Modelling and Simulation a Solar Farm Energy-Based Smart Grid for Tshwane University of Technology (Emalahleni Campus), South Africa: Feasibility and Analysis Studies

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Abstract: - In eMalahleni, high solar irradiation makes it ideal for solar farms. The proposed photovoltaic (PV) systems are designed to meet the entire energy demand of the Tshwane University of Technology's eMalahleni campus. These systems are expected to produce approximately 876 MWh of electricity per annum. The campus building presentations promoting such designs have roofs tilted at 25 degrees and can support the installation of a 625-kW solar PV system. The current proposal will install a 150 kW PV system with a 100-kW inverter, designed to maximize conversion efficiency and system performance. This setup is expected to be viable, with returns estimated in a period of 14 months due to the low LCOE value of 0.6 Rands/kWh. In total, this project has an estimated lifetime saving of about 30 million Rands. According to detailed simulations, the model used to predict the global solar radiation for the region is highly efficient, that is, it follows actual values very well. This tracking ability is very important for making the best use of how well the system can work. This accuracy is critical for maximizing the efficiency of solar energy production. The performance of the PV system reaches its peak at 125 kW around midday, highlighting the benefits of precise solar radiation modeling in enhancing energy output. Moreover, the shift to solar energy is expected to have substantial environmental benefits. Over a period of ten years, the transition will reduce carbon dioxide (CO_2) emissions by 6,515 tons, nitrogen oxides (NOx) by 27 tons, and sulfur oxides (SOx) by 53 tons. This reduction in greenhouse gases and pollutants will contribute significantly to climate change mitigation, improved air quality, and decreased acid rain. The overall impact underscores the significant economic and environmental advantages of adopting solar power in eMalahleni.

Key-Words: - Energy, eMalahleni, LCOE, Inverter, Power, Renewable energy, Solar farm, South Africa.

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1 Introduction

South Africa's persistent electricity challenges stem directly from the deteriorating condition of state-owned Eskom's aging, heavily utilized, and frequently malfunctioning fleet of coal-fired power plants. These operational issues have resulted in severe power outages that have profoundly impacted the country's economy for nearly 15 years, [1]. In response, efforts were made to address this infrastructure crisis by boosting generation capacity and replacing outdated facilities. This led to the development of the two biggest coal-fired power stations in the world, Medupi and Kusile, currently being built, respectively, in Limpopo and Mpumalanga in South Africa, [2]. These two mega projects have faced myriad delays since their construction began some 15-odd years ago. Some 9,600 MW of installed capacity between Medupi and Kusile is currently generating about half of its designed output. Coupled with technical failures, construction delays, and accidents, each has appeared to undermine their contribution to the national grid thoroughly. Meanwhile, the country of South Africa has dealt with surging records of annual power outages over the past three years. In fact, one could argue that 2015 was the "best" year in terms of electricity reliability, with about 852 hours of outage time which accounts for about 10% of the year. Between 2020-2021, the country experienced 859 hours (around 10% of the year) of outages, followed by an alarming increase to 1169 hours (approximately 13% of the year) in 2021-2022, marking a troubling trend, [3]. The situation worsened dramatically in 2022, as South Africa endured a staggering 205 days of rolling blackouts as shown in Figure 1.

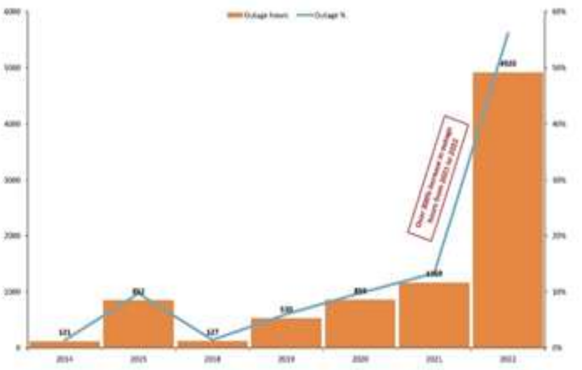

Fig. 1: Electricity outage records for the past three years in South Africa, [2]

This surge in outage duration was primarily attributed to the breakdowns of aging coal-fired power plants, compounded by Eskom's financial struggles to procure diesel for emergency generators. Looking ahead to January 2023, the outlook remains bleak, with expectations of further deterioration compared to the previous year. Eskom, responsible for a nominal generation capacity of about 46,000 MW, faced significant challenges in late December 2022 and early January 2023. Nearly half of this capacity, approximately 23,000 MW, was offline due to breakdowns and maintenance, exacerbating an already strained situation. During peak demand periods, South Africa typically requires between 28,000 MW and 34,000 MW of electricity, underscoring the severity of the supply-demand gap. Renewable Energy Sources (RESs) are increasingly displacing traditional power plants, offering the dual benefits of cost reduction and sustainable energy provision. Legacy power grids were designed for unidirectional centralized generation flow toward consumers and are increasingly outdated. Failure emanating from these central nodes can easily result in a wide-area service disruption, thus pinpointing the vulnerability of our infrastructures, [4]. The increase in Renewable Energy Sources (RESs) greatly affects the stability of the grid. For example, at times of high solar generation, typically around midday, an imbalance often prevails between supply and demand as shown in Figure 2.

Therefore, it contradicts grid management strategies. High-level control methodologies are required for the exploitation of the diversified potentials by RESs, [5]. However, such an advancement has been constrained by the limited data capabilities of the present grid, [4], [5], [6]. In this context, Distributed System Operations (DSOs) emerge as important actors where they not only play the role of electricity distribution but also electricity quality according to well-set performance levels, [7], [8].

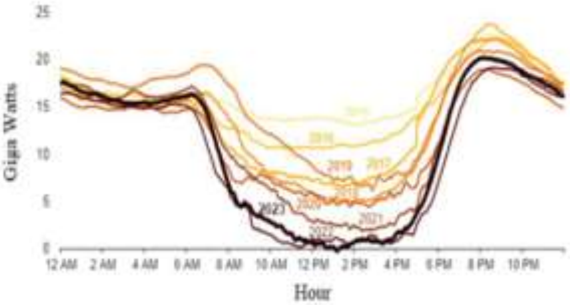

Fig. 2: Duck curve of demand curve, [4]

Voltage disturbances normally initiated by overloads from new RES connections are becoming the major risk. DSO silently accepting vim of unbalancing will generate the possibility of having localized blackouts by activating protective devices within the distribution network, [9], [10]. Therefore, as recommended proactive management and upgrade of grid infrastructure is important to accommodate rising shares of RESs and maintain the stability of the grid in more and more variable and demand-fluctuating circumstances. Migration to Smart Grids (SGs) or microgrids comes because of the necessity for highly efficient systems of electricity supply. These include the integration of Renewable Energy Sources and decentralized station sot, therefore, improving system reliability, [11]. They enable fault detection and autonomous repair mechanisms, which reduce manual interventions and, in the same way, strengthen resilience against natural disasters or deliberate sabotage, [12]. In addition, by allowing the active participation of consumers in the management of power flow, [7], [8], [13], [14], [15], [16], [17], SGs also strengthen consumers. This complexity requires thorough investigations of SGs, [18]. Many methods have been examined in terms of how to efficiently combine and transport RSs over long-distance routes in SG, [19]. These two enhance the abilities of SGs in energy-dispatch and enhance the performance of the grid in general, [18], [19], [20].

2 Methodology

In this present work, the eMalahleni campus of Tshwane University of Technology was chosen to integrate the campus with RESs development. The PV systems were simulated using PVsyst, and shade analysis was conducted by means of SketchUp. eMalahleni campus of Tshwane University of Technology is one of the nine campuses of Tshwane

University of Technology which was founded in 2002 and is located at the Centre of eMalahleni city in the province of Mpumalanga which has a Latitude and longitude coordinates of -25.872782 and 29.255323 respectively as shown in the google maps in Figure 3. eMalahleni city is particularly suitable for photovoltaic (PV) farms. The eMalahleni campus of Tshwane University of Technology enjoys significantly higher solar radiation levels compared to many European countries. The average specific energy yield in eMalahleni is approximately 1,700 kWh/kWp/year.

Fig. 3: Google map of TUT (eMalahleni Campus), [21]

This means that for every kilowatt peak (kWp) of solar panels installed, one can expect them to produce an average of 1,700 kilowatt-hours (kWh) of energy annually, [20]. The proposed project aims to cover energy consumption over a period of 10 years. To determine the proportion of solar energy needed to fulfill the Campus consumption, careful analysis has been undertaken. The proposed model integrates photovoltaic (PV) as the primary renewable energy source. This choice is motivated by the need for a simple and cost-effective controller structure, which is crucial for achieving reliable operation in industrial and high-performance applications. To evaluate the performance of the designed farms, several software platforms have been utilized. In the following sections, a detailed technical analysis of the designed PV and wind farms will be carried out based on the assessed Sun Peak Energy (SPE) and local solar data collected using the Photovoltaic Geographical Information System (PVGIS) tool for eMalahleni. Thus, in this study, we assumed that the PV farms would meet 100% of the energy demand.

3 Problem Solution

While it is not a completely exhaustive list, each of these elements forms the basis of designing a photovoltaic (PV) farm; The steps are as follows: System sizing, Technology election, Electrical design, Environmental impact, Installation method, Financial analysis, and Integration with Grid and Energy management. By carrying out the above steps and taking consideration of the above factors, one can successfully design an efficient, reliable, and environmentally sustainable PV farm.

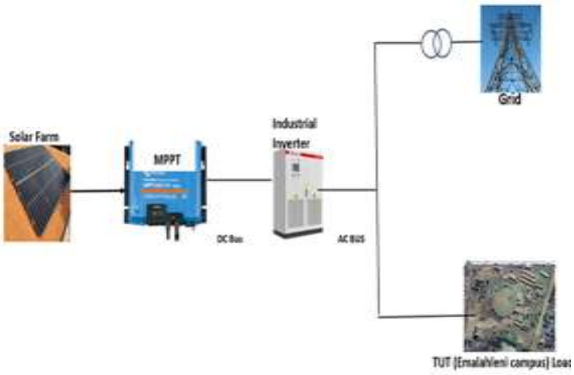

Fig. 4: design block diagram

Each step is carefully planned and developed in collaboration with experts in solar energy, engineering, and regulatory compliance to ensure successful project implementation. In a solar farm, modelling as shown in Figure 4, the components including photovoltaic panels (PVs), each of the Maximum Power Point Trackers (MPPTs), the inverters, and the batteries are a crucial and tedious task. Every individual component is chosen and adjusted to give birth to the best possible solar energy generation system in terms of functionality, effectiveness, and reliability. Factors such as battery chemistry (lithium-ion, lead-acid), capacity, cycle life, and charging/discharging characteristics are analyzed to optimize energy management and enhance grid stability. Each component's design and integration are carefully planned to achieve a balance between initial investment costs, operational efficiency, and long-term reliability. Advanced modeling techniques and Simulation tools are used to forecast system performance, confirm design decisions, and maximize the total economic value and environmental benefit of the solar plant. Such a holistic approach assists in fulfilling the desired objectives of sustainability, resiliency, and economics of the solar energy systems over their operational lifetimes, [10].

3.1 Rooftop Mounting Design

A fixed-tilt solar PV system is widely recognized as the most prevalent type of solar installation. Rooftops are ideal locations for smaller-scale solar

PV setups due to several advantageous factors. Firstly, rooftops often feature large, unoccupied areas that can be effectively utilized for solar panel deployment without occupying additional land or disrupting existing land use. Secondly, there is usually sufficient solar light on the roof all day and therefore there is more electricity produced by the PV system. Because roofs are so high up, they are usually less shaded than those at ground level, thereby increasing the amount of solar light and energy production. Furthermore, rooftop solar PV installation can help to improve buildings' energy efficiency by taking renewable energy as the source of consumption, [19]. Moreover, roof-mounted solar PV is also sustainable development by reducing fossil fuels and reducing emissions. This is not only eco-friendly but also energy self-sufficiency and sustainability at the community level. Rooftop PV farm designs consist of taking advantage of available space with structural integrity, orientation, and electrical connectivity in mind. Rooftop mounting design will be applied in this present project because rooftop PV system rooftop mounting was planned and integrated during the building roof of campus buildings. This preventative action makes sure the rooftops are primed for solar panels, in line with our sustainability agenda, and make the most of available space for clean energy generation. The rooftop area and the space available for the PV solar farm were carefully assessed using the latest devices like Google Maps. This was a process of precisely measuring the roof-top area that could be put in place for panels, with special attention to getting the plan right in line with true north to maximize sunlight. This was achieved by sat-nav imagery and map-ping detail and then the entire rooftop area was measured and analyzed, [17]. This Google Maps app gave accurate measurements of the roof's size and orientation which was necessary to know exactly where to put PV panels to absorb the maximum amount of sunlight and produce the most amount of energy. The geographical latitude is an angle of reference for the calculation of the spotlight position over the surface of the Earth. The latitudinal position is crucial to find what would be the best-fixed roof angle for the panel because the angle of the roof determines the solar energy striking the panel according to the geographical location. The angle with the horizontal involves the amount of sunlight striking the solar panel. Geographical location also influences the optimum angle at which the panels should be installed for the best yearly performance. Energy generated by a solar photovoltaic cell depends on the angle at which sunlight strikes the panel. This angle depends on the geographical latitude of the installed location. Calculated values of solar panel angles recommend changes in the planar angles of roof-mounted solar panels from the general recommendation of 15° to $2\theta \pm 4.54°$ - 9.34°.

The best angle for a solar panel can be determined by using location coordinates such as latitude and longitude if the solar panel is facing true south, in line with true north. The optimum angle for a solar panel coincides with the latitude of the location. The best median power production value for a location is obtained at a time when the solar panel is facing true north. In any case, this is the desirable time. It also shows that the comparisons among the left-side systems can be fair considering the true north scenario. This is because the maximum difference noticed between the least and the most productive system is just 5.625% and the time duration for the maximum power, which may be recorded, may last for a few minutes.

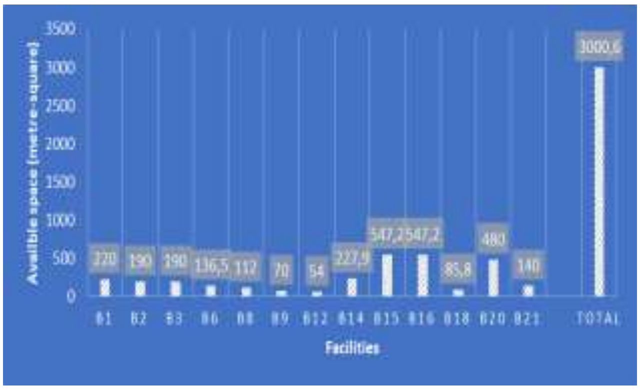

Fig. 5: Available space for PV installations chart

A comprehensive examination of approximately fifteen facilities was precisely carried out to locate suitable sites for the installation of a photovoltaic (PV) solar farm. After conducting a thorough assessment and carefully analyzing specific criteria, a total of thirteen facilities emerged as the top choices due to their highly advantageous rooftop conditions and exceptional solar exposure qualities. It is worth highlighting that these selected facilities collectively presented a sizable total rooftop area of around 3000 square meters, as clearly illustrated in Figure 5 of the analysis. Each individual facility underwent rigorous scrutiny to ensure that it unequivocally met the stringent installation requirements for a PV solar farm. Crucial factors such as precise roof orientation, impeccable structural integrity, and least shading were exhaustively evaluated to determine the suitability of each venue. The encompassing survey process encompassed the utilization of advanced tools, including cutting-edge satellite imagery technology and highly accurate mapping applications, to specifically measure and distinctly plot the available rooftop areas. The final decision to concentrate solely on these esteemed thirteen facilities was made based on their excellent probability to generate an abundance of solar energy output, while concurrently aligning with the overarching objectives of sustenance and seamlessly integrating renewable energy sources within the project parameters. By strategically focusing on facilities endowed with ideal rooftop characteristics, the project aspired to optimize the efficiency of energy production and concurrently minimize the potential environmental impact. As the project advances, accurate arrangement and precise design will be executed to further refine the overall layout and implement an astute installation strategy for the PV solar farm across these critically selected facilities.

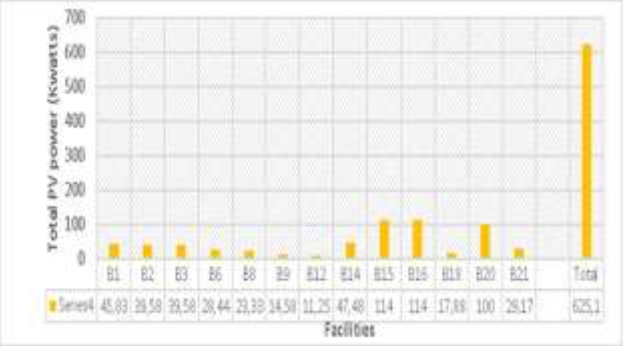

Fig. 6: Solar farm power capacity chart

Careful strategizing and a particular selection of high-efficiency 500-watt monocrystalline solar panels have not only helped the project meet energy generation objectives but have also aligned with sustainability goals. The panels are designed to generate the maximum energy per square meter while taking up 2.4 square meters of space, thus using the maximum area of the rooftop space. With a total installed capacity of approximately 625 kW as indicated in Figure 6, the PV solar farm represents the potential for sustainable energy production from these facilities. Pioneer in the Field The project only uses state-of-the-art technology and innovative solutions. Continuous measurement and maintenance will translate to improved performance, thus reinforcing the choice of Canadian 500-watt monocrystalline solar panels.

3.2 Campus Energy Consumption Calculation

The energy (E) in kilowatt-hours (kWh) per day is equal to the power (P) in watts (W) times number of usage hours per day (t) divided by 1000 watts per kilowatt.

$$E(\text{kWh/day}) = \frac{Powr\ X\ Time}{1000} \tag{1}$$

Based on the six-month energy consumption bills of the campus, as depicted in Figure 7, it is evident that the campus depletes an average of 54,198.83 kWh monthly and has an instantaneous power consumption of 75.28 kW. This indicates that over the course of a year, the campus consumes approximately 650,386 kWh annually.

Fig. 7: eMalahleni campus of Tshwane University of Technology average monthly energy consumption

These figures underscore the substantial energy requirements of the campus, highlighting the importance of efficient energy management strategies to ensure sustainability and cost-effectiveness in the long term. Because of the approved tariff structure of R2.55 per kWh for commercial conventional three-phase electricity in the 2023/2024 financial year of eMalahleni Local Municipality, it can be calculated that the campus spent approximately R1.7 million on electricity annually.

Fig. 8: Fluke 1738 Three-Phase Power Logging Process

This expenditure reflects the significant financial commitment required to sustain the campus' operations, emphasizing the need for efficient energy management practices and possibly exploring renewable energy sources to mitigate costs and environmental impact in the long term. Cost analysis is primarily important for budgeting and sustainability of the campus infrastructure system. Figure 8 was employed to systematically aggregate and log instantaneous power consumption data on the campus over 7 days. Throughout the monitoring period, the logger captured various power usage parameters, and an absolute maximum power of 75,556 kW was recorded. This peak value corresponded quite well with the Local Municipality data of 54,198.83 kWh (per month) energy consumption thereby once more proving correctness & reliability for Fluke 1738 in its data logging capabilities. The logger's readings were very similar to those from the municipality; therefore, Fluke 1738 accurately measured Power Consumption at campus.

3.3 Inverter Selection

Based on the highest power usage of 75,556 kW recorded during monitoring, a 25% margin has been added for future variation and unknown power requirements. The extra margin of 25% is meant to take care of any unforeseen increase in power consumption, over and above the recorded peak usage. It is therefore suggested to install an inverter of capacity 100kW for this project, to meet the maximum recorded power demand plus the buffer. This makes sure the inverter covers peak consumption and has enough reserve, allowing the power system to reliably adapt and flexibly meet any potential overload or extra requirement that could arise in future. By taking such a preemptive step for inverter sizing, it will help ensure stability of power supply under varying loads without interruption. It was strategically decided to implement five 20 kW hybrid three-phase inverters in this project. Using appropriate inverters efficiently in hybrid energy systems is important when Solar PV generation and energy storage facilities are available. The 20 kW Hybrid Inverter is shown in Table 1 and constitutes among the most advanced suitable options for such medium-to-large-sized applications. The units are designed to integrate renewable generation (solar PV arrays) with energy storage systems (ESS — typically battery) seamlessly.

The hybrid operation of the inverter ensures simultaneous and proper control of outputs from both the solar PV system and the battery. It focuses on the self-consumption of solar energy and back charging storage for further consumption, optimizing the energy use. The five units hooked up in parallel also allow for greater scale and flexibility. Such configuration enables the tuning of system capacity with respect to energy demands and expansion at a later stage. These inverters allow for easy engagement with the electrical grid, creating a grid-tied system.

Table 1. 20Kwatts Hybrid Inverter specifications

PARAMETERS	RATING
Rated Power	20KW
Min PPT Voltage	480 V
Max PPT Voltage	800 V
DC Startup Voltage	480 V
DC Shutdown Voltage	450 V
Max Input Voltage	1000V
Max DC Power	26000W
Max AC Power (5 Minutes)	22,000 W
Max DC Current	60 A
Max AC Current	30,6A
Euro Efficiency	95 %
Transformer	HF
Has Integrated DC Switch	Yes
Grid type	Three phase

This capability is further complemented by the ability to assist grid stabilization and take part in grid services to increase grid reliability and resilience. Plus, the provision of these inverters is also in line with the project objectives of minimizing the carbon footprint, maximizing energy use, and facilitating the growth of renewable energy in the community. It represents a commitment to the use of technology-based solutions for long-term energy diversification and resilience. Although a solar photovoltaic (PV) system of an estimated 625kW capacity may be viable, this project will need more targeted specifications. This time around the goal is to efficiently drive a 100 KW inverter for a current project. The solar PV system designed and installed thus needs to be designed to meet the energy needs of this inverter. Since our inverter size is 100 KW, a solar PV system should be installed that can always generate enough power to run the entire 100 KW inverter. It is basically the ratio of installed DC capacity: the amount of power that the system has from solar panels to the AC power rating of a given inverter. In general, it is beneficial to oversize the solar array so that the DC-to-AC ratio is greater than 1. By capturing all available energy like this, even if the solar production is not high enough to reach the inverter's maximum capacity (which is the case for most of the day), this strategy enables ideal energy capture. The inverter clipping occurs when the power inverter's DC/AC ratio is not large enough to support the peak power output during midday. Inverter clipping, or power limiting, refers to wasted energy from higher DC power harvested by solar panels, exceeding the inverter's capacity to fully process it. The loss of potential energy as the inverter is unable to process the excess DC power generated by the solar panels is called inverter clipping, effectively limiting the power output to the inverter's maximum capacity. This phenomenon occurs when the DC/AC ratio of a power inverter is too low to adjust the peak power output during midday:

$$\text{AC Inverter Capacity} = \frac{\textbf{DC PV Capacity}}{\textbf{DC to AC ratio}} \quad (2)$$

To make sure the inverter's AC output in relation to the DC power produced by solar panels matches, thus enabling optimal energy conversion efficiency matching. If the DC to AC ratio is 1.50, then it means that the installed DC capacity of a PV array is 50% greater than the inverter's AC power rating. For a solar PV farm with total DC capacity of 150 kW, a 100-kW inverter is found to be required using equation (2) with DC to AC ratio of 1.50. This method allows the solar farm to function at its full rated output without compromising equipment longevity or reliability. Additionally, using a 100-kW inverter complies with industry practice and this improves the economics of project by balancing cost efficiency and performance.

3.4 Feasibility Study of the PV Farm

The design criteria for the PV farm are provided in Table 2, include PV panel and inverter specifications, costs and optimum installation slant angle thereof. This includes important factors like annual energy degradation rate of PV panels decreasing efficiency, output consistency over time and O&M inflation costs during their lifetime. The economic viability of the chosen PV components has also been analysed apart from technical parameters. These economic factors help determine lifecycle cost of PV farm and evaluate its feasibility analysis. Table 2 includes the feasibility checks for ten years to ensure the design is financially viable. Financially viable variables must be examined in depth to vet long-term prospects of project and ensure its sustenance. Levelized Cost of Energy (LCOE) or Levelized Cost of Electricity (LEC), expressed in Rands per kilowatt-hour (kWh) provides a common metric for comparison between various energy sources by thoroughly evaluating all the costs involved within feasibility study, design, installation and commissioning of PV farms. Capital, operational, maintenance and other costs applicable over a period of 10 years including Table 3.

Table 2. Specifications and cost analysis of the proposed solar farm

Degradation	First Year: 2%
	After: 0.55%
Tariff Inflation	First Year: 15,10 % [
	After: 15.7%
O&M Inflation	First Year: 2%
	After: 5%
System Power	PV: 150 kW
	Inverter: 100 kW
Selected Devices Power rating	PV: 500W
	Inverter: 20 kW
Quantities of solar devices	PV: 300
	Inverter: 5
Unit price	PV: R5000
	Inverter: R60000
Total cost	PV: R 1500000
	Inverter: R 300000
	Total: 1800000
Installation cost per 1kW	At 30% of the total cost of the solar system **R540000**
Logistic and Transportations	At 10% of the total cost of the solar system **180000**
Total cost	2 520 000 + Contingence (20% of Total cost)
Estimated total cost	**R 3 024 000**

Table 3. A summary of a 10-year economic viability study

Year	**Energy produced MWh/year)**	**System cost (R)**	**Saving rate (R)**	**Cash flow (R)**
2024	0	3024000	0	-3024000
2025	657	60480	1675350	-1348650
2026	643,86	63504	1889761,29	541111,293
2027	640,3188	66679,2	2163152,11	2704263,41
2028	636,797	70013,16	2476094,25	5180357,66
2029	633,2946	73513,82	2834309,57	8014667,22
2030	629,8115	77189,51	3244347,71	11259014,9
2031	626,3475	81048,98	3713705,88	14972720,8
2032	622,9026	85101,43	4250965,85	19223686,7
2033	619,4767	89356,51	4865950,95	24089637,6
2024	616,0696	93824,33	5569905,64	29659543,3
	Total 6325,878	**Total 3784711**	**Average** 3268354	

This comprehensive method helps the PV farm meet its energy production targets and stay financially viable in the long run. LCOE helps calculate pay-back period i.e. the duration required for benefits accrued financially from PV farms to repay an initial investment. These PV systems are cost-effective to set up and provide significant financial benefits.

The outcome is that these systems will cut operational costs by about 3 million South African rands each year. They also have an appealing payback period of 14 months, with a very low energy cost of around 0.6 per kilowatt-hour. This setup is good at making a lot of money, and the PV system should save 30 million Rands throughout its working life.

The formula for calculating LCOE for a PV system can be expressed as:

$$\text{LCOE} = \left(\frac{\textbf{Total Present Value of Costs}}{\textbf{CostsTotal Present Value of Energy Produced}}\right)_{10} \tag{3}$$

$$\text{LCOE} = \left(\frac{3784711}{6325878}\right)_{10}$$

LCOE = R 0,60/KWh

To determine the payback period of the photovoltaic (PV) system, one can utilize Equation (4) in the following manner:

$$\text{Payback Period} = \frac{\textbf{Total system cost}}{\textbf{Saving rate}} \tag{4}$$

$$\text{Payback Period} = \frac{3784711}{3268354}$$

Payback Period = 1,16 years
Payback Period = 14 months

To envisage and have a better understanding these financial evaluations, a cash flow diagram of the system is presented in Figure 9. This graph shows the forecasted cash inflows and outflows during the 10 year period, including revenue from energy sales, operational costs, maintenance expenses, and asset depreciation.

This graphical representation of financial flows enables the stakeholders to interpret, with ease, the financial performance of the PV farms which would include reaching major milestones like breakeven points or profitability thresholds and making appropriate investment and operational strategies accordingly. This integrated approach will ensure that the economic analysis of PV farms is valid and complete to an extent that stakeholders will have enough clarity to confidently proceed with the project and optimize its financial results.

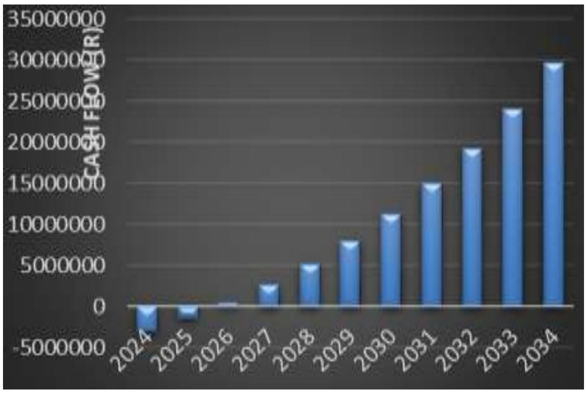

Fig. 9: Cash flow diagram

3.5 Towards Net Zero Achievement

It can also mean Carbon neutrality, which is a state of balance between greenhouse gases emitted into the atmosphere and those removed. The concept is core in fighting against climate change; it seeks to decrease the level of emission through different ways before offsetting the remaining ones by absorption of an equivalent amount from the atmosphere. As tabulated by ESKOM, the primary electricity supplier in South Africa, each MWh of electrical energy produced through the combustion of coal produces very high amounts of resultant pollutants. To be more specific, this generates 1.03 tons of CO_2 a strong greenhouse gas that contributes to global warming, while 4.39 kg of NOx is emitted; these are some of the harmful pollutants responsible for the creation of smog and respiratory problems. In addition, there are 8.49 kilograms of Sulphur oxides (SOx) emitted, which cause acid rain and have undesirable effects on the environment and human health. These quantities denote the environmental and human health costs due to coal-fired electricity generation in South Africa and call for cleaner energy substitutes. Generating 6,325,878 MWh of electrical energy through coal combustion in South Africa will emit considerable amounts of GHG and contaminants. Approximate Estimated Carbon Dioxide Emission Savings: 6 515 t bid of CO_2, NOx of 27 t, and SOx of 53 t over a period of 10 years using the data supplied by ESKOM. These savings do have the potential for significant environmental benefits. Over the last ten years, avoiding 6,515 tons of CO_2 emissions has gone a long way toward fighting climate change. CO_2 is a standard GHG that contributes to global warming by trapping heat in the atmosphere and adding to extreme weather events, sea-level rise, and disruptions to ecosystems. NOx emissions prevention of 27 tons over the ten-year period plays an important role in enhancing air quality and improving public health. Once released into the atmosphere, NOx compounds cause respiratory problems, smog (ground-level ozone), and acid rain. On the other hand, preventing 53 tons of SOx from being launched into the atmosphere during the same period correspondingly frees the environment and human health from considerable damage. SOx are noxious pollutants causing respiratory diseases and precursors of fine particulate matter, causing serious health effects. SOx compounds are one of the major causes of acid rain that destroys forests, aquatic systems, and infrastructure. These reductions highlight the positive effect spurred by the adoption of cleaner energy sources and efficient technologies. Hence, lowering the coal-fired generation of power will be counted among the wide-ranging steps for environmental and public health protection. This will help increase sustainability and make life resilient in the future.

4 Simulations

Determination of the maximum output power from a photovoltaic farm during the day is indispensable for achieving optimization in energy efficiency and the performance of the farm. This process is known as Maximum PowerPoint Tracking. MPPT is typically realized through either a sophisticated algorithm implemented in solar inverters or by analyzing the I-V curve of performance of the PV panels. That means MPPT will dynamically change operating points at all instances to maximize power output from photovoltaic solar panels with respect of varying conditions of sunlight intensity and temperature.

This becomes necessary to obtain the maximum energy extracted from the PV array to further enhance both the system and energy performance. Below is the proposed simulation system block diagram, Figure 10.

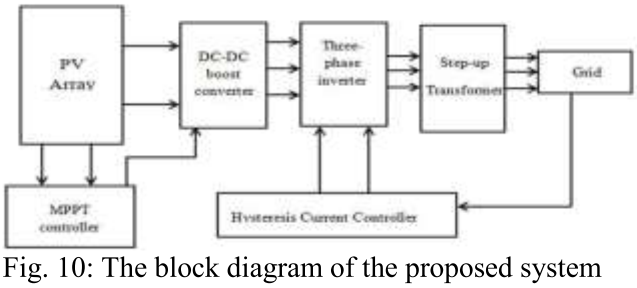

Fig. 10: The block diagram of the proposed system

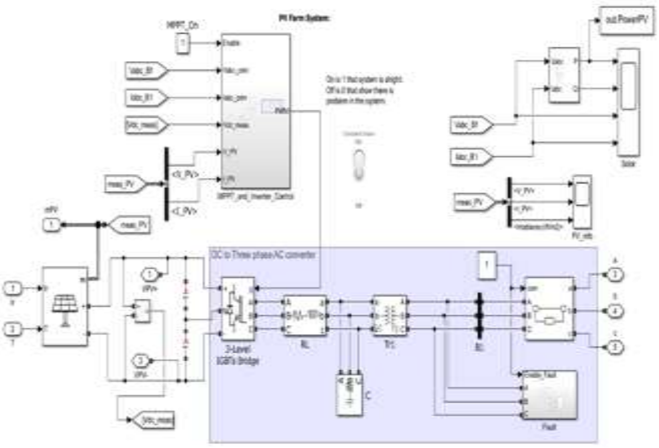

Fig. 11: Simulink model of PV Farm

These days, MPPT algorithms have usually been integrated into modern solar inverters to dynamically drive the voltage and current to ensure the operation of the PV systems at their maximum power points. These algorithms function based on real-time measurements of the characteristics in the PV array may be in terms of voltage, current, and temperature to determine the optimal operating point. MPPT techniques can also be performed by analyzing the I-V curve of the PV panels. The I-V curve shows the relation of current output, I, and voltage output, V, of the PV panels in specified sunlight conditions. This curve again could be monitored and analyzed for the optimum operation point or any alteration toward maximum power output.

The proposed photovoltaic system has been supported by a 150kW subsystem that integrates multiple interlink operating components for efficient management of energy. It includes the three-phase voltage regulator, which ensures constant energy supply to the grids. Each of these critical parts of the subsystem improves the efficiency and reliability of the whole system's performance. Further details of the subsystems of the large-scale photovoltaic farm are provided in an insightful illustration within the MATLAB-Simulink model shown in Figure 11. It describes the layout and interaction of these different components to achieve the operational goals set forth by the overall system.

MATLAB-Simulink is a powerful tool one can utilize in simulating and analyzing complex systems that are complex, PV systems included. In relation to modeling PV arrays, MATLAB-Simulink provides a good avenue through which engineers and researchers will be able to run simulations of electrical characteristics of PV panels, simulate different MPPT algorithms, and assess overall system performance for various operating conditions. The module data utilized has been determined according to the details depicted in Figure 12.

Fig. 12: PV Array settings

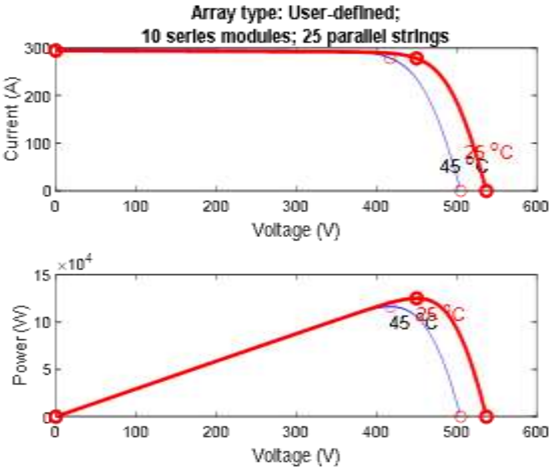

Fig. 13: PV Array Current and Power

Figure 13 gives an elaborate graphical representation of the voltage and current characteristics of the PV farm for different values of irradiance, assuming the system operates under ideal conditions with no faults. Figure 14 shows how the voltage and current metrics of the PV farm vary with changes in the intensities of solar irradiance, providing insights into the performance and efficiency of the system under varying sunlight conditions.

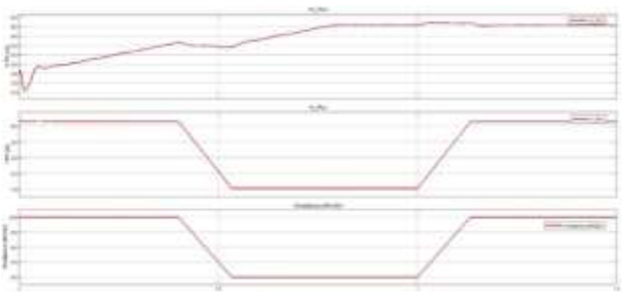

Fig. 14: PV Array Voltage, current, and irradiances

It provides the parameters from which, for ideal conditions, the total record of the operational behavior of the PV farm is obtained along with energy output from the system. For system converter simulation, a three-level IGBT bridge controlled by PWM is used. Capacitor C acts as the harmonics filter while resistance and inductance RL act as the inverter choke. The inverter is connected to the electrical grid through a three-phase circuit breaker and a transformer of 250 kVA with voltage ratings of 250V/25kV. When the simulation is started, expected signals are generated and analyzed through several scopes as shown in Figure 15.

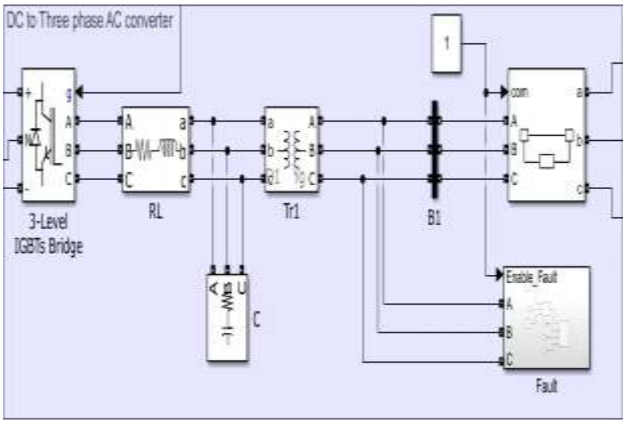

Fig. 15: Simulink Model of DC to 3phase AC converter

The initial conditions of the PV array model include an irradiance level of 1000 W/m² and an operating temperature of 45°C. At these conditions, the PV voltage, denoted as Vdc_means, is 481 V, and the power extracted from the array, referred to as Pdc_mean, ranges from 179 to 200 kW once the system reaches a steady state around t = 0.15 seconds as indicated in Figure 16. At t = 0.3 seconds, there is a rapid decrease in the sun’s irradiance from 1000 W/m² to 200 W/m². In response to this change, the control system adjusts the VDC reference to 464 V through the Maximum Power Point Tracking (MPPT) operation.

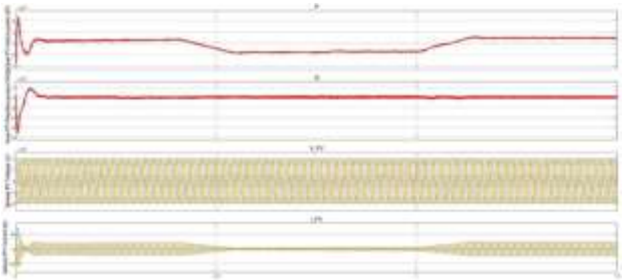

Fig. 16: Three-phase PV Voltage

The MPPT controller, which utilizes the **Perturb and Observes (P&O)** as shown in Figure 17 illustrates a method to optimize power extraction from the photovoltaic (PV) system. The controller energetically adjusts the reference signal for the inverter's DC voltage (VDC) regulator, safeguarding maximum power that is constantly harvested from the PV system. This method is implemented using a MATLAB function block to regulate the DC voltage of the PV array.

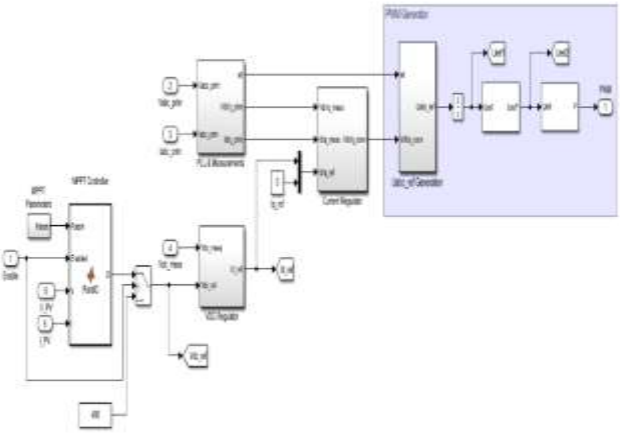

Fig. 17: Simulink Model of MPPT and Inverter Control

The Perturb and Observe (P&O) algorithm, serves as the MPPT controller of the MATLAB function block. It courses inputs such as the PV array's current (I) and terminal voltage (V) to operate with key parameters, including the initial reference voltage (Dinit), the minimum and maximum allowable voltages (Dmax and Dmin), and the voltage increment (deltaD). By continuously monitoring the power and voltage outputs of the PV array, the controller determines the optimal reference voltage for maximizing power production. Modifications to the reference voltage are done incrementally, based on variations in power and voltage; while ensuring it stays within the defined limits. This approach enables efficient and reliable tracking of the maximum power point for the PV system. Figure 18 illustrates the grid model's architecture, detailing its primary components and configurations. The grid model features two 25kV feeders responsible for distributing electrical power across the grid. These feeders connect to an equivalent 120kV transmission system, which functions as the high-voltage backbone for long-distance electricity transmission.

The model also contains a fault block intended to introduce different types of faults from the grid side. For this reason, it enables the investigation of the behaviours of the grid under consideration for various types of electrical faults, a very important aspect regarding the establishment of stability and dependability in respect of worse conditions. It also includes a transformer that steps down the voltage from transmission to distribution levels.

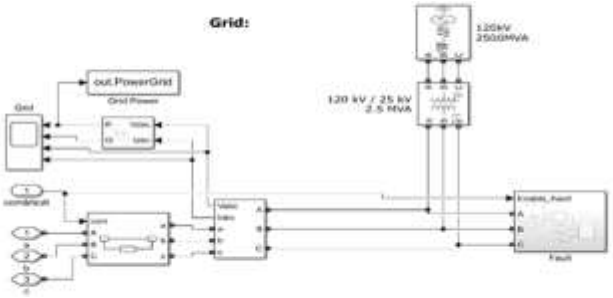

Fig. 18: Simulink Model of the grid

5 Conclusion

In eMalahleni, the region's moderate solar irradiation provides an excellent opportunity for advancing solar power projects. The area's solar conditions make it ideal for photovoltaic (PV) stations, which are intended to fulfill 100% of the camp's energy needs. These PV systems are projected to produce approximately 876 megawatt-hours (MWh) of electricity annually, showcasing a strong commitment to utilizing advanced technologies for sustainable and resilient energy solutions. While a solar PV system with a capacity of around 625 kW is technically viable, the project's specific requirements call for a more tailored solution. focusing on clarity and flow. To ensure the reliable operation of a 100-kW inverter, the PV system must consistently generate enough power to meet its demands. By maintaining a DC to AC ratio of 1.50, a 100-kW inverter is deemed optimal for a solar PV farm with DC production. The investment in these PV stations is expected to be recouped within just 14 months, thanks to a low Levelized Cost of Electricity (LCOE) of 0.6 Rands per kilowatt-hour (kWh). This cost efficiency guarantees a quick return on investment and offers significant financial benefits. Over its lifetime, the PV system is projected to save 30 million Rands.

In addition to economic gains, the switch to solar energy brings notable environmental advantages. Simulations show that the model used to predict global solar radiation in eMalahleni is highly accurate, closely matching observed data and demonstrating its reliability. This precision is critical for solar energy applications, where accurate predictions directly impact system performance.

The study showed significant improvements in the photovoltaic (PV) system's performance, particularly during midday when solar radiation peaks. During these hours, the system reached a maximum output of 125 kW, highlighting the importance of accurate solar radiation models in maximizing efficiency and output.

Overall, the findings underscore the crucial role of precise solar radiation modeling in enhancing the performance and effectiveness of renewable energy systems in eMalahleni. For comparison, generating 6,325,878 MWh of electricity from coal in South Africa would release substantial greenhouse gases (GHGs) and pollutants. According to ESKOM data, this would result in approximately 6,515 tons of carbon dioxide (CO2), 27 tons of nitrogen oxides (NOx), and 53 tons of sulfur oxides (SOx). Switching to solar power could prevent these emissions over a 10-year period.

Avoiding 6,515 tons of CO2 alone significantly contributes to combating climate change, as CO2 is a major greenhouse gas responsible for global warming, leading to extreme weather, rising sea levels, and ecosystem disruptions. Additionally, avoiding 27 tons of NOx emissions improves air quality and public health, as NOx can cause respiratory issues and contribute to smog. Preventing 53 tons of SOx emissions further benefits the environment by reducing acid rain and its associated health risks.

In conclusion, investing in PV solar stations in eMalahleni offers substantial economic returns while promoting environmental sustainability. By reducing harmful emissions and supporting clean energy, this initiative greatly enhances both financial and ecological well-being. With a total capacity of 150 kW, the system ensures efficient energy conversion and optimal alignment between the inverter's AC output and the solar panels.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used QuillBot in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Conflict of Interest

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