Minimising cost of behind-the-meter electricity generation:

The reduction in expenditure on energy consumption is an important motivating factor for the installation of DG units to the grid, and studies have been performed on the optimisation of location and size of these DG units in order to achieve minimum generation costs. However, there are not sufficient number of studies that consider renewable small scale residential DG units and the reduction of generation costs in such systems [79]. This is a matter of significance as the high investment costs that must be spent in order to install such a system can discourage many consumers from switching over to an SSEG based energy model for their homes.

3) Maximising system reliability:

Studies are done on intentional islanding, where DG units are incorporated with Automatic Sectionalising Switching Devices (ASSD), and the optimal placement and quantity of ASSD will help improve system reliability by supplying electricity to certain areas of the distribution network that are undergoing load shedding or line faults [80] however, its effects on stability and safety need to be examined in detail. Other studies [53], [76], [77] focus on finding the optimal placement and sizing of DG units on the distribution network that helps to maximise system reliability.

4) Minimising power losses:

DG systems are installed near the load location and therefore bypass the need for long and complex transmission and distribution systems. This also means that there are low levels of power loss associated with DG systems. The wrong size and location of DG units, however, can lead to voltage instability and an increase in power loss of the system. It was observed that the optimal sizing of DG units in order to achieve minimum power loss will vary depending on the load model of the system under study [81].

5) Minimising voltage deviation:

The minimisation of voltage deviation from the grid standards is also used as an objective function, and the optimal location and sizing of DG units in order to achieve this objective has been extensively studied [82]. Multi-objective problems maximising voltage profile improvement and minimising power flow from the DG into critical feeder lines, and minimising the transmission line loss were studied and tested [83], results of which establish the need for optimal placement and sizing of DG units. In [84], the impact of reactive power injected by different DG units on the voltage stability of the system is analysed by using optimisation techniques, more specifically particle swarm optimisation, to find the optimal size and location of DG that will improve voltage stability and reduce reactive power loss.

C. Optimisation Solutions for PV based Grid Integrated Systems

Optimal sizing of a building integrated PV system (BIPV) depends on the amount of load required by the buildings in the area. An energy audit will give details on the load profile of the buildings, and will help determine the minimum and maximum load demand which can be set as the constraints of the optimisation problem. The optimal location for the system can be calculated, and the electricity generated through such a system can be used for the area's common electricity needs.

In a BIPV system, a portion of the electricity generated is used to supply the load demand, and the rest or excess is given off to the utility grid. A study performed in Sohar, Oman demonstrates the modelling and simulation of a photovoltaic system in order to analyse and estimate the photovoltaic power output capacity of a particular location [85]. The modelling principles used in this study can be applied to recreate a probable building integrated photovoltaic system, and then find its optimal placement and sizing.

In the case of distributed generator PV systems, the entire electricity generated is supplied directly to the grid. Optimal placement of the PV system will be of top priority in this case, as there is no constraint in the form of satisfying local load demand. This means that the placement of the PV system will not be confined to a small area, instead a large area where there are offices, housing complexes and schools can be considered. A roof top PV model will help in the efficient utilisation of space in an urban setting. The sizing of such a system depends on the load that can be handled by the utility grid. The drawbacks of large power penetration into the grid has been discussed in the previous sections, therefore a limit must be maintained to the maximum power allowed to be supplied.

Optimisation studies are not limited to placement and sizing, and can be extended to the optimal tilt angle of PV arrays, optimal size of inverter and battery backup storage used and more. A multi-objective optimisation problem can help to create a more efficient and accurate model of the PV system in study. In [86], priority is given for lowering the costs incurred by residents who have PV systems installed and this is accomplished through an energy management approach that makes use of optimisation techniques.

In [87], modelling of the PV system used in a residential system is performed and the optimal size of the PV array and battery storage is found out with minimising the daily costs incurred in terms of operation and maintenance as the objective. The relationship between optimal PV sizing and feed in tariffs was also established through this study. The possibility of battery storage sizing to help reduce costs incurred by residents is further studied in [88]. It is also possible to minimise the overall payback time of a PV system in a residential area as shown in [89] by calculating the optimal value for the rating of the PV system.

D. Optimisation Solutions for Wind based Grid Integrated Systems

Wind energy power optimisation has been performed in [90], wherein the wind turbine that uses a doubly fed induction generator is connected to the grid. The optimal power sent to the grid and the speed of the turbine shaft is determined using the perturbation and observation process, so that the active and reactive power generated by the turbine can be controlled with the help of sliding mode controller.

In [91], the optimal design of a grid connected wind and PV system based in Spain is discussed. The optimal size of the hybrid system such that the life cycle cost, while successfully being able to meet the demand, can be minimised. Genetic algorithm with the help of the global optimisation toolbox in Matlab was used for this study.

E. Simulation Studies to Validate Optimisation Results

The most suitable algorithm, analytical, numerical or genetic, must be used depending on the type of objective function and constraints. The optimal result obtained must be then tested using simulation. Various simulation studies have been performed to understand the grid better during conditions of grid integration. Digsilent Power Factory, ETAP and Matlab Simulink are some of the most commonly used software programmes relevant to this field of study. In [92], an IEEE 13 bus system is modelled using PSCAD and tested for changes during the high penetration of photovoltaic electricity into low voltage residential feeder network. A very similar study was performed using Digsilent Power Factory to model an IEEE 13 bus system with modified load data in [93]. The voltage profile was plotted at each bus for varying levels of penetration using the voltage profile optimisation function in Digsilent, and residential and industrial load profiles relevant to the location were applied to the system to monitor voltage changes in the most sensitive bus.

In [94], a comparative study of Digsilent and Matlab-PSASP (Power System Analysis Software Package) is performed to analyse a simple IEEE 9 bus system's ability to recover after a fault has been introduced while it stays connected to a PV system. In [95] a dynamic model of a PV plant is created using Digislent and fitted with control features such as maximum power point tracking and relay protection control. The focus of this study is on control functions that can be used for large scale PV plants; in this case a 10 MW plant in China, and hence has different results from that of a residential PV system. In [96], an extensive comparative simulation study on the various reactive power control strategies was performed using Digsilent. The modelling of a 20 bus power system with a PV set connected to each node, along with the data used for each of the power system elements were indicated.

IV. CONCLUSION

Studies performed on the electrification programme in South Africa have established the significance of coal in the country's energy mix. It is not practical to abruptly end the country's relationship with coal in order to reduce its carbon emissions. This is mainly because renewable energy is not ready to become the primary source of energy, with many constraints such as advancement in technology and optimal design of renewable power system components. However, the country also needs to change from its coal intensive ways in order to meet its renewable energy targets introduced in the REIPPP initiative.

In order to make the best of energy security provided by coal and incorporate renewable power into the country's energy model, the most practical solution is to adopt a hybrid and bidirectional energy model, wherein the consumers stay connected to the grid yet remain powered by renewable energy sources through small and medium scale distributed generators that can be installed within the consumer's premises. Grid connected DG systems can help reduce carbon emissions, provide flexible and reliable power supply option to the consumers and reduce the impact of tariff hikes.

The various technical issues faced during the integration of DG systems onto the grid have been discussed, along with a comprehensive study on the use of optimisation techniques to mitigate these technical concerns. Extensive and exclusive research into minimising transmission power losses and net cost of installing and operating such a DG system, while maintaining the voltage and frequency levels of the network, can give consumers and the country's policy makers an insight into the practical employment of a grid connected small to medium scale distributed generators that are powered by renewable energy sources.

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