Sustainable Initiative towards a Zero-CO_2 Economy in Sub-Saharan Africa

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The growing demand for renewable energy (RE) is driven by the need for reliable and cost-effective energy, as well as the urgency to address climate change. Global energy requirements encounter challenges due to rapid industrialization, urbanization, and population growth in the Global South. Fossil fuel exploitation faces limitations, such as resource constraints, price fluctuations, subsidies, and environmental concerns. This study focuses on establishing a zero-CO_2 emissions electricity system for traditional markets in sub-Saharan Africa (TMSSA). It provides a thorough analysis of CO_2 in greenhouse gases (GHG) and emphasizes the importance of decarbonisation. The study proposes a RE-based scheme, utilising the NEW Motor Spare Parts Market in Nnewi, Nigeria, as a case study for supplying clean electricity to TMSSA. It demonstrates the viability of a photovoltaic (PV) scheme for traditional markets through meticulous design, optimization, and economic assessment. Results at optimal azimuth and tilt angles of 180° and 7°, respectively, include parameters for potential, performance and financial assessments. The project is deemed feasible, technically and financially based on the study's results of annual total PV generation, PR, and avoidable CO_2 emissions of 3.724 GWh, 77.5%, and 729,430 kg/year, respectively.

Keywords: *Traditional markets; Renewable energy; Global South energy challenges; Zero-CO_2 emissions; Climate change mitigate*

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1. Introduction

The significance of energy to human socio-economic development cannot be overstated. Energy is a fundamental driver that underpins virtually every aspect of modern society and plays a critical role in shaping economic, social, and technological progress. Energy is a key factor in industrial processes, manufacturing, and infrastructure development. Access to reliable and affordable energy sources allows industries to operate efficiently, leading to increased production, economic growth, and job creation. Modern agriculture heavily relies on energy for mechanization, irrigation, and transportation. Energy-powered machinery and technologies enhance agricultural productivity, contributing to food security and rural development. It is essential for powering medical facilities, refrigeration for vaccines and medicines, lighting for schools, and electronic devices for educational purposes. Reliable energy supply improves healthcare services and educational opportunities, leading to improved human capital and overall societal well-being.

1.1. Power inadequacy and renewable energy in SSA

In sub-Saharan Africa (SSA), the peak of individuals lacking access to electricity was observed in 2013, as initiatives to expand access outpaced population growth. However, due to the combined impact of the pandemic and the energy crisis, the number of people without electricity has nearly returned to historical highs. According to IEA, lack of access rose from 580 million in 2019 to 600 million and 558.8 million in 2022 and 2023, respectively [1, 2]. According Energy Sector Management Assistance Program (ESMAP) 2020 report – decentralising and expanding RE infrastructure and solutions could provide electricity to 265 million people, reduce reliance on fossil fuels, and enhance energy security by 2030 [3]. Solar PV and wind energy are expected to play significant roles because of their huge potential in SSA. The region has an exceptional solar potential of an average solar irradiance of 2,000 kWh/m²/year and estimated wind energy of over 1,300 GW [4]. Presently, less than a fifth of African countries have established targets for achieving universal electricity access by 2030. Additionally, 45% of the continent has set targets for electricity access, although these goals are less ambitious than those outlined in Sustainable Development Goal 7. The region's power grid (exclusion of South Africa), especially in rural and underserved communities, is known for its unreliability, with frequent power outages and inadequate electricity supply [5, 6]. As a result, individuals, businesses industries, and essential services rely on fossil fuel generators to ensure a stable and continuous power supply.

1.2. Demerits of fossil fuel generators

The use of fossil fuel generators, such as those powered by petrol or diesel, comes with various consequences, affecting the environment, health, and overall sustainability [7, 8]. Fossil fuel generators emit GHGs and particulate matter into the atmosphere, contributing to climate change [9, 10]. These pollutants can have detrimental effects on respiratory health and exacerbate existing conditions, such as asthma and other respiratory diseases. The accumulation of GHGs leads to global warming and associated environmental issues, including rising sea levels and extreme weather events. Generators produce noise during operation, contributing to noise pollution in residential and industrial areas. Prolonged exposure to high levels of noise can have negative impacts on human health, causing stress, sleep disturbances, and hearing problems. To mitigate these consequences, there is a growing emphasis on transitioning to cleaner and more sustainable energy sources, such as solar, wind, hydro, and geothermal.

1.3. Aim, objectives, and scope of the study

The movement within the power sector towards sustainable energy transition (SET) is being driven by several factors, including the limited availability of fossil fuel resources, and the rising energy demand. Others are the growing rates of industrialisation, population and urbanisation, and the global environmental concerns arising from electricity generation and consumption. Consequently, the need to explore RE sources has become imperative, and advancements in technologies related to wind turbines, geothermal energy, small hydropower, batteries, and photovoltaics (PV) have further bolstered the utilisation of RE. Therefore, this study aims to increase electricity access while reducing the emission of harmful gases emanating from power generation for fossil fuel. The traditional market system in SSA has been identified in this study as a source of CO2 emissions in the region. The objectives of this study include a comprehensive analysis of CO2 in GHGs and the significance of decarbonisation; identification of RE sources in SSA; x-raying of the concept of a traditional market system; and selection of a case study for a traditional market electrification. Other objectives are the identification of an appropriate RE technology for the chosen market; the determination of the technical and financial feasibility of the RE scheme and the evaluation of carbon emissions avoided by deploying the RE system.

1.4. Significance of the study

The energy consumption as it relates to sources of energy and CO2 emissions in the traditional market system in SSA has little or no attention. This study could not find any published research article or report that deals with RE deployments in the TMSSA. A significant portion of the SSA population spends 6 to 8 hours daily in these markets, requiring substantial power, which leads to considerable pollution due to the prevalent use of fossil fuel generators. Additionally, this article is novel in its integrative approach, connecting energy access with socio-economic development, addressing specific regional challenges in SSA, critically analysing the impact of fossil fuel generators, and providing a practical case study to explore the feasibility of RE solutions. This multi-dimensional perspective makes a significant contribution to the discourse on sustainable energy transitions in developing regions.

1.5. Structure of the article

The paper is structured systematically to address the identified gaps as follows: in addition to the introduction in section 1, section 2 takes a glance at global, regional, and country GHG emissions; in section 3, the study analyses CO2 in GHGs and the significance of decarbonisation. In section 3, the study adopts a method of providing of carry out the objectives, which includes a traditional description of the traditional market; identification of RE sources in SSA; selection of a traditional market for a case study; and selection of an appropriate RE technology for the market location. Section 4 deals with the determination of RE source technical feasibility; carbon emission avoided; and RE system financial assessment.

2. A glimpse at GHG emissions

In 2019 [11], global GHG emissions totalled 55.3 billion tonnes of CO_2 equivalent, with CO_2 contributing 76%, CH4 16%, N_2O 6%, and F-gases 2%. Fossil fuel combustion, industrial processes, and land use change were the primary sources of CO_2 emissions. Specifically, in 2019 [12], fossil fuel-related CO_2 emissions were 34.8 billion tonnes, with coal at 40%, oil at 34%, and natural gas at 20%. Land use change contributed 5.8 billion tonnes. By 2022, global GHG emissions were estimated at 36.8 billion tonnes of CO_2 equivalent, where CO_2 made up 94%, CH4 4%, N_2O 1.6% and F-gases 0.4%. Fossil fuel combustion, industrial processes, and land use change remained major CO_2 sources. In 2022, fossil fuel-related CO_2 emissions were 34.8 billion tonnes, with coal at 44%, oil at 32%, and natural gas at 20%. Land use change contributed to 2.0 billion tonnes [13]. However, countries in the Global South, especially, within SSA, stand among the world's most impoverished nations, with notably low levels of CO_2 emissions. Despite comprising 14% of the global population, the region contributes a mere 7.1% to the planet's overall GHG emissions and this portrays a low level of industrialisation. According to the data obtained from the Emissions Database for Global Atmospheric Research (EDGAR), Africa emitted about 1446.22 million tonnes (Mt) of CO_2 [14]. A recent investigation indicates that over 8 million individuals globally die annually due to inhaling contaminated air laden with particulates arising from fossil fuels [15]. The volume of emissions by the various regions and some countries is presented in Fig 1.

Although the majority of SSA countries make a limited contribution to CO_2 emissions, there are noteworthy exceptions. South Africa (SA), endowed with abundant coal reserves, emits a higher amount of CO_2 than the United Kingdom, despite having an economy only one-eighth the size and a population smaller by 10 million. One of the significant emitters, Sasol's petrochemical complex in Secunda, SA, stands among the world's largest localized sources of greenhouse gases (GHG). In terms of CO_2 emissions among SSA countries, South Africa leads, followed by Nigeria and Zambia.

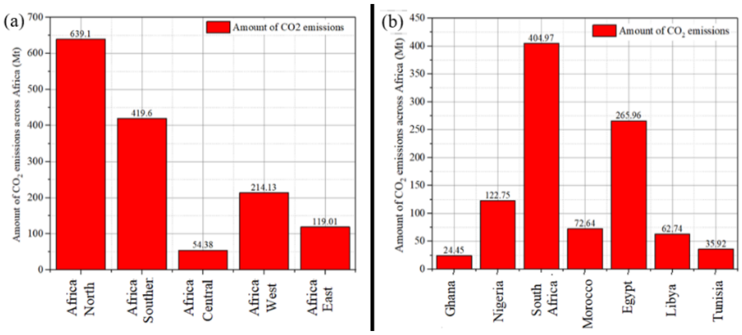

Fig. 1. The CO_2 emissions in African regions and some countries as of 2022 [16].

Notably, Zambia's emissions related to land use exceed those of Brazil, and in Nigeria, both households and businesses rely on outdated and polluting diesel and gasoline generators for approximately 14 GW of power, surpassing the country's grid installed capacity of 10 GW [17]. Nevertheless, the susceptibility of SSA to climate change is evident due to its modest economic growth, limited technological advancement, and heavy reliance on natural resources for agricultural activities [18]. Presently, the region is confronting a spectrum of direct and indirect consequences, underscored by a surge in climate change-induced natural calamities. These encompass occurrences, such as floods, escalating sea levels, droughts, cyclones, and temperature fluctuations.

2.1. CO_2 in greenhouse gases (GHGs)

Carbon dioxide stands as the primary GHG released due to human activities. In 2021, a substantial 79% of the GHG emissions originating from human actions in the United States can be attributed to CO_2 [19]. Nature already maintains a presence of CO_2 in the atmosphere as an integral component of Earth's carbon cycle - a natural process involving the exchange of carbon among the atmosphere, oceans, soil, flora, and fauna. However, human endeavours are currently modifying this carbon cycle in two significant ways - by introducing more CO_2 into the atmosphere and by influencing the capacity of natural reservoirs, such as forests and soils, to take in and retain CO_2 from the atmosphere. Even though CO_2 emissions do stem from various natural sources, the upsurge observed in the atmosphere since the Industrial Revolution can be credited to emissions linked to human activities. In 2022, levels of the major GHGs - CO_2, methane, and nitrous oxide—continued their historically high rates of increase, according to National Oceanic and Atmospheric Administration (NOAA) scientists. The global average for CO_2 rose by 2.13 parts per million to reach 417.06 ppm, maintaining a consistent trend over the past decade. CO_2 levels are now 50% higher than pre-industrial levels. Notably, 2022 marked the 11th consecutive year with a CO_2 increase of over 2 ppm, representing the highest sustained rate in the 65 years of monitoring. Additionally, atmospheric methane, a more potent but less abundant GHG than CO_2, reached an average of 1,911.9 parts per billion in 2022, with a 14.0 ppb increase—the fourth-largest annual rise since NOAA's systematic measurements began in 1983. This follows record growth in 2020 and 2021, and methane levels are now more than two and a half times higher than their pre-industrial levels [20].

2.2. Significance of decarbonisation

The Intergovernmental Panel on Climate Change (IPCC) states clearly in its AR5 assessment report4: "Anthropogenic GHG emissions have increased since the pre-industrial era, driven largely by economic and population growth and are now higher than ever [21]. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years [22]. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century ". When contemplating the issue of global warming, a seemingly minor 1°C increase in temperature may appear inconsequential. However, it is crucial to recognise that even this modest temperature rise can have significant repercussions for both the climate and natural systems [23]. To address global warming at any level, it is of utmost importance to substantially reduce the release of CO_2 and other GHGs until they are nearly eliminated. Measures like reforestation or the application of Biomass Energy with Carbon Capture and Storage (BECCS) will become essential to counteract any temperature escalation, ensuring stability.

3. Study Method

To substantially deal with this study, it identifies the RE sources in SSA; x-rays the concept of the traditional market system in SSA; selects a case study for a traditional market; and identifies an appropriate RE technology for the chosen market electrification; Other objectives to be implemented are technical and financial feasibility, and performance evaluation of the identified RE system through computational modelling; and the evaluation of carbon emission avoided by deploying RE. The layout of the sequence of this study's objectives is schematically represented in Fig 2.

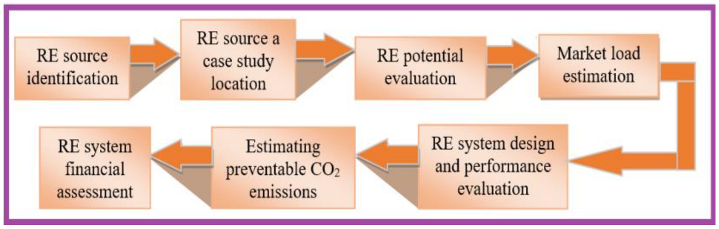

Fig 2: The study's objectives sequence layout

3.1. The concept of traditional markets in SSA

A traditional market in SSA refers to a conventional marketplace where goods and services are bought and sold in a manner that is characteristic of local and regional trading practices. These markets play a significant role in the economic and social fabric of the region, serving as hubs of commerce, social interaction, and cultural exchange [24, 25]. A typical conventional market in SSA is a bustling and vibrant gathering place characterized by a diverse array of stalls, vendors, and customers. These markets are often located in urban centres, towns, or rural areas and they can range in size from small, informal setups to larger, more organized complexes. Some markets might also have designated areas for specific types of products, such as fruits and vegetables, clothing, electronics, crafts, and household items [26]. Vendors in these markets are often local entrepreneurs who sell products they have produced or sourced themselves. These can range from farmers bringing in their crops to artisans displaying their artistry. Relationships between vendors and customers are often built on familiarity and trust. The sceneries of a traditional market in SSA are shown in Fig 3.

Fig 3: Traditional market sceneries in SSA

These markets go beyond being places of trade; they serve as important social and cultural hubs. People from diverse backgrounds converge and spend 6 - 8 hours daily here, fostering interactions, conversations, and the exchange of ideas. These markets are also spaces where cultural traditions, languages, and local customs are preserved and celebrated. These markets contribute significantly to the local economy by generating revenue for the government and income for vendors, suppliers, and service providers. They provide employment and apprenticeship opportunities, particularly for young girls and boys and informal workers, and play a role in poverty alleviation. While these markets are integral to the social and economic fabric of the region, they also face challenges. The traders spend the greater part of their time in these markets, and issues such as sanitation, waste management, and adequate infrastructure like electricity and access to modern technology influence the overall experience and efficiency of these markets. Among these limitations, electricity is very significant in these markets, as it is needed for comfort, lighting, and changing of phones and computer systems.

3.2. Traditional market case study: New Motor Spare Parts Market, Nnewi, Nigeria

Nnewi is a popular commercial town located in the eastern part of Nigeria where traditional markets are cultural and significant to the socio-economic development of the people. Nnewi is renowned for its vibrant automotive industry and is often referred to as the "Japan of Africa" due to the concentration of automobile manufacturing and spare parts businesses in the region. Four out of the many traditional markets in Nnewi stand out in terms of organisation, number of shops, and customer strength. These four markets are the Nkwo Nnewi New Motorcycle Spare Parts, New Motor Spare Parts (truck and car parts), Electronics, and Nkwo Nnewi Main (Ime Afia) Markets. Each of these markets has over 1,500 shops and they play host to customers from all parts of Nigeria and ECOWAS countries. These markets open by 8:30 Am and close by 5:30 PM, which means 8 hours every day, Monday – Saturday. Over 70% of the population of Nnewi spends more time in these markets than in any other place.

The New Motor Spare Parts Market in Nnewi is a hub for the buying and selling of automotive components. The presence of numerous factories and workshops engaged in the production of vehicles and spare parts contributes to the growth and significance of the spare parts market. The market offers a wide variety of motor spare parts, catering to different types and models of vehicles. This includes components, such as engine parts, body parts, electrical parts, suspension systems, and accessories. Businesses in the New Motor Spare Parts Market are often organised into clusters, where shops specialising in specific types of spare parts are grouped. This arrangement enhances customer convenience and provides a competitive market environment. The market accommodates both locally manufactured spare parts and imported ones. This diversity allows customers to choose from a range of options based on their preferences and budget considerations. The New Motor Spare Parts Market significantly contributes to the local economy by providing employment opportunities and fostering business growth. It plays a vital. Despite its successes, the New Motor Spare Parts Market faces challenges in infrastructure, such as issues with electricity, water, and toilets to service the market. A section of the New Motor Spare Parts Market is shown in Fig 4(a).

Fig 4: (a) A section of New Motor Spare Parts Market, Nnewi, Nigeria; (b) Cluster of generators in a marketplace

These traditional markets are clusters of shops, and they have a proliferation of two-stroke power generator engines, as shown in Fig 4(b), which are characterised by incomplete combustion, causing CO and CO_2 emissions and noise pollution. This is the consequence of the inadequate power supply through the national grid, which is a common occurrence among the conventional markets in SSA (excluding South Africa). The traders are compelled to rely on diesel and petrol-generating sets for electricity. Electricity is primarily needed in these shops for lighting, phone charging, powering fans for human comfort, and displaying product information. Given the region's relatively warm climate, enduring the dry and summer seasons without a fan or an air conditioner is nearly impossible. The national grid power supply to these markets is inadequate and consequently, traders are compelled to resort to fossil fuel-powered generators for an average of five hours daily. This constitutes a significant source of noise and air pollution that contributes to climate change that further exacerbates global warming.

3.3. Identification of RE sources in SSA

The region's abundant RE sources offer viable solutions to bridge the current energy deficit. Africa possesses the world's largest reserves of RE resources, capable of satisfying the anticipated future energy requirements for the continent [27]. Every country in SSA possesses a clean energy potential that is, at a minimum, equal to their present domestic energy consumption except a handful of smaller nations, such as Equatorial Guinea, Rwanda, Cape Verde, and Comoros. The majority of these countries boast of potentials that far exceed their existing energy consumption levels. The African Development Bank (AfDB) approximated Africa's renewable electricity potential as follows - 350 Gigawatts (GW) for hydroelectricity, 15 GW for geothermal energy, and 1000 GW for solar power [28, 29]. The various RE sources in the region are presented in Table 1.

Table 1: The sources RE in SSA [30]

S/N	RE Source	Description	Countries with huge potential
1	Solar power	SSA has abundant sunlight, making solar power a viable RE source. The implementation of solar PV systems for both grid-connected and off-grid applications can help meet the region's energy needs.	Entire SSA [31, 32]
2	Wind energy	Certain regions in SSA experience consistent wind patterns, making wind energy a promising option. Wind farms can be established to harness wind power for electricity generation	Mozambique, South Africa, Somalia, Madagascar, Morocco Lesotho, Malawi, Zambia, Eritrea, Djibouti, Ethiopia, Kenya, Tanzania, Niger, Chad, and Sudan [33, 34]
3	Small hydropower (SHP)	SSA is endowed with rivers and water bodies suitable for SHP generation. Small-scale and large-scale hydropower projects can contribute to the energy mix, providing reliable and continuous electricity.	Congo, Gabon, Congo Democratic Republic, Nigeria, Rwanda [35, 36]
4	Biomass energy	Biomass, including agricultural residues and organic waste, can be utilized for energy production. Bioenergy projects, such as biogas and biomass power plants, can contribute to a sustainable energy mix.	Mauritania, Chad, CAR, Mali, Niger, Namibia, Botswana, Angola [37, 38]
5	Geothermal energy	Regions with geothermal potential can tap into the Earth's heat for electricity generation. Geothermal power plants can provide a stable and continuous source of energy	Namibia, Kenya, Ethiopia, Tanzania, Djibouti, Rwanda, Uganda, Comoros, Eritrea [39, 40].

3.4. Traditional markets RE scheme

This paper considers the adoption of RE systems to power markets in SSA, which will substantially provide clean electricity and curtail CO_2 emissions adequately. By replacing fossil-based generators with RE alternatives, considerable progress will be made in electricity supply and mitigating climate change. Despite a growing sense of CO_2 emissions and its role in climate change and the urgency for decarbonisation, the deployment of RE technologies is being frustrated by many factors. These include a lack of information, high-cost PV components (battery, inverter and PV panel), inadequate policy and lack of political will. Several assessments and feasibility studies have shown that the potential of PV energy resources is enormous in SSA [41, 42]. The concept of deploying RE in SSA conventional markets involves leveraging sustainable and environmentally friendly sources of power to address energy challenges, and promote clean energy usage, and economic development [36, 43]. Particularly, wind turbines and PV systems have emerged as standout options due to their versatility in generation and deployment. Among the RE sources identified in the region, is only solar PV that is adequately available in Nnewi. Hence, this research endeavours to introduce PV systems as a primary power source of the market. This approach will provide electricity access increase and curb CO_2 emissions linked to fossil fuel generators. The direct transformation of solar energy into a sustainable and clean electrical energy source, facilitated by solar PV or flexible panels, is a critical method for providing power to various sectors.

3.5. Evaluation of PV potential and system performance

This study examines the solar PV availability in the Nnewi area through computational modelling, utilising data sourced from the NASA database [46]. Additionally, it explores potential solar energy applications, encompassing direct utilisation in processes, as indirect applications through the conversion into electricity. The effectiveness of these applications is scrutinised based on different levels of data (daily, monthly, and yearly) obtained from the existing literature. This comprehensive study seeks to establish a blueprint for PV systems in SSA's traditional markets. It encompasses the design and optimisation of a PV energy system and subsequently evaluates the outcomes to assess the economic viability of employing such a system in off-grid scenarios. To achieve these objectives, the study will leverage Solargis and PV*SOL, tools capable of modelling and optimising power utilisation, while determining the economic feasibility of the source.

3.5.1. Computation of irradiance

The computation of irradiance involves calculating the amount of solar radiation received on a given surface over a specific period, typically expressed in terms of energy per unit area (kWh/m²). There are three components of solar irradiance - Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DIF) and they are expressed mathematically as follows [44, 45]:

$$GHI = DNI \cdot cos(Z) + DIF \tag{1}$$

$$DNI = G_{extraterrestrial} \cdot cos(Z) \tag{2}$$

$$DIF = GHI - DNI \cdot cos(Z) \tag{3}$$

Where Z is the solar zenith angle, representing the angle between the sun and the vertical axis and $G_{\text{extraterrestrial}}$ is the extra-terrestrial radiation.

The relationship between solar irradiance and the generation of a PV system is fundamental, as solar irradiance represents the amount of sunlight energy per unit area. It is a crucial factor influencing the power output of PV panels. The relationship is direct; as solar irradiance increases, the power generation of a PV system tends to increase proportionally. The relationship is often described by the equation [46, 47]:

$$PVOUT = A * GTI * \eta \tag{4}$$

Where $PVOUT$ is the power output; A is the area of the PV panel; GTI is the Global Tilt irradiance; and η is the efficiency of the PV panel. This equation illustrates the direct correlation between irradiance and power output.

These calculations involve trigonometric functions and depend on the position of the sun, which is influenced by factors, such as time of day, date, and geographical location. These are simplified equations, some more complex models consider additional factors, such as atmospheric conditions, albedo (reflectivity of surfaces), and shading effects for a more accurate assessment of solar irradiance. However, specialised software tools and solar radiation databases were used for comprehensive solar resource assessments in this work.

3.6. Photovoltaic potential and system performance influencing parameters

Some of the direct influencing parameters are ambient conditions (temperature, wind, dust), geographical location, time of day and year, and lifetime. Others are system efficiency, shading, hours of daylight, solar elevation and azimuth, latitude, altitude, and terrain and obstructions. The indirect influencing parameters include cooling degree-days (CDD) and heating degree-days (HDD). Understanding and optimising these influencing factors are essential for maximising the efficiency and output of PV systems. Meteorological parameters play a crucial role in influencing the potential of both LPV and FPV systems.

3.6.1. Effect of elevated temperature on PV panel performance

Higher temperatures generally lead to lower electrical efficiency, highlighting the potential to enhance PV module performance by implementing cooling technologies. The PV panels typically have an optimal operating temperature of around 25°C (77°F) [48, 49]. For every degree Celsius above this temperature, the efficiency of silicon-based PV panels generally decreases by about 0.4-0.5% [50]. This is due to the increased resistance in the semiconductor materials, which reduces the voltage output. The performance of a PV module is evaluated under standard test conditions (STC) and nominal operating cell temperature (NOCT). Typically, STC conditions are ambient temperature (T_{amb}) of 25 °C (77°F), electrical efficiency (η_o), and irradiance of 1000 W/m² [51]. At STC, the η_o is used as a reference point. The actual operating TEMP and electrical efficiency (η_{el}) can be calculated using the expressions [52, 53]:

$$T_m = T_{amb} + (NOCT - 20)x\frac{G}{800} \tag{5}$$

$$\eta_{el} = \eta_o\left(1 - \beta\left(T - 25\right)\right) \tag{6}$$

Where T_m is the PV module temperature, β is the temperature coefficient specific to the PV module material.

3.6.2. Effect of wind speed (WS) on PV panel performance

Wind speed and direction play a critical role in maintaining the efficiency of PV panels by providing a cooling effect, but it must be within an optimal range to avoid physical damage. Wind can have both positive and negative effects on PV performance. Moderate wind speeds can help cool PV panels, maintaining their efficiency. However, very high winds can cause physical damage to the panels or supporting structures. According to a study, the mean electricity generated under southerly winds was 20.4-42.9% higher compared to northerly winds [54]. This was attributed to differences in surface cooling capabilities due to the asymmetry of the PV array. The impacts of various WS ranges on PV panel energy generation are presented in Table 2.

Table 2: Categorisation of WS and their impacts on PV panel and mounting elements.

Classification of WS	**Range (m/s)**	**Impact**
Low WS [55]	0-1	Very low WS, the cooling effect is minimal
Moderate WS [55]	2-5	This range helps to dissipate heat and aids PV panel performance.
Optimal WS [56]	6-10	the cooling effect is maximised in this range without posing a risk of damage
High WS [57]	11-15	Although cooling is provided, the high wind speeds introduce mechanical stress risk and

		potential damage to PV panels and their mounting elements.
Very High WS [58]	>15	At range, the risk of mechanical damage to PV panels and mounting elements increases substantially.

3.6.3. Effect of relative humidity (RH)

Photovoltaic units suffer efficiency loss and decreased electrical output when water contacts their components, leading to corrosion of metal joints and damage to the cell's structure. Relative humidity, which is the ratio of actual to saturated water vapour pressure at a given temperature, varies with water vapour saturation pressure influenced by temperature. In hot, humid climates, moisture can infiltrate cracks in PV cells, significantly lowering productivity. The impact of moisture on solar cells depends on production methods, with moisture penetrating the polymer layer and damaging interconnections, resulting in issues like weld joint corrosion. Studies have investigated the effects of RH on solar cells, emphasising the need to consider other climatic factors as well. A study identified corrosion of PV cells as a significant impact of humidity, noting that prolonged exposure to temperatures over 40 °C and RH levels up to 60% reduce cell performance and lifespan [59]. Additionally, these conditions promote fungal growth, especially when humidity ranges from 75% to 95%.

3.6.4. Influence of PV panel geometry

The PV panel geometry is mostly defined by azimuth and tilt angles [60]. The cardinal orientation or azimuth angle, representing the compass direction in which panels face, has a significant impact on total annual energy production. Optimal performance is achieved when panels in the Northern Hemisphere face true south, receiving maximum annual solar exposure. Conversely, in the Southern Hemisphere, facing true north is optimal. The tilt angle determines the extent to which panels are perpendicular to incoming sunlight, influencing both seasonal and daily performance. The optimal tilt angle varies based on geographic location and system objectives. Typically, for fixed-tilt systems, the tilt angle is set equal to the site's latitude to maximise annual energy production. However, seasonal adjustments in tilt may enhance performance in specific cases.

3.6.5. Impact of Elevated Temperature on PV Panel Performance

In general, increased temperatures result in decreased electrical efficiency for PV panels, which suggests that the implementation of cooling technologies could improve their performance. PV panels exhibit an optimal operating temperature of approximately 25°C (77°F) [50]. For every degree Celsius above this benchmark, the efficiency of silicon-based PV panels tends to decrease by approximately 0.4-0.5% [3]. This decline is primarily due to heightened resistance within the semiconductor materials, which subsequently lowers the voltage output. The performance of PV modules is assessed under standard test conditions (STC) and nominal operating cell temperature (NOCT). Standard test conditions typically include an ambient temperature (TEMP) of 25 °C (77°F), a reference electrical efficiency (ηo), and an irradiance level of 1000 W/m² [4]. In STC, the ηo serves as a benchmark. The actual operating conditions of electrical efficiency (ηel) can be determined using specific formulas [52, 53]:

$$\eta_{el} = \eta_o\left(1-\beta\left(T-25\right)\right) \tag{7}$$

$$T_m = T_{amb} + (NOCT-20)x\frac{G}{800} \tag{8}$$

3.6.6. Computational modelling of a PV system

This segment addresses all technical facets of the PV system, spanning from evaluating the potential to configuring the hypothetical installed capacity for assessing PV system performance, exploiting Solargis and PV*SOL software applications. It encompasses an intricate depiction of site locations, PV system setup, and simulations conducted at the chosen sites. The ensuing reports from these selected locations will be utilised to scrutinise and deliberate on solar PV potential, considering factors such as irradiation, power generation output, performance ratio (PR), and capacity ratio (CR).

3.6.7. Estimation of the market electrical load

There are 3000 lockup shops in the New Motorcycle Spare Parts Market of 125 building blocks and each block accommodates 24 shops. The shops have the same dimensions, as the breadth, length, and area of the rooftop per shop are 2 m, 3 m, and 6 m^2, respectively. These building blocks are close as a result they cast a shadow on one another and prevent sufficient sunlight from getting to the shops, as shown in Fig 5.

Fig 5: The need for electricity in the market (a) poor illumination; (b) better illumination; (c) and (d) use of fans

The shops require electricity to power illumination, environment comfort, and phone and computer system charging facilities. These sources of electrical loads, as the ones presented in Table 3 are considered light loads. Table 3 presents the power for basic and total needs, and details of the available rooftop surface area for PV installation.

The total power for basic needs for 3000 shops is 974,700 W (974.7 kW) and this power runs for an average of 6 hours daily. The daily and annual energy consumption are 5848.2 kWh and 2134591 kWh, respectively. Considering the data in Table 3, the available installation area of the rooftop for a PV system can produce power more than the market's needs.

3.6.8. Configuration of PV system

The study's results are specific to the location and the configuration parameters of the PV system. The input parameters required to evaluate of PV potential and system performance are outlined in Table 4.

Table 3: Total electrical load per shop

S/N	Appliances/shop	Power rating (W)	Watt (W)	Quantity	Total power (W)
1.	Fan	40	40	2	35

2.	Lighting	15	30	2	200
3.	Laptop	65	65	1	65
4.	Handset	5	6	4	24
Power for basic needs per shop					**324**
Power for basic needs for 3000 shops (324*3000)					**972,000**
Other power needs					
5.	Fridge		135	20	2,700
				Total power	**974,700**

Available installation rooftop area			
No of shop	**Basic power required (kW)**	**Surface area available (m^2)**	**PV power capacity based on the area (kWp)**
1	0.324	6	0.9276
24	7.776	144	22.2635
3000	972	18,000	2,782.9314

Table 4: Configuration of PV system

PV system configuration of the 2782.9314 kWp c-Si			
PV system type		Rooftop large, tilted roof	
PV Field Orientation			
Fixed plane (orientation)	**Azimuth/Tilt (α/β)°**	**Installation type**	Roof mount
Nnewi	180/7	**Location coordinate**	06.020733°, 006.905819°
No of modules	34 units (P: 300 Wp; η: 18.1 %)	**Pnom total**	2782.9314 kWp
PV cell type (%)	c-Si (mono/poly)	**Soiling losses at PV modules**	Monthly soiling losses of up to 3.5 %;
System availability	98 %	**Cabling losses**	DC cabling 1 %; DC mismatch 0.5 %; AC cabling 0.4 %

Table 5: Financial inputs

Price of electricity		**System installation costs**	
Power purchase agreement/Feed-in tariff (USD/kWh)	0.15	Installed capacity (kWp)	2782.9314
Tariff indexation rate (%)	0.50	System installation costs (USD)	6,122,449
Annual operational costs		Unit system costs (USD/kWp)	1,671 2,200.00
Annual operational costs (USD)	55,659	CAPEX (USD)	6,122,449
Maintenance reserve account (USD/annually)	25,510.2	Loan (USD)	4,897,959.2
Year of inverter replacement (years)	12.0	Equity (USD)	1,224,489.8
OPEX (USD/annually)	81,169.2	Debt to equity ratio (%)	80
OPEX inflation rate (%)	2.00	Interest rate (%)	3.00
PV system configuration		Loan period (years)	15
Project's years of operation (years)	25.0	Linear loan repayment (USD/annually)	410,285.3
System availability %	98.00	**Accounting information**	
PVOUT_total (year 0) (kWh)	3,723,559.1	Discount rate (%)	0.00
Degradation first year (%)	0.80	Taxes on profit (%)	20.00
Degradation next year (%)	0.50	Linear tax depreciation (years)	10.0

3.7. Configuration of PV system

To assess the financial feasibility of implementing a solar PV system in Nnewi, Nigeria, several factors need consideration. The economic performance of the PV system hinges on several crucial factors, including the financial framework, federal and local policies, utility rates, and the technical potential accessible to commercial PV rooftops. There are several models to estimate the financial feasibility of a PV system and the choice of model depends on various factors, including project specifics, available data, and the level of detail required in the analysis. A thorough financial analysis is essential to evaluate the economic advantages of a PV system and a few commonly used models for assessing the financial feasibility of PV systems are - the levelized cost of energy (LCOE); return on investment (ROI); net present value (NPV); and internal rate of return (IRR) [61, 62]. Others are the operating expenses (OPEX) model and capital expenditure (CAPEX) models [60].

The combination of these models will be used to provide a comprehensive assessment of the financial feasibility of a PV system. The IRR represents the percentage profit an investor gains from investing in a solar PV system; ROI provides a simplified perspective on the cumulative savings an investor can achieve over the typical lifespan of a solar project for 25 years. The LCOE is the anticipated revenue necessary to cover the expenses of generating and operating a generator within a specified cost recovery period. In other words, it represents the selling price of electricity from a known source required to break even over the project's lifetime [63]. While the OPEX model enables the adoption of solar energy without significant initial expenditures, the CAPEX model requires consumers to take ownership, along with associated responsibilities for ensuring quality and safety (CAPEX) [64].

Levelised Cost of Energy is a widely used metric that represents the per-unit cost of electricity generated over the system's lifetime. It is suitable for comparing the cost-effectiveness of different energy generation technologies and considers both capital and operational costs, helping determine the feasibility of an energy project. Equation (14) is utilised to calculate the LCOE [63]:

$$LCOE = \frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{\left(1+r\right)^t}}{\sum_{t=1}^{n}\frac{E_t}{\left(1+r\right)^t}} \tag{9}$$

Considering CAPEX as a primary input in the calculation of LCOE, utilising the available most harmonised data set, equation (12) can be used [3]:

$$LCOE = 1\frac{\sum_{t=1}^{n}\frac{CAPEX_t+OPEX_t}{\left(1+r\right)^t}}{\sum_{t=1}^{n}\frac{PVOUT_t}{\left(1+r\right)^t}} \tag{10}$$

Here, with t representing the year, the variables are defined as follows: I_t denotes the investment expenses in year t; M_t corresponds to the maintenance and operations costs in year t; F_t stands for the fuel costs in year t (with $t = 0$ representing zero fuel costs for PV electricity); E_t represents the electricity produced in year t; r is the discount rate, and n signifies the investment period in years.

Among these derived financial metrics, the simplified LCOE, representing the cost of producing one unit of energy, is commonly employed to articulate the economic viability of solar PV. This is because LCOE encompasses CAPEX, OPEX, the cost of PV technology, discount rate, and the lifetime of the PV plant. Additionally, LCOE allows for comparison across different types of energy generation technologies by providing a standardised measure of the cost-effectiveness of an energy project. Therefore, LCOE is a fundamental tool in the assessment of RE projects, enabling stakeholders to make informed decisions based on the cost-effectiveness and economic sustainability of different energy generation options.

4. Results

Solar insolation plays a pivotal role in the electricity generation of PV systems, with the amount of generated electricity contingent on the intensity of irradiation. However, various meteorological variables impact PV power production, energy availability, and the ageing of a PV system. These variables encompass air temperature (TEMP) in Celsius, relative humidity (RH) in percentage, wind speed (WS) in meters per second, precipitation (PREC) in millimetres, precipitable water (PWAT) in kilograms per square meter, and albedo. The results presented here are derived from the high-resolution meteorological database maintained by Solargis. This section is categorized into two segments: the assessment of solar insolation resources and the evaluation of solar PV generation potential.

4.1. Configuration of PV system

The technical viability of the solar PV potential in Nnewi is assessed based on the solar radiation data provided. In general, solar radiation values equal to 1000 kWh/m^2 and above are regarded as higher radiation values, which indicates greater solar PV potential for energy generation. Considering the irradiance data obtained in this study, as presented in Fig 6(a), a total yearly GHI, DNI, and DIF of 1716 kWh/m², 845 kWh/m², and 1075 kWh/m², respectively, are high and suggests good solar potential. Considering these values, the solar potential in Nnewi appears to be quite viable. However, the viability also depends on other factors, such as the PV panel's orientation and tilt, local climate, shading, and the efficiency of solar technologies deployed. An optimised panel's orientation and tilt creates higher irradiance reception, as shown in Fig 6(b) and this occurrence generates more electricity. The three components make the same monthly sum profiles with the highest and smallest monthly sum observed in December and August, respectively. The average monthly sum is higher in the dry season (November to March) than during the rainy season (April to October).

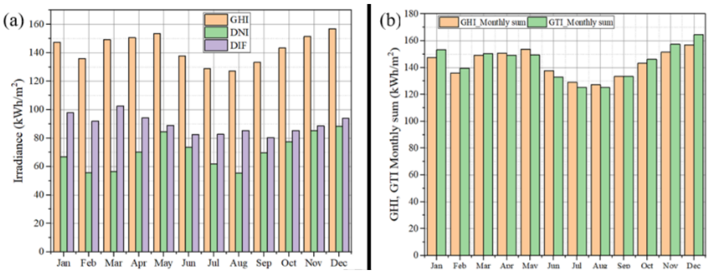

Fig 6: Meteorological parameters (a) components of irradiance; (b) Monthly profile of GHI and GTI

Ambient factors, such as RH, WS, precipitation (PREC) in mm, and precipitable water in kg/m^2 (PWAT), TEMP, and length of day and night are responsible for the different magnitudes of irradiance reported across the months, as represented in Fig 7(a) & (b). Based on the study's report, the yearly average TEMP of 26.6 °C will reduce the PV system performance a little since the TEMP exceeds 25 °C while RH of 80% at 26.6 °C will insignificantly affect PV panel performance. The moderate WS of 1.9 m/s will slightly cool the PV panels, which support effective PV generation. Relative humidity, PREC, and PWAT are relatively higher in the months of the rainy season than in the dry season. These elements are responsible for the lower average monthly sum of GTI observed from June to September (core months of the rainy season) than from October to May (mostly months of the dry season). The RH is highest in these months but there is an exception of the trend of GTI in February due to heavy dust and hazes orchestrated by harmattan season; February is the epic of harmattan in Nnewi. The Harmattan is a season in West Africa that takes place from late November to mid-March. It is marked by a dry and dusty northeasterly trade wind, also called the Harmattan, which blows from the Sahara across West Africa to the Gulf of Guinea [65].

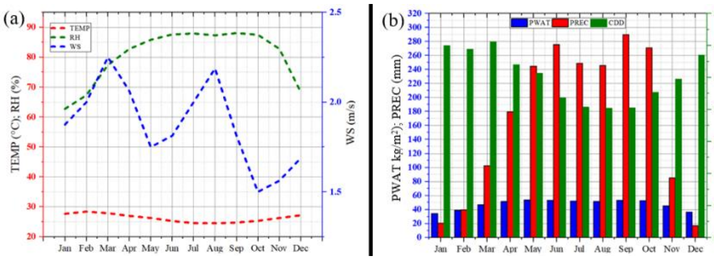

Fig 7: Monthly profiles of key ambient factors that influence irradiance (a) TEMP, RH, and WS; (b) PWAT, PREC, and CDD

These three factors—RH, PREC, and precipitable water PWAT—contribute to the reduction of solar irradiance. They influence DNI by scattering and absorbing sunlight, and they influence DIF by causing cloud cover. Consequently, this decrease in solar irradiance has a direct effect on the overall energy production of PV panels. This study examined these atmospheric conditions to accurately forecast the performance of PV systems in Nnewi. By employing advanced solar modelling tools, such as Solargis and PV*SOL, these variables are integrated to provide more precise predictions of solar irradiance at locations.

4.2. Evaluation of solar PV generation potential.

Based on the obtained study data, the specific and total *PVOUT* profiles follow the same pattern with the *GTI,* as presented in Fig 8, validates the proportionality relation between the irradiance and *PVOUT*, represented in equation (4). Solar irradiance plays a crucial role in determining the power output of a PV system.

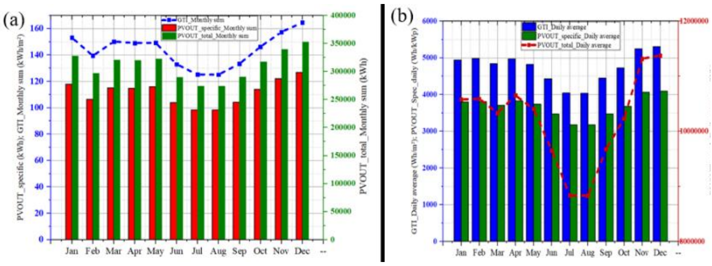

Fig 8: PV potential and system performance parameters (a) Monthly GTI and PVOUT; (b) Daily GTI and PVOUT specific and average

As depicted in Fig 9(a), it is noticeable that the GHI is less than the GTI, and this can be ascribed to mainly the PV panel geometry in the context of GTI, as defined by azimuth and tilt angles. This study considered an optimal PV orientation of 180 °C and 7 °C as the azimuth and tilt, respectively. The quality of production as measured by the annual average Performance Ratio (PR) is 77.5%, as shown in Fig 9(b), indicating a high PVOUT performance, demonstrating the technical viability of the PV system in Nnewi.

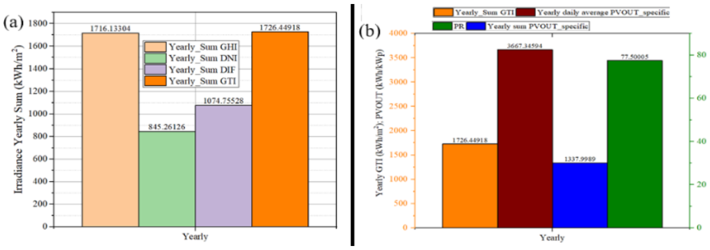

Fig 9: Impact of PV panel orientation and tilt (a) GHI and GTI irradiance; (b) PVOUT and PR

5. Avoidable CO2 emissions

The use of PV systems in Nnewi's New Motor Spare Parts Market offers significant benefits by replacing fossil fuel-based electricity generation. Utilising solar energy through PV systems notably decreases the carbon footprint linked to traditional power sources, as they produce electricity without greenhouse gas emissions, resulting in lower CO_2 output. A specific PV system has led to a reduction of 729,430 kg/year of CO_2 emissions, generating an annual total of 3.724 GWh at a specific output of 1398.38 kWh/kWp. Implementing PV systems in Nnewi's four largest markets—Nkwo Nnewi New Motorcycle Spare Parts, New Motor Spare Parts, Electrical/Electronics, and Nkwo Main (Ime Afia) Markets—could increase the avoided CO_2 emissions to 2.2 million kg/year. If adopted across all traditional markets in Nigeria and Sub-Saharan Africa, this initiative could significantly mitigate CO_2 emissions.

5.1. Financial feasibility

The PV project's financial study requires many parameters, as presented in Table 5, to be considered before making a final decision. By thoroughly examining these financial factors, this study developed a comprehensive financial feasibility analysis for implementing a solar PV system in Nnewi, Nigeria. This analysis will help stakeholders make informed decisions regarding the financial viability and benefits of such a project.

Key financial parameters from the study's report, include an IRR of 5.31% for the project, 8.58% for equity, a ROI of 33.87%, and an LCOE of 0.11888 USD/kWh. The project's IRR is lower than that for equity, suggesting insufficient returns for equity investors. Despite the lower overall project IRR, the higher equity IRR and strong ROI indicate potential appeal to investors. Additionally, the LCOE falls within the global average for solar PV systems, which ranges from 0.03 to 0.18 USD/kWh, further demonstrating the project's feasibility due to its competitive electricity generation costs [66].

The LCOE for off-grid solar PV systems is $0.20/kWh, compared to diesel and gasoline generators, which range from $0.40 to $0.71/kWh [67]. This positions off-grid solar PV systems as a cost-competitive alternative. Despite the lower initial costs of fossil-fuel-powered generators, their operational expenses are highly dependent on fuel availability and prices. In contrast, solar PV systems benefit from free and abundant fuel. Combined cycle natural gas has the lowest LCOE, between $0.05 and $0.07/kWh, but it requires extensive supply and distribution infrastructure.

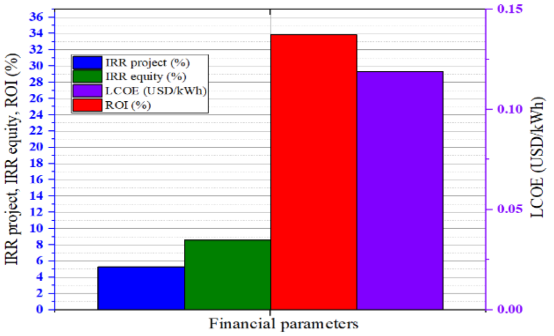

Fig 6: PV project key financial parameters

This study's financial results aligned with the previous studies within the same climate and other climates in Nigeria other climates, especially LCOE, which is the main tool used to determine the feasibility of PV projects. The LCOE of electricity in Nigeria is in the range of 0.05 $/kWh to 0.27 $/kWh and the average LCOE across the country is 0.21 $/kWh, as presented in Table 6 [68].

Table 6: Financial parameters comparison

Study	LCOE ($/kW)	Climate	Date
This study	0.11888	Tropical Savanna	2024
[69]	0.18	Warm desert	2021
	0.19	Warm semi-Arid	
	0.2	Tropical Savanna	
	0.27	Monsoon	

Nigeria exhibits significant solar PV potential based on climate variations, which is categorised into – monsoon (1600-1750 kWh/m^2), tropical savanna (1750-1900 kWh/m^2), warm semi-arid desert (1900-2050 kWh/m^2), and warm desert (2050-2200 kWh/m^2) [70]. It can be seen from Table 7 that LCOE is proportional to the solar PV potential. Additionally, the northern arid zones (Sokoto, Katsina, Kano, Plateau, and Jigawa) experience wind speeds greater than 7 m/s, while the forest and guinea savannah zones have wind speeds less than 4.4 m/s [71].

6. Conclusion

The call to exploit RE is increasing, propelled by the need for adequate and cheap energy supply; and the need for clean energy to mitigate climate change. The global energy need is challenging because of the rapid industrialisation, population growth, and urbanisation in the Global South. The exploitation of fossil fuel to meet the needed energy has these challenges - limited resource deposits, fluctuating global prices, subsidy issues, and global environmental challenges. This study focuses on developing a zero-CO2 emissions electricity scheme to power traditional markets in TMSSA. This is to increase access to clean energy in SSA while reducing the emission of harmful gases, emanating from fossil-based power generation. The TMSSA has been identified in this study as a source of CO2 emissions in the region. The study presents a comprehensive analysis of CO2 in GHGs and the significance of decarbonisation. The study proposes a RE resource potential-based scheme to supply clean electricity to TMSSA, using the NEW Motor Spare Parts Market in Nnewi, Nigeria. The study highlighted the viability of the RE system through a rigorous design, optimisation, and economic assessment of the solar PV system in Nnewi, Nigeria. Overall, the study presented solar PV as feasible in both technical and financial aspects based on the following results obtained at optimisation orientation azimuth and tilt angles of 180º and 7º respectively:

i. The annual sum of GHI, DNI. DIF, and GTI as 1716.1 kWh/m2, 845.3 kWh/m2, 1074.8 kWh/m2, and GTI 1726.4 kWh/m2, respectively.

ii. The specific PVOUT, annual total PVOUT, and PR as 1338.0 kWh/kWp, 3.724 GWh, and 77.5%, respectively.

iii. The annual sum of CO2 emissions avoidable if a PV system is implemented is 729,430 kg

iv. Financial parameters include the IRR for the project (5.31%), IRR for equity (8.58%), ROI (33.87%), and LCOE (0.11888 USD/kWh).

7. Acknowledgements

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