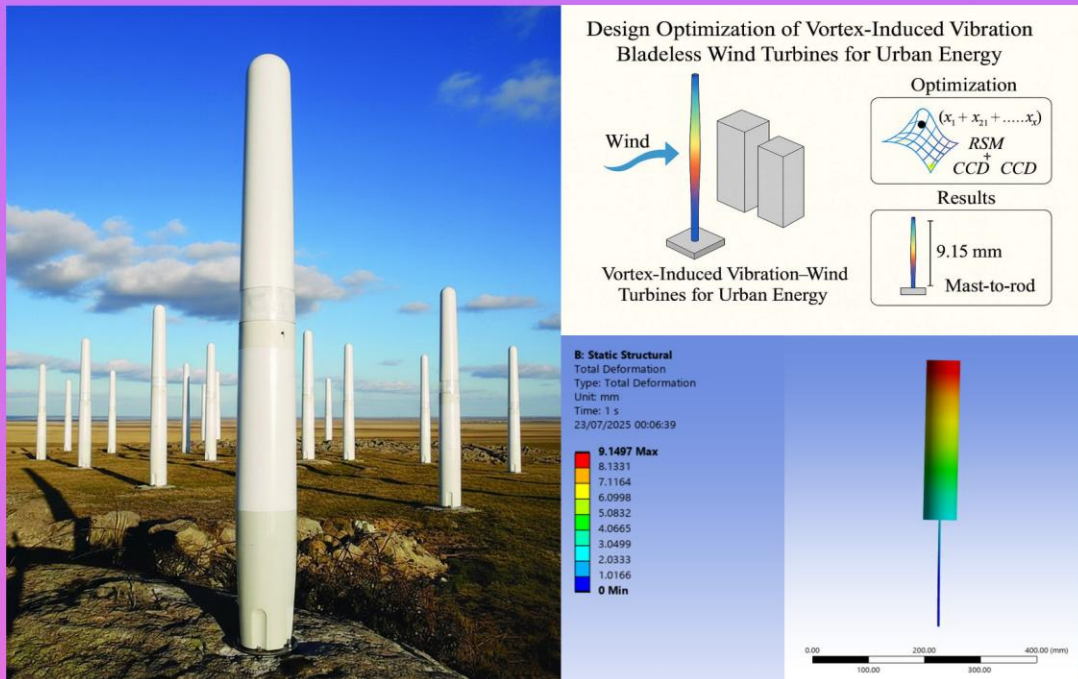


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Cover image: Vortex-Induced Vibration Bladeless Wind Turbines Article by Kwong and Han



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Renewable Energy Revolution: Transforming Africa's Energy Landscape through Solar, Wind, and Hydropower

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This study examines how the plentiful solar, wind, and hydroelectric resources in Africa are transforming the continent's energy landscape. Africa faces significant challenges in achieving energy access and sustainability due to the growth of its population and urbanization. This analysis analyzes the transformational capacity of renewable energy, emphasizing pioneering initiatives like Morocco's Noor Ouarzazate Solar Complex and Kenya's Lake Turkana Wind Project. We examine the economic advantages of decentralized energy systems, such as mini-grids and pay-as-you-go solar solutions, which have empowered millions and invigorated local economies. Progress in hybrid systems and energy storage technologies is essential for improving grid stability and dependability. The success of this revolution depends on strong legislative frameworks, new financial structures, and regional collaboration to address infrastructural deficiencies and regulatory obstacles. This assessment highlights the need for inclusive strategies that include local people and tackle environmental issues related to large-scale projects. Africa is positioned to lead in renewable energy, underscoring the critical need for collaboration among governments, corporate sectors, and foreign partners to facilitate this transition. By using its extensive renewable resources, Africa may attain energy security, economic development, and environmental sustainability, therefore fostering a resilient future.

Keywords: Renewable Energy; Africa; Solar Energy; Wind Energy; Hydropower; Policy Frameworks; Sustainable Development

1. Introduction

Africa is a crucial hub for the renewable energy revolution because of its vast natural resources and socio-economic difficulties. Africa, with over 600 million people devoid of dependable energy, has considerable potential for the advancement of solar, wind, and hydroelectric resources [1]. The optimal use of these resources is intricate and necessitates innovative solutions and joint endeavors. Solar energy provides a substantial opportunity for Africa, especially in regions with elevated solar irradiation, such as the Sahara Desert. The 100 MW Noor Ouarzazate Solar Complex in Morocco is a pivotal initiative that generates clean energy and exemplifies the potential of large-scale solar projects to bolster national energy security [1]. Wind energy offers significant potential, particularly in coastal regions and high areas. The Lake Turkana Wind Power Project in

Kenya, boasting a capacity of 310 MW [2], demonstrates the viability of significant wind energy investments, providing about 17% of the country's electricity needs and promoting local job prospects [3]. South Africa's investment in wind energy has led to the creation of several wind farms, showcasing the country's commitment to diversifying its energy portfolio [4].

Historically, hydropower has been essential to Africa's energy generation, as shown by major projects like Ethiopia's Grand Renaissance Dam, projected to produce 6,450 MW [5]. Large-scale dam projects may displace populations and disrupt local ecosystems, necessitating careful planning and stakeholder engagement to mitigate negative impacts. Africa continues to have substantial challenges regarding energy availability, with more than 600 million people devoid of power [1], mostly in rural areas where grid connectivity is limited or nonexistent [6]. Innovative alternatives, such as solar home systems and mini-grids, are becoming more significant, with companies like M-KOPA Solar providing affordable pay-as-you-go solar solutions to off-grid residences in Kenya and Tanzania [7]. These innovations have improved the quality of life for several people [8], illustrating that decentralized energy solutions may effectively mitigate energy inequality [9].

Insufficient regulatory frameworks and investment obstacles [10] are hindering Africa's efficient transition to renewable energy [9]. Initiatives such as green bonds [11] and public-private partnerships may stimulate investments in renewable energy projects [12]. The African Development Bank's Desert to Power initiative aims to harness solar energy across the Sahel region, with a total capacity of 10 GW by 2025 [1]. Renewable energy has emerged as a crucial driver of economic development in Africa [13], addressing energy poverty while promoting job creation [14], enhancing local economies [15], and facilitating sustainable growth [16]. The transition from fossil fuels to renewable energy sources offers unique opportunities for developing resilient economies [17] and mitigating the adverse impacts of climate change [18].

Renewable energy is essential for enhancing energy security and resilience [19], particularly in light of climate uncertainty and geopolitical dangers associated with fossil fuel use [20]. Countries such as Ethiopia are at the forefront of integrating renewable energy to enhance energy stability and diminish susceptibility [21]. The Grand Ethiopian Renaissance Dam, projected to generate 6,450 MW of hydropower, is anticipated to bolster energy security and facilitate regional economic integration via cross-border energy trade [1]. The renewable energy industry in Africa is drawing international investment owing to the decreasing costs of renewable technologies and their economic benefits [1]. The African Development Bank's Desert to Power program seeks to use the solar potential of the Sahel region, targeting a total capacity of 10 GW by 2025 [1]. This ambitious plan is anticipated to attract billions of dollars in investments, stimulating economic development and job creation across the area.

Moreover, the advent of innovative financing mechanisms, such as green bonds and climate finance, is enabling the funding of renewable initiatives in African countries. Nations such as Nigeria and Kenya have used green bonds to encourage sustainable investment and enhance resource allocation for clean energy initiatives. Investing in renewable energy is closely associated with several Sustainable Development Goals (SDGs), including affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), and climate action (SDG 13)[8]. Countries such as Morocco have set high renewable energy goals, aiming for 52% of their energy supply to derive from renewable sources by 2030 [22]. Technological developments are spearheading Africa's

renewable energy revolution [23], enabling the continent to surmount traditional energy challenges and accelerate the deployment of solar [24], wind [25], and hydropower solutions [26]. Cutting-edge technology is used to improve energy accessibility [27], efficiency [28], and sustainability [29], including advancements in energy storage and smart grid integration [30].

A significant technological advancement impacting Africa's energy industry is the quick decline in the cost of solar photovoltaic (PV) systems [31]. The cost of solar PV technology has reduced by around 80% since 2010, making it an increasingly viable option for large-scale and off-grid applications across the continent [1]. Energy storage technologies represent a significant advancement transforming Africa's renewable energy landscape [32]. Progress in battery storage technology is alleviating the challenges of integrating renewables into the grid [33]. Lithium-ion battery technology has advanced swiftly, with costs decreasing by around 90% over the last decade [6], hence improving its accessibility for both utility-scale and residential applications. Hybrid energy systems that combine solar power with battery storage are exhibiting significant impacts in rural and off-grid regions, decreasing reliance on fossil fuels and enhancing energy security.

Alongside grid management, digital technologies such as the Internet of Things (IoT) and blockchain are used to enhance energy accessibility and transparency [34]. In Nigeria, the blockchain company WePower enables peer-to-peer energy trading, allowing users to directly buy and sell excess solar energy [35], reducing transaction costs, and empowering local people to participate actively in the renewable energy market [36]. Africa's renewable energy industry is seeing notable technical progress, with run-of-the-river (ROR) systems and micro-hydropower technologies emerging as more sustainable options [16]. The Rukarara II small hydropower station in Rwanda supplies electricity to remote communities, exemplifying the capabilities of modular hydropower systems [6]. Micro-hydropower technologies, shown as the Mwenga Hydro Project in Tanzania, provide sustainable energy solutions for off-grid regions, fostering economic development while safeguarding the environment.

The effective shift to renewable energy in Africa depends on strong policy frameworks and governance structures. Countries such as Morocco have established ambitious renewable energy goals and laws to enhance energy accessibility and sustainability. Morocco's National Energy Strategy is to get 52% of its energy generation capacity from renewable sources by 2030 [6], promoting the development of large-scale initiatives such as the Noor Ouarzazate Solar Complex. South Africa's Integrated Resource Plan (IRP) seeks to generate 20,400 MW of renewable energy by 2030 [6], facilitating competitive bidding and significant investments in wind and solar initiatives. Innovative regulatory tools are crucial for advancing renewable energy adoption in Africa, including feed-in tariffs (FiTs) and power purchase agreements (PPAs)[37], which provide assured remuneration for electricity generated from renewable sources. Countries such as Kenya have effectively implemented Feed-in Tariffs for wind and solar projects, resulting in the rapid growth of renewable energy capacity [6].

Regional collaboration is essential for advancing renewable energy in Africa, as the African Renewable Energy Initiative (AREI) seeks to harness the continent's plentiful renewable resources via cooperative efforts and investment. The AREI seeks to mobilize capital and facilitate knowledge transfer among member states by establishing a cohesive framework for renewable energy initiatives. Nevertheless, several challenges persist in the effective implementation of renewable energy initiatives across Africa. Fragmented regulatory frameworks, discrepancies between national and local regulations, and

bureaucratic inefficiencies may hinder investment and project advancement. Financial constraints provide a considerable barrier to realizing ambitious renewable energy goals, since several African countries have difficulties in securing foreign investment owing to perceived risks associated with political instability, inadequate infrastructure, and regulatory uncertainties. Innovative financial frameworks, such as green bonds and hybrid finance models, are essential for tackling these difficulties.

Efficient governance in the renewable energy sector requires stakeholder involvement and community engagement. The Lake Turkana Wind Power Project in Kenya emphasizes community engagement by including local stakeholders in decision-making processes [38] and providing economic benefits to surrounding communities. The Renewable Energy Revolution in Africa addresses the continent's energy challenges [1] while also having the potential to transform its socio-economic structure.

Africa faces increasing energy demand and the urgent need for sustainable development, making renewable energy a crucial element in modernizing the continent's energy framework. This assessment examines the huge unexploited potential of solar, wind, and hydropower in Africa [39], as well as the technical innovations and current progress propelling the continent towards a more sustainable energy future [40]. Although hydropower continues to be fundamental, solar and wind energy are seeing fast expansion owing to decreasing prices and enhanced technology. Achieving widespread renewable adoption requires strong regulatory frameworks, favorable policies, and smart investments [41]. The ongoing shift is characterized by new themes, including energy storage and regional collaboration, which are poised to expedite advancement [42].

The subsequent sections of this study encompass Energy Demand and Current Landscape in Africa; Solar Energy Potential and Developments in Africa; Wind Energy Potential and Progress in Africa; Hydropower as a Cornerstone of Africa's Renewable Energy Future; Regulatory and Policy Frameworks to Facilitate Renewable Energy Adoption; Emerging Trends and Prospective Outlook; and Summary and Conclusion. The Energy Demand and Current Landscape in Africa examines the impact of population growth and economic development on the rising energy demand, especially in metropolitan regions. This section analyzes the existing energy sources used on the continent and their ecological consequences. The section on Solar Energy Potential and Developments in Africa examines how solar energy is becoming a crucial component of renewable energy advancement on the continent thanks to ample sunshine and falling solar technology prices, which are fostering sector expansion. It also examines the many solar projects and activities now in progress throughout the continent to use this potential and sustainably address the increasing energy demand. The Wind Energy Potential and Progress in Africa section examines the increasing use of wind energy as a renewable resource across the continent, highlighting the substantial wind resources that provide a significant potential for clean energy production. It underscores the advancements achieved in the development of wind energy projects and infrastructure to harness this potential and facilitate the region's energy transition. The section on Hydropower as a Cornerstone of Africa's Renewable Energy Future examines the pivotal role of hydropower in Africa's renewable energy landscape, highlighting its plentiful water resources as a dependable source of clean energy. It also addresses the significance of investing in hydroelectric infrastructure to exploit this potential and promote sustainable development across the continent. The section on Regulatory and Policy Frameworks to Facilitate Renewable Energy Adoption examines the critical role of regulatory and policy frameworks in fostering an environment conducive to renewable energy adoption in

Africa. Governments may attract investment and foster the development of renewable energy projects in the area by instituting explicit standards and incentives. This section emphasizes the need for cooperation among stakeholders to develop effective policies that facilitate the transition to a more sustainable energy mix in Africa. The Emerging Trends and Prospective Outlook section examines how technical breakthroughs, like the integration of smart grids and energy storage options, are influencing the future of renewable energy in Africa. These developments signify a transition towards a more decentralized and robust energy infrastructure capable of effectively addressing the continent's increasing energy demands while diminishing dependence on fossil fuels. This assessment emphasizes the present condition of Africa's renewable energy revolution while providing a prospective analysis on how these sectors might influence a sustainable and resilient energy future for the continent, serving as a paradigm for global energy transitions.

2. Energy Demand and Current Landscape in Africa

2.1 Current Energy Generation Mix and Distribution: Fossil Fuels vs. Renewables

Africa's energy environment has a heterogeneous generating mix that reflects the continent's diversified resources, economic goals, and issues related to energy availability. Although fossil fuels, especially coal, oil, and natural gas, remain predominant in energy production, there is a discernible transition towards renewable energy sources, including solar, wind, and hydropower. This sub-section examines the present energy generating composition in Africa, the allocation of energy resources, and the consequences for future energy demand and sustainability.

Recent statistics indicate that fossil fuels provide a substantial share of Africa's energy production, with coal, oil, and natural gas representing over 70% of the overall energy composition [2]. Countries such as South Africa and Nigeria are significantly dependent on coal and natural gas for energy production [2]. In South Africa, almost 80% of energy is produced by coal-fired power plants [2], which significantly contribute to economic activity and considerable greenhouse gas emissions [3]. Nigeria's energy industry is primarily powered by natural gas, which constitutes over 90% of its electricity output, despite the country's significant renewable energy potential [37].

The substantial dependence on fossil fuels presents considerable concerns, such as energy security threats [43], environmental deterioration [44], and heightened susceptibility to global oil price volatility [45]. The current shift to renewable energy is not just a question of sustainability but also of economic stability and energy resiliency [46].

Unlike the fossil fuel-centric environment, renewable energy sources are increasingly gaining prominence due to technical innovations, declining expenses, and favorable legislation. IRENA reported that renewable energy capacity in Africa reached 51 GW in 2020, reflecting an increase over 10% from the prior year [47]. Solar energy has become a leader, with nations such as Egypt, Morocco, and South Africa spearheading extensive solar installations [7].

The Benban Solar Park in Egypt is among the biggest solar installations globally, with a capacity of 1.8 GW, illustrating this transition [48]. It is anticipated to provide clean energy to more than 1 million homes, aiding Egypt in achieving its objective of producing 20% of its power from renewable sources by 2022 [49]. The Noor Ouarzazate Solar Complex in Morocco, with a capacity of 580 MW, exemplifies large-scale solar

initiatives and signifies the country's dedication to sourcing 52% of its energy from renewable resources by 2030 [50].

Wind energy is making considerable advancements, especially in East Africa. The Lake Turkana Wind Power Project in Kenya, with a capacity of 310 MW [49], is the biggest wind farm in Africa and is essential in diversifying the nation's energy portfolio, supplying around 17% of its power requirements [50].

Notwithstanding the increasing capability for renewable energy, the distribution of energy production throughout the continent remains inequitable [49]. Numerous areas, especially in sub-Saharan Africa, continue to depend significantly on traditional biomass for cooking and heating, resulting in health complications and environmental deterioration. The insufficiency of appropriate infrastructure, investment, and funding methods exacerbates the challenges of integrating renewables into the grid, especially in rural and isolated regions.

Novel solutions are arising to tackle these difficulties. Off-grid and mini-grid solar systems are gaining popularity as a method to provide power to underprivileged populations [5]. Companies such as M-KOPA Solar and SunCulture are using pay-as-you-go methods to provide cost-effective solar home systems and energy-efficient appliances, therefore empowering families and diminishing dependence on fossil fuels [6].

2.2 Statistics on Energy Poverty and Access to Electricity in Urban vs. Rural Areas

Energy poverty continues to be a critical issue in Africa, profoundly affecting economic growth, public health, and overall quality of life. The significant disparity in power availability between urban and rural regions highlights the intricacy of meeting energy requirements across the continent. This sub-section analyzes data about energy poverty, investigating the inequalities between urban and rural people, the consequences of these disparities, and new solutions designed to enhance access.

In 2021, around 600 million individuals in Africa were without electricity, constituting approximately 48% of the continent's population [6]. Although metropolitan regions often benefit from superior electrical availability, considerable disparities remain. The International Energy Agency (IEA) reports that around 93% of urban people have access to electricity, in contrast to just 43% of the rural population [6]. This difference illustrates the historical emphasis on electrifying metropolitan areas, sometimes to the detriment of rural regions.

In Nigeria, almost 60% of urban households have electricity access; however, this percentage falls to just 24% in rural regions [49]. In Kenya, urban electricity rates are around 75%, and rural access is about 30% [49]. These numbers underscore the pressing need to tackle energy poverty in rural areas, where dependence on traditional biomass for cooking and heating intensifies health hazards and environmental deterioration.

Energy deprivation in rural regions has extensive consequences. The absence of electricity restricts economic prospects, impedes education, and negatively impacts health results. Children in energy-deprived homes may have difficulties studying after dark, perpetuating cycles of poverty and constraining educational achievement. The World bank asserts that access to electricity enhances educational achievements by facilitating nighttime study sessions and supplying necessary learning resources [49].

Moreover, energy poverty exacerbates health hazards linked to the dependence on kerosene lights and conventional biomass for cooking. The World bank approximates that

indoor air pollution from these sources results in almost 4 million premature deaths per year, with rural women and children being disproportionately impacted [49]. Innovative solutions are developing to address the difficulties of energy poverty and improve access in rural regions. Decentralized renewable energy solutions, including solar household systems and mini-grids, are shown efficacy in closing the power access gap. M-KOPA Solar's pay-as-you-go solar home systems have delivered cheap electricity to more than 750,000 families in Kenya, markedly enhancing living conditions in rural areas [49]. The World Bank's Lighting Africa program is a significant project that advocates for off-grid solar solutions to provide power to underprivileged communities. The initiative has enabled access to clean and inexpensive energy for millions throughout the continent by assisting local entrepreneurs in distributing solar goods [50].

Governments are increasingly acknowledging the significance of tailored strategies to mitigate gaps in energy access. Ethiopia's Energy Sector Policy is to attain universal energy access by 2025, emphasizing the expansion of off-grid alternatives in rural regions [49]. This thorough approach emphasizes the possibility of incorporating renewable energy solutions into national electrification efforts.

2.3 Projected Energy Demand Over the Next 20-30 Years

As Africa undergoes urbanization and economic development, energy consumption is anticipated to rise substantially over the next two to three decades. This anticipated increase in energy use offers both prospects and obstacles for the continent's energy framework. Comprehending these developments is essential for policymakers, investors, and stakeholders to formulate policies that guarantee sustainable energy access and address the increasing needs of African people.

The International Energy Agency (IEA) projects that Africa's energy consumption may over double by 2040, mostly due to population increase, urbanization, and economic advancement [6]. The continent's population is projected to attain over 2.5 billion by 2050 [50], with metropolitan regions proliferating as individuals migrate to cities in pursuit of enhanced chances. This population transition would undoubtedly elevate energy requirements across several sectors, including residential, industrial, and transportation.

The International Energy Agency projects that energy demand in Sub-Saharan Africa would rise by around 80% by 2040, with electricity consumption anticipated to expand at an annual rate of 5% [49]. The power demand in nations like Nigeria and South Africa is expected to exceed supply if existing infrastructure and investment levels are unaltered [51].

Distinct industries will encounter varied amounts of energy demand growth. The residential sector, driven by population expansion and improved living standards, is anticipated to have the most significant rise in power usage. The International Renewable Energy Agency (IRENA) forecasts that the number of homes with electricity access in Africa would rise from around 600 million to over 1.2 billion by 2040, markedly increasing residential energy consumption [52].

The industrial sector is positioned for expansion, especially in manufacturing, mining, and agriculture. The African Union's Agenda 2063 identifies industrialization as a fundamental component of economic growth, forecasting an annual increase of 4-6% in energy consumption within the industrial sector [1]. Investments in renewable energy and energy efficiency technology will be essential to satisfy this increasing demand while mitigating environmental concerns.

The anticipated rise in energy consumption offers Africa a chance to expedite the shift to renewable energy sources. The continent has vast renewable resources, such as solar, wind, and hydropower, which are essential for responsibly addressing future energy requirements.

The African Renewable Energy Initiative (AREI) seeks to attain a minimum of 10 GW of new and supplementary renewable energy capacity by 2020 and 300 GW by 2030 [1]. Achievement of these aims might substantially aid in fulfilling the anticipated energy demand, enhancing energy security, and reducing carbon emissions [1]. Ethiopia exemplifies the potential for large-scale renewable projects to satisfy increasing demand, with plans to augment its hydropower capacity from 4,000 MW to over 17,000 MW by 2030 [1].

Notwithstanding the favorable forecasts for renewable energy expansion, several hurdles must be confronted to satisfy the anticipated energy demand. Infrastructure deficiencies, regulatory obstacles, and financial limitations provide substantial challenges to amplifying investments in renewable energy. The World Bank estimates that attaining universal power access in Africa by 2030 requires around \$25 billion in yearly expenditures [49].

Furthermore, the shift to renewable energy must be meticulously managed to provide energy security. An optimal energy mix including both renewable and conventional energy sources may be essential in the short to medium term to avoid supply constraints amid increasing demand.

2.4 Infrastructure Gaps, Grid Reliability, and Energy Costs

Africa's energy environment is marked by considerable infrastructural deficiencies, issues with grid dependability, and elevated energy prices, all of which affect the continent's capacity to satisfy increasing energy demand. Resolving these difficulties is crucial for stimulating economic growth, enhancing energy accessibility, and advancing sustainable development.

A significant difficulty for Africa's energy economy is the insufficient infrastructure. Numerous nations contend with antiquated and inadequate energy infrastructures, which impede the proliferation of power access, especially in rural and isolated regions. The International Energy Agency (IEA) reports that around 600 million people in Africa remain without electricity, mostly in sub-Saharan Africa, where infrastructural deficiencies are most severe [1]. In Nigeria, a nation rich in energy resources, the current power system is inadequately built, resulting in substantial transmission and distribution losses, estimated at over 40% [1]. This inefficiency restricts the electricity accessible to customers and intensifies energy poverty since several communities depend on costly and unreliable backup options, such as diesel generators.

The dependability of energy provision is a significant issue in Africa. Frequent power interruptions and voltage fluctuations provide an unstable environment for home users and companies alike. The World Bank indicates that African enterprises forfeit around 5% of sales owing to power disruptions, severely impeding productivity and development [49]. Countries like South Africa have seen significant load shedding as a result of deteriorating infrastructure, maintenance deficits, and heightened demand. Eskom, the state-owned energy provider, has been unable to provide a dependable power supply, resulting in rolling blackouts that hinder economic operations [50]. In Malawi, insufficient investment in generating capacity has led to extended outages, significantly affecting companies and governmental services [49]. Emerging innovative technologies,

like smart grid technology and decentralized energy systems, aim to enhance grid stability. In Kenya, the incorporation of mini-grids and off-grid solar systems has improved energy stability in rural regions, ensuring constant power supply while alleviating pressure on the national grid [50].

Elevated energy expenses are a substantial obstacle to accessibility and affordability in Africa. The interplay of insufficient infrastructure, dependence on fossil fuels, and restricted investment in renewable energy sources results in heightened power costs. Energy expenses constitute a significant share of expenditures for many homes and small enterprises, sometimes resulting in energy poverty and financial distress. In South Africa, energy costs have surged significantly in recent years, as Eskom has instituted many rate increases to mitigate financial difficulties, resulting in electricity being more unaffordable for low-income families [49]. Conversely, renewable energy solutions have the capacity to lower energy expenses. The levelized cost of solar energy has significantly decreased, making it one of the most economical sources of power. Recent auctions in South Africa have shown solar power costs down to as low as 50 USD/MWh [6]. Innovative financing methods, including pay-as-you-go approaches for solar home systems, are assisting in mitigating the financial strain of elevated energy bills for low-income families. Firms such as M-KOPA Solar are offering economical solar solutions that enable households to get power without the initial expenses often linked to conventional energy sources [6].

2.5 Policy Bottlenecks, Financing Challenges, and Technology Access

Addressing energy demand in Africa requires a thorough comprehension of the legislative impediments, financial obstacles, and technological access issues that hinder the establishment of a sustainable energy framework. Each of these components is essential in influencing the region's energy future and assessing the efficacy of initiatives aimed at improving energy availability and efficiency.

The inconsistency and fragmentation of energy policy across African states substantially impede the development of the renewable energy industry. National energy policies often exhibit a lack of coherence and fail to fit with overarching economic and environmental objectives. Although several governments have established lofty renewable energy objectives, bureaucratic impediments and regulatory ambiguity may hinder project execution. In Zambia, while a renewable energy feed-in tariff policy exists, prospective investors encounter protracted approval procedures and ambiguous laws, which discourage investment [52]. The absence of cohesive planning across energy, transportation, and urban development policies may result in ineffective resource distribution and lost possibilities for synergy. In Ghana, dependence on fossil fuels for power production persists despite substantial expenditures in solar energy, mostly owing to regulatory inertia and insufficient grid infrastructure for renewable integration [53].

Access to financing continues to be a major obstacle to energy development in Africa. The continent necessitates around \$25 billion each year to get universal power access by 2030 [49]. Nevertheless, conventional finance sources often prove inadequate, and private sector investments are hindered by perceived risks and uncertainties. Novel financing tools, like blended finance and green bonds, are arising to tackle these difficulties. The African Development Bank's "Desert to Power" plan seeks to mobilize \$20 billion to produce 10 GW of solar energy in the Sahel area, using both public and private sector financing [49]. These efforts illustrate the capacity of innovative finance structures to garner investment and propel renewable energy projects. Crowdfunding

platforms are becoming popular in Africa, offering an alternative finance source for small-scale renewable projects. Energicity's crowdfunding initiatives in Ghana have effectively garnered money to enhance solar energy accessibility in off-grid areas, demonstrating the potential of community-driven finance to advance energy projects [50].

Access to contemporary energy technology is essential for meeting energy demand and facilitating the transition to sustainable energy systems. Nevertheless, several African nations encounter substantial obstacles to technological transmission and adoption. Significant initial expenses, insufficient qualified workforce, and restricted access to maintenance services impede the use of new energy technology. Governments and international organizations are collaborating to enhance technological access via partnerships and capacity-building efforts. The World Bank has played a crucial role in enabling knowledge transfer in renewable energy and fostering local production and maintenance of solar goods in nations such as Ethiopia [49]. Furthermore, public-private partnerships (PPPs) have surfaced as a viable strategy to improve technology accessibility. In Kenya, collaborations between the government and private sector entities have resulted in the creation of indigenous solar manufacturing facilities, therefore lowering prices and enhancing availability [49]. These programs not only improve technological accessibility but also foster job creation and economic advancement.

2.6 Environmental and Social Challenges: Deforestation, Emissions, and Land Use

Africa has significant environmental and social difficulties, notably with deforestation, greenhouse gas emissions, and changes in land use, as it addresses its energy demands and development objectives. These challenges are fundamentally connected to the continent's energy decisions and have considerable ramifications for sustainable development, biodiversity, and the lives of millions.

Deforestation is a critical environmental concern in Africa, mostly fueled by dependence on biomass for energy. About 70% of Africa's population relies on traditional biomass, including wood and charcoal, for cooking and heating [49]. This reliance results in considerable forest degradation, especially in nations like Madagascar and the Democratic Republic of the Congo (DRC), where deforestation occurs at alarming rates. Madagascar has seen a loss of nearly 80% of its forest cover as a result of logging, agriculture, and charcoal manufacturing [50]. This not only contributes to the loss of biodiversity but also intensifies climate change via elevated carbon emissions. The World Bank estimates that deforestation contributes around 20% of global greenhouse gas emissions, with Africa's impact being considerable owing to poor land management practices [49]. Novel alternatives are emerging to combat deforestation while fulfilling energy requirements. Initiatives advocating for energy-efficient stoves and alternative cooking fuels, including biogas and solar cookers, have shown potential in decreasing biomass use. The Clean Cooking Alliance is disseminating clean cooking solutions across Africa to mitigate deforestation and enhance public health [50].

Africa has abundant natural resources, and the extraction of fossil fuels is exacerbating greenhouse gas emissions. Africa, accountable for around 3% of worldwide emissions, is anticipated to see an increase in emissions owing to escalating energy consumption and industrialization [6]. Nations such as Nigeria and South Africa, which depend extensively on coal and oil, are major contributors to the continent's carbon emissions. The South African energy industry is a significant contributor to greenhouse gas emissions in Africa, mostly attributable to coal-fired power stations. South Africa

seeks to diversify its energy portfolio and diminish emissions via projects such as the Integrated Resource Plan (IRP), which intends to integrate more renewable energy sources. The Integrated Resource Plan (IRP) seeks to attain a goal of 20 GW of renewable energy capacity by 2030, facilitating emission reduction while fulfilling energy requirements [54].

The shift to renewable energy and the development of energy infrastructure may result in changes to land use that affect local ecosystems and populations. Extensive renewable energy initiatives, such as solar farms and wind parks, need considerable land expanses, potentially resulting in disputes over land rights and the relocation of local communities. In some instances, the implementation of these projects may infringe upon essential agricultural land, jeopardizing food security. The establishment of the Noor Ouarzazate Solar Complex in Morocco, while advantageous for renewable energy production, has elicited apprehensions over land use and its impact on local residents and agriculture [54]. Confronting these difficulties requires meticulous planning, stakeholder involvement, and assessment of societal repercussions.

3. Solar Energy Potential and Developments in Africa

3.1 Solar Irradiation Levels throughout Various African Areas

Africa has some of the greatest sun irradiation levels globally [55], making it an optimal continent for the use of solar energy [56]. The capacity for solar energy production differs markedly across places [57], shaped by geographical [58], climatic [59], and seasonal variables [60]. Comprehending these variances is essential for the efficient development of solar energy initiatives [61] and policies designed to enhance access to renewable energy [62].

3.1.1 *Regions with Elevated Solar Potential*

North Africa: Nations like Egypt, Algeria, and Morocco have very elevated sun irradiation levels, often surpassing 2,500 kWh/m² annually [63]. The Sahara Desert is an ideal site for solar energy initiatives because of its extensive, unimpeded terrain and constantly elevated solar insolation. The Noor Ouarzazate Solar Complex in Morocco exemplifies a facility designed to produce 580 MW of concentrated solar power (CSP) using the area's elevated sun irradiation [63].

Sub-Saharan Africa: This area has considerable solar potential, with nations such as South Africa, Namibia, and Kenya exhibiting elevated irradiance levels. For example, South Africa's sun irradiation may attain up to 2,200 kWh/m² annually in regions like the Northern Cape [64]. The nation has leveraged this potential via programs such as the Renewable Energy Independent Power Producer Procurement Program (REIPPPP), which has garnered significant investments in solar projects [65].

East Africa: Nations such as Kenya and Tanzania have favorable solar irradiation values, often between 1,800 and 2,000 kWh/m² annually [22]. The Lake Turkana Wind Power project in Kenya, although mostly wind-driven, enhances solar endeavors by using the area's many renewable resources. Moreover, off-grid solar solutions are swiftly gaining popularity in rural regions, delivering crucial energy access in the absence of conventional grid infrastructure [66].

3.1.2 *Fluctuations and Seasonal Patterns*

Although average yearly sun irradiance levels provide a valuable summary, it is crucial to account for seasonal fluctuations [67]. Regions near the equator, such as Uganda and Ghana, have generally stable sun irradiance year-round, with maximum insolation occurring during the dry season. Conversely, North Africa exhibits more significant seasonal fluctuations, characterized by substantial decreases in irradiance throughout the winter months, potentially affecting energy production [52].

3.1.3 Novel Solutions and Technologies

Progress in solar technology is making the exploitation of Africa's solar potential more viable, irrespective of regional variations in irradiance. Bifacial solar panels, capable of harnessing sunlight from both sides, are gaining popularity in areas with high reflectivity, such as sandy or snowy landscapes. Initiatives such as the 100 MW Solar Park in Ajaokuta, Nigeria, are using these technologies to optimize energy collection in regions with fluctuating irradiance levels [52].

Furthermore, solar energy storage systems are being included in projects to mitigate the intermittency of solar power output [68], guaranteeing a reliable energy supply during times of insufficient sunshine [69]. The integration of solar power production with battery storage devices may substantially improve energy dependability [70], especially in distant and off-grid regions.

3.2 Potential for Decentralized Off-Grid Solutions in Rural Areas

Africa has considerable obstacles in energy accessibility, especially in rural regions, making localized off-grid solar solutions a revolutionary possibility [71]. These solutions may mitigate the energy deficit by delivering dependable [72] and sustainable power to places often neglected by national grid infrastructure [73]. The potential for decentralized solutions is vast, with several creative models and efforts already exhibiting success around the continent [74].

3.2.1 The Necessity for Decentralized Solutions

Approximately 600 million individuals in Africa are deprived of electricity, with rural communities being disproportionately impacted [75]. Conventional grid expansion is often economically impractical in these regions owing to elevated costs and sparse population density. Consequently, decentralized off-grid solar systems have arisen as a viable option, providing localized energy production that can be customized to meet the distinct requirements of communities.

3.2.2 Innovative Models of Off-Grid Solutions

Solar Home Systems (SHS): Solar home systems have become more prevalent as a solution for supplying power to rural homes. These systems generally include solar panels, batteries, and appliances, enabling households to energize lights, phones, and other electronics. In Tanzania, firms such as M-KOPA have effectively executed a pay-as-you-go strategy for solar home systems, allowing families to get solar electricity without substantial initial expenses. As of 2021, M-KOPA has established connections to over 1 million households, illustrating the feasibility of this method [37].

Mini-Grids: Mini-grids, defined as small-scale energy systems capable of functioning autonomously or in tandem with the main grid, provide a viable alternative for rural electrification. In Kenya, the Kenya Power and Lighting Company has collaborated with private entrepreneurs to create mini-grids in distant regions, markedly

improving electricity accessibility. The Lake Turkana Wind Power project enhances existing initiatives by supplying supplementary renewable energy to local mini-grids, exemplifying a comprehensive strategy for energy access [2].

Community Solar Projects: Community solar efforts include collaborative investment in solar energy projects that serve local communities. The Solar for Schools initiative in Uganda has implemented solar systems in educational institutions, enabling schools to function as energy centers for adjacent communities. This method supplies power for illumination and educational initiatives while promoting community involvement and sustainability [37].

3.2.3 Obstacles and Considerations

The potential of decentralized off-grid solutions is considerable, although several problems must be resolved to optimize their effectiveness. Initially, regulatory regimes must endorse off-grid technology, ensuring that regulations promote rather than obstruct growth. Furthermore, funding methods must be readily available to both investors and consumers, since some rural families may find it challenging to finance early investments, even with novel payment arrangements.

Capacity development and training are crucial for ensuring the sustainability of these systems. Local experts must possess the capability to maintain and repair solar technologies to avert malfunctions and extend system longevity. Initiatives like as the Solar Market Development Group aim to provide training and resources for local entrepreneurs and technicians, cultivating a proficient workforce to facilitate off-grid solutions [2].

3.3 Recent Innovations in Photovoltaic (PV) Technology, Solar Thermal, and Storage Systems

The advancement of solar energy technology has been crucial in improving energy accessibility and sustainability in Africa. Recent advancements in photovoltaic (PV) technology, solar thermal systems, and energy storage technologies are revolutionizing solar energy implementation [76], enhancing its efficiency [77], affordability [78], and adaptability to the continent's distinct issues [79].

3.3.1 Progress in Photovoltaic (PV) Technology

Bifacial Solar Panels: A notable advancement in photovoltaic technology is the introduction of bifacial solar panels, which harness sunlight from both surfaces, hence increasing energy output substantially. These panels may produce 10–20% more power than conventional monofacial panels [80], especially in regions with elevated ground reflectance, like deserts. The Noor Ouarzazate Solar Complex in Morocco has used bifacial technology to enhance energy output from its CSP systems, illustrating the potential for increased efficiency in large-scale solar initiatives [4].

Building-Integrated Photovoltaics (BIPV): BIPV systems integrate solar panels into building materials, therefore converting buildings into energy producers. This invention is especially pertinent in urban environments where space is constrained. Initiatives such as the Green Roof Initiative in South Africa have effectively implemented BIPV systems that produce electricity while enhancing building aesthetics and energy efficiency [37].

Perovskite Solar Cells: Perovskite materials have emerged as a transformative substitute for conventional silicon-based solar cells, providing superior efficiency rates at

reduced manufacturing costs. Research organizations in South Africa and Kenya are investigating perovskite technology for use in residential and commercial applications. Preliminary field experiments suggest that these cells may attain efficiencies above 25%, positioning them as a viable alternative for the future of solar energy in Africa [3].

3.3.2 *Advancements in Solar Thermal Systems*

Solar thermal systems capture sunlight to produce heat, used for power production or direct heating purposes. Recent advancements encompass:

Concentrated Solar Power (CSP): CSP technology uses mirrors or lenses to focus sunlight into a confined area, creating heat that may create steam for power production. The Crescent Dunes Solar Energy Project in Nevada, although not located in Africa, exemplifies a prototype for forthcoming CSP initiatives in the area. The system is capable of storing thermal energy for use during periods without sunlight, ensuring a dependable energy source [81]. African initiatives, exemplified by Morocco's Noor III, are using thermal storage to improve grid stability and reduce dependence on fossil fuels.

Sun Water Heating: Solar water heating systems have gained significant popularity for residential and commercial use, especially in nations with elevated sun irradiation. The usage of solar water heaters in Kenya has increased markedly, boosted by government incentives and domestic production. This method diminishes dependence on electricity for heating and minimizes family energy expenses, making it a feasible choice for rural populations [75]

3.3.3 *Innovations in Energy Storage*

The amalgamation of energy storage systems with solar technology is essential for mitigating the intermittency of solar energy. Recent developments encompass:

Lithium-Ion Batteries: The reduction in prices and improvements in the efficiency of lithium-ion batteries have made them a preferred option for solar energy storage. Initiatives around Africa, such as the SolarHome project in Uganda, are deploying solar-plus storage systems to provide dependable electricity for residences. These systems enable consumers to retain surplus energy produced throughout the day for nocturnal use, hence significantly improving energy accessibility [48].

Flow Batteries: Flow battery technology, which provides extended discharge durations and enhanced scalability compared to traditional batteries, is attracting interest for large-scale solar initiatives. In South Africa, enterprises are investigating the incorporation of flow batteries with renewable energy systems to enhance grid support and stabilize electricity supply [48]. These systems may also exhibit more sustainability, since they use available materials and provide simple recycling.

Hybrid Systems: Hybrid systems integrating several storage technologies, including lithium-ion batteries and pumped hydroelectric storage, are being developed to enhance energy management. Hybrid systems are being evaluated in locations such as Lake Turkana, Kenya, to improve the dependability of wind and solar energy, hence offering a holistic solution for renewable energy storage [48].

3.4 Case Studies of Successful Solar Energy Projects in Africa

Africa is seeing a fast proliferation of solar energy projects, with several significant efforts showcasing the capacity of solar technology to enhance energy accessibility and promote sustainable development. This section emphasizes significant case studies, such as Morocco's Noor Ouarzazate Solar Complex and Egypt's Benban

Solar Park, illustrating creative methodologies, technical progress, and insights gained [48].

3.4.1 Noor Ouarzazate Solar Complex in Morocco

The Noor Ouarzazate Solar Complex, situated in Ouarzazate, is among the biggest solar power installations globally. The complex covers more than 3,000 hectares and incorporates both photovoltaic (PV) and concentrated solar power (CSP) technologies, achieving a total capacity of 580 MW [48].

Technology and Innovation: The complex has three primary phases: Noor I, Noor II, and Noor III. Noor I, completed in 2016, employs concentrated solar power (CSP) technology with parabolic troughs and thermal storage, enabling electricity provision during periods of little sunshine. Noor III, active since 2020, has a central tower concentrated solar power architecture, improving efficiency and storage capacity [75].

Impact: The complex is anticipated to provide clean energy to more than 1.1 million individuals and diminish carbon emissions by around 760,000 tons per year. It is integral to Morocco's objective of sourcing 52% of its energy from renewable resources by 2030 [49].

Economic and Social Benefits: The project has created thousands of employment opportunities throughout its building and operational phases, hence fostering local economic growth. It functions as a teaching center for renewable energy technology, cultivating local proficiency [52].

3.4.2 Benban Solar Park in Egypt

The Benban Solar Park, situated in the Aswan Governorate of Egypt, is among the biggest solar parks worldwide, with a total capacity of 1.8 GW [52]. Covering 37 square kilometers, it comprises several solar initiatives undertaken by different firms [52].

Technology and Innovation: The park primarily employs utility-scale photovoltaic technology, using sophisticated solar panels and inverters to optimize efficiency. The Egyptian government promoted investments by simplifying regulatory procedures and offering a feed-in tariff, therefore attracting substantial foreign and domestic investment [52].

Impact: Benban is projected to produce around 2 billion kWh of energy per year, providing power to nearly 1 million homes. The initiative seeks to diminish Egypt's dependence on fossil fuels, supporting a national objective of producing 20% of power from renewable sources by 2022 [52].

Community Engagement and Benefits: The project has promoted community participation via local collaborations, guaranteeing that local people benefit from employment opportunities and energy accessibility. The Benban Solar Park has built a specialized training facility to improve local workforce competencies in solar technology [52].

3.4.3 Additional Significant Projects

Kisii Solar Initiative, Kenya: This groundbreaking initiative seeks to provide electricity to more than 60,000 residences with a blend of solar photovoltaic technology and energy storage systems [52]. The project delivers sustainable energy while prioritizing community involvement via the creation of local cooperatives that oversee the solar systems [5].

Scaling Solar Program, Ghana: The Scaling Solar Program in Ghana includes the establishment of several solar photovoltaic plants around the country, promoting private sector investment and fostering competitiveness. The initiative has resulted in a substantial decrease in solar energy expenses, illustrating the feasibility for widespread use of solar technology [52].

3.5 Current Policy Incentives for Solar Energy in Africa

Policy frameworks are essential for facilitating the uptake and integration of solar energy across Africa. Diverse incentives, such as feed-in tariffs (FiTs), subsidies, and tax incentives, have been established to promote investment in solar technology [52]. This sub-section analyzes the existing policy incentives in various African nations, highlighting unique instances and their effects for solar energy advancement.

3.5.1 Feed-in Tariffs (FiTs)

Feed-in tariffs have served as a prevalent technique for promoting renewable energy investments by ensuring guaranteed remuneration for energy providers over a designated duration. These tariffs provide income predictability for investors and may substantially mitigate the financial risks linked to solar projects.

South Africa: The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) uses Feed-in Tariffs (FiTs) to facilitate extensive solar initiatives. Initiated in 2011, the initiative has garnered over \$14 billion in investments and enabled the building of more than 6,000 MW of renewable energy capacity, including notable contributions from solar photovoltaic systems [52]. The competitive bidding procedure has reduced prices, with recent rounds attaining pricing of \$0.03 per kWh [52].

Kenya: The Feed-in Tariff (FiT) program established in 2008 has stimulated investments in renewable energy, particularly solar energy. The Kenyan government created a pricing framework that ensures developers get certain compensation for energy produced by solar power facilities. This methodology has catalyzed initiatives like the 50 MW Garissa Solar Power Plant, the biggest in East and Central Africa [52].

3.5.2 Financial Assistance and Endowments

Direct subsidies and incentives for solar initiatives alleviate the initial financial load for developers and customers, enhancing the accessibility of solar energy.

Morocco: The Moroccan Agency for Sustainable Energy (MASEN) offers financial assistance for solar initiatives, especially for the Noor Ouarzazate Solar Complex. The government provides incentives to both domestic and foreign investors, promoting the development of extensive solar infrastructure. The Solar Plan seeks to provide access to economical solar water heaters via subsidies, hence increasing energy efficiency in residential areas [52].

Ethiopia: The Ethiopian government has implemented incentives for solar household systems to promote rural electricity. Initiatives such as the Ethiopia Renewable Energy Program (EREP) provide financial assistance to local producers and distributors, promoting the extensive use of solar technology. The government's dedication to attaining universal energy access by 2025 is significantly dependent on the efficacy of these subsidy schemes [52].

3.5.3 Fiscal Incentives and Additional Financial Instruments

Tax incentives may augment the appeal of solar investments, allowing developers to recover expenses more rapidly. The Ghanaian government has instituted several tax exemptions for renewable energy initiatives, including VAT exemptions on solar equipment and components. The Ghana Renewable Energy Act enables power purchase agreements (PPAs) that permit private sector involvement in renewable energy production, fostering a conducive investment environment [52].

The Nigerian government has implemented financial incentives for solar producers, which include exemptions from import duties on solar panels and related equipment. The Renewable Energy Master Plan delineates methods for incorporating renewable energy sources into the national grid, accompanied by financial incentives aimed at attracting both domestic and international investments in the solar industry [52].

3.5.4 Novel Financial Frameworks

Innovative finance approaches, such as pay-as-you-go (PAYG) systems, are transforming the solar energy access scenario in Africa. These versions enable users to utilize solar technology with few initial expenses.

Pay-as-You-Go Solar: Enterprises such as M-KOPA in Kenya and Lumeter in Nigeria have innovated PAYG models, allowing low-income people to acquire solar home systems via economical daily or weekly installments. This novel financing strategy has significantly enhanced solar adoption in off-grid regions, benefiting millions of families across the continent [52].

4. Wind Energy Potential and Progress in Africa

4.1 Examination of Wind Resources Throughout African Regions

Wind energy has become an essential element of Africa's renewable energy sector since the continent has substantial wind resources that remain mostly unexploited. This sub-section analyzes the distribution and potential of wind resources in many African locations, including coastal and highland areas, phasing unique instances and pertinent data.

4.1.1 Maritime Zones

African coastal areas are often characterized by stable and strong wind patterns owing to their closeness to extensive water bodies. These regions are optimal for wind energy production, with substantial potential for both onshore and offshore wind farms.

North Africa: The coastal regions of Morocco, especially next to the Atlantic Ocean, have exceptional wind resources. The Tarfaya Wind Farm, among the biggest in Africa, has an installed capacity of 301 MW and capitalizes on the region's advantageous wind velocities, which range from 7 to 9 m/s [52]. This project has substantially enhanced the country's energy portfolio and established a standard for forthcoming wind energy initiatives in the area.

East Africa: The Lake Turkana Wind Power Project in Kenya has emerged as a flagship initiative, with 365 wind turbines with an aggregate capacity of 310 MW [52]. Wind velocities in the region often surpass 8 m/s, establishing it as one of the premier sites for wind energy production in Africa [52]. The project's results have significantly improved Kenya's energy supply and fostered economic growth in the area.

West Africa: The coastal areas of Ghana have significant potential for wind energy. The Aboadze Wind Farm, now in the development phase, is anticipated to use the region's typical wind speeds of around 6 to 7 m/s. This initiative seeks to diversify Ghana's energy portfolio and reduce dependence on fossil fuels [52].

4.1.2 Highland Regions

Elevated regions in Africa often encounter robust and persistent winds attributable to their altitude and topographical characteristics. These areas are especially conducive to wind energy production.

Ethiopia: The Ashegoda Wind Farm, situated in the Ethiopian Highlands, exemplifies the use of highland wind resources. Possessing an installed capacity of 120 MW, it capitalizes on average wind speeds above 7.5 m/s [52]. This initiative is integral to Ethiopia's comprehensive plan to enhance renewable energy production and decrease carbon emissions [52].

South Africa: The Gansbaai Wind Farm, situated in the Western Cape, utilizes the area's robust winds, which average around 8 m/s. With a capacity of 138 MW, it illustrates the potential of highland regions in South Africa to further the nation's renewable energy objectives. The initiative emphasizes the significance of local community engagement and advantages [52].

4.1.3 Assessment of Regional Wind Resources

Wind resource evaluations across Africa demonstrate diverse potentials shaped by regional meteorological and topographical factors.

Wind Resource Maps: The African Wind Atlas, created by the World Bank and its collaborators, offers extensive data on wind velocities and patterns across the continent. Assessments reveal that areas in Northern Africa, especially Algeria and Tunisia, provide significant potential for wind energy production, with average wind speeds between 7 and 9 m/s [49].

Potential for Offshore Wind: The coastal areas of South Africa and Mauritius have been recognized as viable locations for the development of offshore wind energy. The Mossel Bay Offshore Wind Project seeks to use the wind potential along South Africa's coastline, with research suggesting advantageous conditions for offshore turbines [50].

4.1.4 Obstacles and Factors

Despite the abundant wind resources across Africa, certain problems persist that may impede the advancement of wind energy initiatives.

Infrastructure and Investment: Numerous places are deficient in the requisite infrastructure to facilitate large-scale wind energy initiatives, including transmission lines and access roads. Furthermore, securing funding continues to be a concern, especially in underdeveloped regions [52].

Policy and Regulatory Frameworks: Inconsistent policies and regulatory obstacles may impede investment in wind energy. Countries with well-defined and supporting frameworks, such as Morocco and Kenya, have had more accelerated growth than those with less established regulations [53].

4.2 Targeted Case Studies of Nations with Significant Wind Energy Potential

Wind energy has become a feasible and sustainable power source in several African nations, particularly in Kenya and South Africa. This sub-section provides detailed case studies of these nations, emphasizing their wind energy potential, successful initiatives, and the insights gained from their growth.

4.2.1 Kenya: A Pioneer in Wind Energy

Kenya is seen as a leader in wind energy production in Africa, mostly because of its advantageous meteorological circumstances and strong governmental regulations.

4.2.1.1 Lake Turkana Wind Power Project: Situated in northern Kenya, the Lake Turkana Wind Power Project is among Africa's biggest wind farms with an installed capacity of 310 MW [53]. The project commenced operations in 2018, with 365 turbines, and has substantially improved Kenya's energy supply, contributing around 15% of the nation's power [52].

Innovative Financing and Partnerships: The initiative was established via a public-private partnership with financing obtained from a consortium of foreign investors, including the African Development Bank. The financing plan included a combination of equity and debt, illustrating the feasibility of joint finance strategies in extensive renewable initiatives [52].

Socioeconomic Impact: The project has generated more than 1,500 jobs during construction and continues to provide employment opportunities for local communities via continuing maintenance and operations. It has also enhanced local infrastructure, including roads and communication networks, so contributing to regional growth [1].

Wind Resource Assessment: Kenya's wind energy potential is estimated at 7,000 MW, with the best locations found in the Central and Eastern highlands [1]. The Kenya National Wind Atlas, created by the Kenya Meteorological Department, offers comprehensive evaluations of wind velocities and orientations, facilitating the design and implementation of forthcoming projects [54].

4.2.2 South Africa: Utilizing Coastal and Highland Winds

South Africa has achieved considerable progress in wind energy production, using its varied wind resources across coastal and interior areas.

Gansbaai Wind Farm: Situated in the Western Cape, Gansbaai Wind Farm exemplifies the effective use of wind energy in South Africa. This project has an installed capacity of 138 MW and harnesses the region's strong coastal winds, averaging around 8 m/s [54]. The wind farm produces over 400 GWh of power each year, aiding the nation's renewable energy objectives [1].

Integration with the National Grid: The project is linked to the national grid, and its production is sold to the state utility, Eskom, under a Power Purchase Agreement (PPA). This structure ensures financial certainty for project developers and aids in stabilizing the national energy supply [1].

Community Involvement: The Gansbaai Wind Farm integrates community development initiatives designed to improve local lives. Initiatives include skills training for people, which has enabled local individuals to get jobs in the renewable energy industry [1].

4.2.3 Principal Insights and Prospective Opportunities

Kenya and South Africa provide significant insights on the efficient development of wind energy resources in Africa.

Robust Policy Frameworks: The efficacy of wind energy initiatives in these nations may be ascribed to favorable policies and regulatory structures that promote investment. Feed-in tariffs and competitive bidding mechanisms have been essential in securing private sector participation.

Innovative Financial Models: The use of blended financing and public-private partnerships has shown efficacy in attracting funding for extensive wind projects. Future advancements may derive advantages from emulating these approaches, especially in nations with nascent wind potential.

Community Engagement: Involving local communities and guaranteeing their benefits from wind projects is crucial for promoting acceptability and sustainability. Successful projects have included local development activities, yielding socio-economic advantages in conjunction with renewable energy production.

4.3 Technological Innovations in Wind Turbine Efficiency and Hybrid Systems

The progression of wind energy technology has been crucial in improving the efficiency and dependability of wind power production across Africa. Recent advancements in turbine design, materials, and hybrid systems are establishing new standards in performance and sustainability, enhancing the accessibility and efficacy of wind energy. This sub-section analyzes significant technical progress in wind turbine efficiency and the incorporation of hybrid systems in the African setting.

4.3.1 Improved Wind Turbine Efficiency

Contemporary wind turbines have seen substantial modifications to enhance their efficiency and energy production. Significant progress encompasses:

Aerodynamic Blade Design: Recent advancements in blade technology have produced elongated and lighter blades capable of harnessing more wind energy. Siemens Gamesa's SG 14-222 DD turbine is equipped with blades exceeding 108 meters, allowing for efficient operation in low wind situations [54]. These advancements enhance the capacity factor, enabling turbines to produce more power from the same wind resource.

Variable Speed Technology: Variable speed turbines may modify their rotor velocity in response to wind conditions, hence enhancing performance across various wind speeds. This method reduces degradation of turbine components, hence prolonging their operating lives. The Vestas V150-5.6 MW turbine utilizes variable speed technology to optimize energy collection and improve dependability in diverse wind conditions [38].

Smart Turbine Systems: The amalgamation of IoT and sophisticated analytics has resulted in "smart" wind turbines that use real-time data to enhance performance. These systems can analyze wind patterns and modify turbine operations appropriately, markedly enhancing overall efficiency. GE Renewable Energy's digital wind farm technology employs predictive analytics to enhance turbine performance and minimize downtime [38].

4.3.2 Hybrid Energy Systems

The integration of wind energy with other renewable sources, especially solar electricity, is progressively acknowledged as a means to improve energy security and stability.

Wind-Solar Hybrid Systems: Hybrid systems may enhance energy output by using the synergistic characteristics of wind and solar resources. In South Africa, the

Redstone Solar Thermal Power Project is being constructed to combine solar thermal energy with existing wind farms. This method facilitates a more reliable electricity supply, especially during intervals of diminished wind power [1].

Battery Storage Integration: Integrating energy storage devices with wind farms helps mitigate the intermittency inherent in wind energy. Initiatives such as the Hornsdale electricity reserve in Australia exemplify the efficacy of integrating wind energy with battery storage to enhance grid stability and provide dispatchable electricity. This technique may be duplicated in Africa to improve the dependability of wind energy systems [2].

Case Study: Kenya's Hybrid Systems: The Lake Turkana Wind Power Project in Kenya is investigating the viability of combining wind energy with battery storage to improve grid stability and tackle energy access issues. The project seeks to enhance energy security and diminish dependence on fossil fuels by integrating wind power with energy storage to provide a more steady electricity supply to distant regions [1].

4.3.3 *Advancements in Materials and Production*

Advancements in materials science and manufacturing methods are enhancing wind turbine efficiency.

Lightweight Composites: The use of sophisticated composite materials in turbine blades has produced lighter, stronger, and more resilient constructions. New materials, like carbon fiber composites, are being used in turbine construction, improving performance and decreasing total weight [22].

3D Printing Technologies: The use of 3D printing in the fabrication of turbine components may decrease production expenses and duration. This method enables quick prototyping of turbine components, promoting advancements in design and efficiency. Companies such as Siemens Gamesa are investigating 3D printing for the production of intricate components, resulting in diminished material waste and enhanced performance [22].

4.4 Effective Wind Energy Initiatives and Their Effects

Wind energy initiatives around Africa are revolutionizing the energy sector, promoting economic advancement, enhancing energy security, and encouraging community involvement. This sub-section examines two significant projects: the Lake Turkana Wind Power Project in Kenya and the Roggeveld Wind Farm in South Africa, focusing on their achievements and effects on local populations and national energy policies [22].

4.4.1 *Lake Turkana Wind Power Initiative, Kenya*

The Lake Turkana Wind Power Project (LTWP) is the biEffects on Local Communities with an installed capacity of 310 MW [22]. Located in the desert northern region of Kenya, the project utilizes the robust and steady winds of the area, considerably enhancing the nation's renewable energy portfolio.

Project Overview: Initiated in 2018, LTWP consists of 365 turbines and is designed to produce around 1,230 GWh of power each year [22]. It provides around 15% of Kenya's energy requirements, contributing to the stabilization of the national system [22].

Economic Impacts: The project has yielded significant economic advantages, producing over 1,500 jobs during construction and establishing sustained employment for

local inhabitants in operations and maintenance. It has also stimulated local company expansion, with service providers and suppliers reaping benefits from the surge in economic activity [66].

Community Engagement: LTP has instituted community development initiatives centered on education, healthcare, and infrastructure. Initiatives include the establishment of educational institutions and healthcare facilities and investments in potable water supply systems, markedly improving the quality of life for local residents [52].

Environmental Considerations: The project was conceived with a focus on environmental sustainability. The initiative includes monitoring activities to evaluate and alleviate effects on local wildlife, demonstrating a dedication to responsible energy development.

4.4.2 Roggeveld Wind Farm, South Africa

The Roggeveld Wind Farm, situated in the Western Cape, is a significant renewable energy project in South Africa, aiding the nation's shift towards a sustainable energy future.

Project Overview: Roggeveld, with an installed capacity of 147 MW, consists of 47 turbines and produces around 400 GWh of energy annually, sufficient to provide power to over 120,000 homes. It is integral to the South African government's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) [52].

Economic Impacts: The wind farm has generated employment throughout the building phase and continues to provide work possibilities in operations and maintenance. Moreover, Roggeveld has facilitated local economic growth via community involvement activities that bolster local enterprises [52].

Community Benefits: Roggeveld has established a Community Development Programme that allocates resources to local education, skills training, and infrastructure initiatives. The initiative provides funds for local schools and technical training institutes, therefore equipping citizens with essential skills for the renewable energy industry [52]. The project integrates sophisticated environmental management strategies, including avian and chiropteran monitoring to alleviate effects on indigenous animals. Roggeveld is linked to South Africa's national grid, enabling the incorporation of renewable energy sources and enhancing grid stability [66].

4.5 Evaluation of the Economic viability of wind energy relative to fossil fuels

As Africa pursues sustainable energy options, it is essential to comprehend the economic viability of wind energy in comparison to fossil fuels. This sub-section analyzes the cost dynamics, investment patterns, and overall economic effects of wind energy in comparison to conventional fossil fuel sources, emphasizing creative instances and current data.

5. Hydropower as a Cornerstone of Africa's Renewable Energy Future

5.1 Geographical Examination of River Basins and Prospects for Large-Scale Hydropower

Africa has extensive river systems, many of which have significant opportunities for large-scale hydropower generation. The river basins, located across the continent, provide significant potential to use clean, renewable energy that might propel Africa's

energy revolution and economic development. This section presents a thorough geographical study of significant African river basins, examines their hydropower potential, and showcases creative examples of existing and forthcoming projects.

5.1.1 The Congo River Basin: Africa's Most Extensive Hydropower Resource

The Congo River Basin, the world's second-largest river basin behind the Amazon, is the most substantial hydroelectric potential in Africa. Spanning over 3.7 million square kilometers, it extends across Central Africa, with the Democratic Republic of the Congo (DRC) reaping the most benefits from its potential.

The Grand Inga Dam project on the Congo River, once completed, will be the biggest hydroelectric plant in the world, with an anticipated capacity of 40,000 MW [49]. This capacity exceeds that of China's Three Gorges Dam. It is conceived as a continental energy solution capable of providing power to many African nations, including South Africa, Nigeria, and Egypt. If completely realized, Grand Inga may provide electricity to around 500 million people across the continent [49].

The Grand Inga project has exceptional energy potential; however, it also elicits apprehensions over environmental and societal repercussions. The building of large-scale dams in environmentally sensitive regions may harm local ecosystems and displace populations.

5.1.2 The Nile River Basin: A Historic Artery with Hydropower Capability

The Nile River, the longest river in Africa, traverses eleven nations, including Egypt, Sudan, Ethiopia, and Uganda. The river's importance as a water supply and economic resource for millions is widely recognized, and its hydroelectric potential is substantial.

The Grand Ethiopian Renaissance Dam (GERD), a significant hydropower initiative in Africa, is located on the Blue Nile in Ethiopia and is projected to provide over 6,000 MW of energy upon its completion [49]. The Grand Ethiopian Renaissance Dam (GERD) is fundamental to Ethiopia's energy plan, aimed at electrifying urban and rural regions while facilitating power exports to neighboring nations such as Sudan and Kenya. Notwithstanding political problems with downstream nations, the project signifies a significant advancement in augmenting Africa's renewable energy producing capability [49].

Transboundary Water Management: The Nile traverses many nations, presenting geopolitical obstacles to hydropower development in this area. Collaborative management of the river's resources is crucial to reconcile energy production with agricultural and potable water requirements. Organizations such as the Nile Basin Initiative have been instrumental in promoting cooperation and preventing discord among the nations of the Nile Basin [50].

5.1.3 The Zambezi River Basin: The Hydropower Engine of Southern Africa

The Zambezi River, traversing eight nations such as Zambia, Zimbabwe, Mozambique, and Angola, has significant opportunities for extensive hydropower production. Its geographical extent encompasses Southern and Central Africa, making it an essential energy conduit for the area.

The Kariba Dam, situated on the Zambezi River, has been in operation since the 1950s and is one of Africa's greatest hydroelectric facilities, with a capacity exceeding 1,800 MW [52]. Nevertheless, recent initiatives like the Batoka Gorge Hydropower

Station, which aims to produce around 2,400 MW, exemplify the continuous endeavors to harness the whole potential of the Zambezi. The Batoka Gorge project is a collaborative effort between Zambia and Zimbabwe, highlighting the significance of transnational collaboration in using river resources [52].

The Zambezi Basin is susceptible to climate change, with variations in precipitation patterns directly affecting river flow and hydropower generation. Experts recommend hybrid energy solutions that integrate hydropower with solar and wind to enhance the resilience of the electricity grid [52].

5.1.4 The Niger River Basin: The Developing Hydropower Center of West Africa

The Niger River, traversing nine nations in West Africa, has considerable unexploited potential for hydropower generation. In a region with severe energy poverty, the basin, which spans over 2.1 million square kilometers, has significant potential for extensive renewable energy development [52].

The Kainji and Jebba Dams: Nigeria, the most populous nation in West Africa, derives electricity from the Kainji and Jebba dams located on the Niger River. Collectively, these plants possess a total capacity of over 1,300 MW, serving as an essential source of power for the nation. There exists significant potential for the expansion of hydropower production in the area, including projects in Mali and Niger [66].

Although large-scale projects prevail in discussions, there is an increasing focus on small and medium hydropower facilities within the Niger River Basin. These initiatives provide a decentralized approach to electrifying rural regions when grid expansion is not financially viable. Mini-hydropower plants, with capacities between 1 MW and 30 MW, may provide dependable energy to isolated areas, fostering local development [52].

5.2 The Function of Small- and Micro-Hydropower Systems in Rural Electrification

Small- and micro-hydropower systems are essential to Africa's renewable energy future, especially regarding rural electrification. Although large-scale hydropower initiatives like the Grand Inga Dam and Grand Ethiopian Renaissance Dam are frequently emphasized for their substantial generation capabilities, small- and micro-hydropower systems present a more attainable, decentralized alternative for supplying energy to remote and underserved populations. This sub-section examines the potential, advantages, and innovative illustrations of small- and micro-hydrophone systems in Africa, as well as their contribution to alleviating energy poverty and fostering sustainable development.

5.2.1 The Promise of Small- and Micro-Hydropower Systems

Small- and micro-hydropower systems use electricity from rivers, streams, and waterfalls while minimizing infrastructure and environmental impact. These systems generally possess the following power producing capacities: Small Hydropower (SHP): Generally, varies from 1 MW to 10 MW, and Micro Hydropower (MHP): Produces less than 1 megawatt of energy. Africa has several underutilized minor rivers and streams that are appropriate for these systems, particularly in remote regions where expanding the national grid is logistically and financially impractical. The International Renewable Energy Agency (IRENA) asserts that small-scale hydropower can provide electricity to

millions of households across the continent, especially in hilly and water-abundant areas like East Africa and some sections of Central and West Africa [52].

5.2.2 Small- and Micro-Hydropower as a Decentralized Energy Solution

In rural regions without solid national grid infrastructure, small- and micro-hydropower plants provide an off-grid electricity alternative. These systems are decentralized, allowing for installation at the point of use, hence eliminating the need for vast transmission lines and infrastructure.

The Rufiji River Basin in Tanzania exemplifies decentralized microhydropower, where local communities use micro-hydropower systems to provide electricity to residences, educational institutions, and healthcare facilities. These projects, with capacities between 20 kW and 100 kW, have facilitated energy access for thousands, resulting in better quality of life, economic prospects, and expanded health services [52].

Nepal's micro-hydropower model in Africa: Nepal has historically excelled in micro-hydropower development, and its framework is being modified for rural electrification initiatives in several regions of Africa. In Ethiopia, local microhydropower initiatives modeled after the Nepalese system are being executed to provide clean and dependable electricity to off-grid people in hilly areas. These initiatives are both economically viable and ecologically sustainable, reducing dependence on biomass for cooking and lighting [52].

5.2.3 Advantages of Small- and Micro-Hydropower Systems on Economic and Social Fronts

The implementation of small- and micro-hydropower systems provides several advantages for rural electrification. These include economic expansion, enhanced living standards, and ecological sustainability.

Local Development and Job Creation: Small- and micro-hydropower projects frequently use local labor to build and maintain them, providing significant job opportunities in rural areas. The Mwenga Hydro Project in Tanzania utilizes local engineers and technicians for the operation and maintenance of the systems, therefore enhancing local capacity and technical expertise. The produced energy has bolstered small enterprises and agricultural processing, facilitating local economic growth [66].

Cost-effectiveness and sustainability: These systems are comparatively cheap to install and maintain relative to large-scale initiatives, making them accessible to rural populations with constrained financial resources. Local cooperatives in Uganda have established a network of micro-hydropower systems, supported by money from development organizations. This network has augmented energy accessibility for numerous families, alleviating energy poverty and boosting production in rural regions [52].

Social Impact: Electrification using small- and micro-hydropower has significant social effects, particularly in isolated regions. It enhances access to education and healthcare by energizing schools and clinics, reduces dependence on detrimental kerosene lamps for illumination, and supplies clean energy for cooking, therefore mitigating deforestation and indoor air pollution. Women and children, often responsible for collecting firewood in rural African communities, get substantial advantages from the clean energy transition [49].

5.2.4 Innovative Examples of Small- and Micro-Hydropower Systems

Numerous pioneering initiatives illustrate the efficacy and scalability of small- and micro-hydropower systems across Africa. The Kakira Sugar Works in Uganda has implemented an innovative small hydropower system using the irrigation canals of its sugar plantation. The system produces 22 MW of energy, supplying power to the sugar mill and adjacent towns. This project exemplifies the integration of renewable energy into agricultural sectors, enabling the provision of excess energy to adjacent rural communities [49].

The Tungu-Kabiri Micro-Hydro Power Project in Kenya, backed by the Practical Action group, established a micro-hydro system that produces 20 kW of energy, supplying power to 200 families [49]. This project is distinctive since it was collaboratively designed with the local community, which had an active role in the construction of the plant. Consequently, there exists a strong feeling of ownership, with the community independently overseeing the functioning and upkeep of the system. This participatory method is regarded as a best practice example for other rural regions.

Rwanda's Rukarara Hydropower Plant: Rwanda has innovatively implemented small- and mini-hydropower facilities to enhance rural electricity. The Rukarara hydropower plant, with a capacity of 9.5 MW, has played a crucial role in Rwanda's rural electrification initiative [50]. The produced electricity serves adjacent rural regions, including educational institutions and healthcare facilities, enhancing social services and economic endeavors [49].

5.3 Policies and Frameworks to Mitigate Negative Environmental Impacts

The African continent's advancement in renewable energy needs strong legislative frameworks to mitigate negative environmental impacts due to the fast implementation of solar, wind, and hydroelectric projects. Efficient governance and environmental regulation are crucial to harmonize the imperative of clean energy production with the safeguarding of ecosystems, biodiversity, and local populations. This section examines current regulations and frameworks designed to alleviate the environmental effects of renewable energy initiatives in Africa while emphasizing creative strategies and successful case studies.

5.3.1 National Environmental Impact Assessment (EIA) Regulations

Environmental Impact Assessments (EIAs) are essential instruments for regulating the ecological repercussions of energy initiatives. Numerous African nations have instituted Environmental Impact Assessments (EIAs) as a prerequisite for the licensing of renewable energy projects, guaranteeing that possible environmental hazards are discovered, evaluated, and addressed prior to the commencement of construction.

South Africa's Environmental Impact Assessment Regulations: As a frontrunner in renewable energy implementation, South Africa has established one of the most extensive EIA frameworks in Africa. The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) mandates that all projects complete comprehensive Environmental Impact Assessments (EIAs) to evaluate the environmental and social hazards linked to energy development. The initiative has resulted in the production of almost 6 GW of renewable energy while upholding rigorous environmental protections [52]. This included initiatives to save delicate habitats like Karoo and Namaqualand, which host rare and unique species.

Kenya's EIA Guidelines: Kenya, a significant participant in Africa's renewable energy sector, has instituted EIA mandates for energy projects under its Environmental

Management and Coordination Act (EMCA). This legislation mandates that initiatives like the Lake Turkana Wind Project and the Garissa Solar Power Plant include environmental evaluations to mitigate biodiversity effects and address the displacement of local populations [52]. Assessments often result in the development of Environmental Management Plans (EMPs), which mandate continuous environmental monitoring and mitigation measures during and after construction.

5.3.2 Incorporation of Strategic Environmental Assessments (SEAs)

While Environmental Impact Assessments (EIAs) concentrate on specific projects, Strategic Environmental Assessments (SEAs) provide a more extensive review of possible environmental implications at a regional or sectoral scale. SEAs are especially efficacious in nations where the growth of renewable energy is intended throughout extensive geographical regions, such as solar farms in arid areas or wind projects along shorelines.

Morocco's Strategic Environmental Assessments for Solar Projects: Morocco, recognized for its Noor Ouarzazate Solar Complex, has used SEAs to effectively manage the environmental hazards associated with large-scale solar initiatives in its desert areas. The Strategic Environmental Assessment for solar development in the Saharan Desert assessed effects on biodiversity, water resources, and land use. Consequently, the government implemented steps to safeguard vulnerable regions while advancing renewable energy [52]. This progressive policy strategy has enabled Morocco to emerge as a leader in solar energy while preserving its distinctive ecosystems.

Zambia's hydroelectric Strategic Environmental Assessments: In Zambia, Strategic Environmental Assessments have been used to evaluate the environmental consequences of several hydroelectric initiatives proposed along the Zambezi River. The SEA guarantees that specific dam initiatives, like the Batoka Gorge Dam, are executed with regard to the cumulative environmental impacts on the river ecosystem and adjacent communities [52]. This procedure alleviates downstream consequences, such as diminished water flow, which might affect agriculture and biodiversity.

5.3.3 Global Environmental Agreements and Climate Frameworks

Africa's shift to renewable energy is increasingly regulated by international environmental and climatic frameworks that advocate for sustainable development and mitigate environmental deterioration. These frameworks provide criteria and benchmarks for energy projects, guaranteeing adherence to international sustainability standards. African countries have pledged to diminish greenhouse gas emissions by enhancing their renewable energy capacity in accordance with environmental sustainability under the Paris Climate Agreement. Ethiopia, South Africa, and Egypt have included renewable energy initiatives within their Nationally Determined Contributions (NDCs), which delineate national approaches to emission reduction and ecosystem preservation [52]. Ethiopia's Grand Renaissance Dam is seen as a crucial element of its NDCs, while the government has pledged to mitigate adverse environmental effects by following international best practices in dam development and operation.

The Equator Principles for Renewable Energy Financing is a risk management approach used by financial institutions to identify, evaluate, and mitigate environmental and social risks in projects. Numerous renewable energy initiatives in Africa, particularly those funded by foreign banks and development groups, are required to adhere to the Equator Principles. This guarantees that projects are subjected to environmental and

social risk evaluations, including comprehensive environmental management strategies to alleviate effects on ecosystems and communities [52]. This is especially pertinent in extensive projects such as the Inga III Dam in the Democratic Republic of Congo and the Lake Turkana Wind Farm in Kenya.

5.4 Harmonizing Hydropower with Climate Resilience: Effects of Drought and Climate Variability on Hydroelectric Production

Hydropower is fundamental to renewable energy initiatives across Africa, playing a substantial role in the continent's energy composition. Nevertheless, Africa's dependence on hydropower confronts an escalating challenge: climate change. Erratic precipitation patterns, extended droughts, and altered river flows, all influenced by climate variability, are affecting the dependability and sustainability of hydroelectric power production. This section analyzes the intricate equilibrium between hydropower development and climate resilience, emphasizing measures to alleviate the detrimental impacts of climate change while preserving the viability of hydropower as a principal energy source.

5.4.1 *Susceptibility of Hydropower to Climate Change*

Hydropower facilities rely on stable water flows for energy generation. In Africa, where many rivers are nourished by precipitation and glacier melt, the effects of climate change are becoming more apparent. Areas formerly characterized by predictable hydrological cycles are increasingly encountering fluctuations in water levels, jeopardizing the operating efficiency of current hydroelectric dams and the viability of prospective developments.

Ethiopia's Grand Renaissance Dam (GERD) is the biggest hydroelectric initiative in Africa, capable of producing over 6,000 MW of energy [52]. The project is significantly reliant on water flows from the Blue Nile, which originate from the Ethiopian highlands. Climate change has started altering seasonal precipitation patterns, raising apprehensions about the dam's potential to function at optimal levels in the forthcoming decades. Research forecasts that heightened droughts and fluctuating rainfall in the area may diminish water availability for the GERD, hence impacting power generation and the nation's overall energy security [52]. Notwithstanding these issues, Ethiopia has pledged to enhance water management and adopt steps to alleviate the effects of climatic unpredictability.

The Kariba Dam, situated on the Zambezi River, serves as a vital electrical source for Zambia and Zimbabwe. In recent years, extended droughts in the Zambezi River Basin have markedly reduced water levels, resulting in a reduction in the dam's electricity output by as much as 50% [66]. In 2019, water levels fell to such an extent that the dam was on the verge of halting operations completely, resulting in an energy catastrophe for both nations [66]. The tragedy has shown the susceptibility of significant hydropower initiatives to climate change, prompting Zambia to diversify its energy portfolio with solar and wind projects.

5.4.2 *The Effects of Drought and Seasonal Fluctuations*

The volatility of water flows resulting from climate change poses a significant threat to Africa's nations reliant on hydropower. Droughts, exacerbated by increasing global temperatures, diminish the water supply for hydropower generation and intensify competition for water resources among energy production, agriculture, and human use.

The Turkwel Hydroelectric Power Station in Kenya has seen diminishing water supplies because to persistent droughts in the Turkana Basin. The dam, dependent on the Turkwel River, has seen considerable declines in its producing capability in recent years, compelling Kenya to pursue alternate energy sources during arid seasons [52]. In response to these difficulties, Kenya has begun investments in more climate-resilient energy sources, including geothermal power, which is less vulnerable to climatic fluctuation.

In Southern Africa, including Zimbabwe, Mozambique, and Malawi, the incidence of droughts has escalated, resulting in intermittent reductions in hydropower production. The Cahora Bassa Dam on the Zambezi River in Mozambique, one of Africa's biggest hydroelectric installations, has encountered variable water levels that restrict its capacity for constant energy generation. The region's susceptibility to climate change has prompted dialogues on regional water-sharing agreements and integrated water resource management systems to bolster resilience [52].

5.4.3 Strategies for Enhancing Climate Resilience in Hydropower

African states and energy stakeholders are acknowledging the hazards of climate change and are investigating novel solutions to maintain the sustainability of hydropower amid climatic unpredictability. These techniques include technical innovations, enhancements in water management, and the amalgamation of hydropower with other renewable energy sources to create more robust energy systems.

Adaptive Hydropower Systems: A strategy for enhancing resilience involves the construction of hydropower facilities with increased operating flexibility. This entails the execution of multi-year reservoir management, whereby dams retain surplus water during periods of precipitation for use during droughts. Furthermore, the use of pump storage technologies, which include the re-pumping of water into reservoirs during low demand times, might enhance the stability of electricity generation amidst variable water levels [6].

Hybrid Energy Systems: Integrating hydropower with other renewable energy sources such as solar and wind might alleviate the challenges posed by water shortages. The Rwandan government has combined solar power with hydropower infrastructure to optimize energy generation during the dry season when water resources are scarce. The Nyabarongo Hydropower Project exemplifies the installation of solar panels next to the dam to provide supplemental electric during periods of reduced water levels [6]. These hybrid systems are shown efficacy in mitigating energy deficits resulting from climatic variability.

Transboundary Water Management: Numerous significant hydroelectric initiatives in Africa are situated on transboundary rivers, necessitating appropriate water-sharing agreements for climate resilience. The Nile Basin Initiative has fostered collaboration among upstream and downstream nations, such as Ethiopia, Sudan, and Egypt, to guarantee fair water allocation, even under drought conditions [6]. By enhancing regional collaboration, nations may formulate cohesive strategies for the management of shared water resources, so assuring the sustainable viability of hydropower.

5.4.4 Anticipated Developments and Flexible Strategies

Climate models forecast heightened rainfall variability across Africa, prompting nations to adopt proactive strategies to adapt their hydroelectric infrastructure to the

difficulties posed by climate change. Governments, international organizations, and development banks are collaborating to construct resilient systems and advocate for optimal practices in water resource management.

Ethiopia's Adaptive Hydropower Policy: Ethiopia has established a national hydropower adaptation policy that incorporates routine climate risk assessments and the advancement of ecosystem-based adaptation methods. This entails the restoration of wetlands and reforestation of watersheds to enhance water retention and mitigate drought severity [5]. Ethiopia is investing in research and technology to enhance the efficiency of its hydropower facilities under fluctuating weather circumstances.

Malawi's Green Climate Fund (GCF): The Malawi's Green Climate Fund (GCF) has financed several initiatives across Africa to improve the climate resilience of hydropower. The GCF is financing initiatives in Malawi aimed at watershed restoration and enhancing dam safety to guarantee hydropower facilities are resilient to climate-induced floods and droughts. These initiatives assist nations in embracing proactive strategies for hydropower development that emphasize long-term sustainability.

6. Regulatory and Policy Frameworks to Facilitate Renewable Energy Adoption

The shift to renewable energy in Africa, notably via solar, wind, and hydropower, needs strong legislative and regulatory frameworks to promote extensive acceptance and investment. Due to the continent's varied political and economic environment, African governments have used an array of policy instruments and regulatory frameworks to promote renewable energy production, maintain equitable market competition, and stimulate innovation in the industry. This section examines the main legislative and regulatory mechanisms facilitating renewable energy uptake in Africa, emphasizing creative instances, obstacles, and prospective trajectories.

6.1 National Policies and Objectives for Renewable Energy

Numerous African countries have established extensive national renewable energy plans to enhance the proportion of renewables in their energy composition. Explicit goals, strategic plans, and frameworks supporting these policies are frequently present in order to encourage investment and facilitate sector development.

6.1.1 South Africa's Renewable Energy Independent Power Producer Procurement Program (REIPPPP)

A prominent example of a successful policy framework is South Africa's REIPPPP, initiated in 2011. The initiative aims to stimulate private sector investment in renewable energy via competitive bidding for solar, wind, and hydroelectric projects. REIPPPP has garnered in excess of \$14 billion in investment, resulting in the construction of nearly 6,400 MW of renewable energy capacity by 2020 [6]. This serves as a paradigm for other African countries aiming to enhance renewable energy implementation via transparent procurement procedures and advantageous regulatory frameworks.

6.1.2 Morocco's National Energy Strategy

Morocco has established itself as a frontrunner in renewable energy implementation, aiming to derive 52% of its power from renewable sources by 2030 [6]. The Moroccan Agency for Sustainable Energy (MASEN) has played a significant role in orchestrating renewable energy initiatives, notably the Noor Ouarzazate Solar Complex, the biggest concentrated solar power (CSP) facility globally. Morocco's plan integrates feed-in tariffs, public-private partnerships, and stringent regulatory control, fostering a favorable climate for substantial renewable energy investments [6].

6.2 Feed-in Tariffs (FiTs) and Auction Mechanisms

Feed-in tariffs (FiTs) and auction procedures are two regulatory instruments extensively used to incentivize renewable energy production by providing stable prices for electricity generated from renewable sources. These instruments provide financial inducements that enhance the appeal of renewable energy initiatives to investors.

The implementation of a feed-in tariff for renewable energy in Kenya in 2008 has been significant in promoting private sector participation in the advancement of solar, wind, and hydropower initiatives. The FiT program ensures set remuneration for renewable energy providers, allowing project developers to recoup their investments. This strategy has enabled the advancement of extensive projects, such as the Lake Turkana Wind Power Project, the biggest in Africa, generating up to 310 MW of power [6].

Nigeria initiated a solar auction program in 2016, enabling the government to acquire solar electricity via a competitive bidding procedure. This has resulted in the establishment of several large-scale solar initiatives, aiding Nigeria's objective of producing 30% of its power from renewable sources by 2030 [6]. The auction mechanism promotes cost efficiency and facilitates the growth of the solar energy sector.

6.3 Regulatory Incentives for Decentralized Energy Systems

Decentralized energy solutions, especially in rural and off-grid regions, are essential for enhancing energy access across Africa. To expedite the implementation of off-grid solar, wind, and mini-hydro systems, several governments have established legal frameworks that promote private sector engagement and innovation.

Rwanda has emerged as a regional frontrunner in advocating decentralized energy systems, notably via its National Electrification Plan and incentives for off-grid solar energy. The government provides tax incentives [82], subsidies, and expedited licensing processes for firms engaged in off-grid solar development [83]. Consequently, Rwanda has achieved notable advancements toward its objective of universal energy access by 2024, with off-grid alternatives anticipated to benefit 48% of the population [6].

Ethiopia's mini-hydro regulation permits private developers to own and manage small-scale hydropower systems under its regulatory framework for mini-hydro projects. The government offers advantageous rates and streamlined licensing procedures for mini-hydro projects that benefit rural populations. This has stimulated investment in small-scale hydropower to provide energy to rural regions where grid expansion is impractical [6].

6.4 Global Collaboration and Regional Policy Alignment

Alongside national legislation, regional collaboration and international assistance are essential for the successful transformation of Africa's renewable energy sector [84,85]. Entities like the African Union (AU) and the Economic Community of West African

States (ECOWAS) have been instrumental in standardizing renewable energy policy and facilitating cross-border initiatives.

In 2013, ECOWAS initiated its regional renewable energy strategy, aiming for a 48% contribution of renewable energy to its electrical mix by 2030 [50]. This strategy fosters international cooperation on renewable energy initiatives, exemplified by the West African Power Pool (WAPP), which seeks to incorporate renewable energy into a regional power market. ECOWAS is facilitating the realization of renewable energy potential in West Africa by aligning regulatory regimes and encouraging infrastructure cooperation [50].

The African Union's African Renewable Energy Initiative seeks to increase renewable energy capacity by 300 gigawatts by 2030 [49]. African nations get technical aid, finance, and policy direction to expedite the adoption of renewable energy via the project [86]. The program underscores the significance of sustainable development [87], climate resilience [88], and regional integration in energy planning [89].

7. Emerging Trends and Prospective Outlook

Technology advancements, innovative corporate strategies, and developing legislative frameworks are accelerating Africa's transition to renewable energy. The continent must transition to solar, wind, and hydropower to address energy poverty and climate change, which is crucial for sustainable development. This section examines the rising factors influencing Africa's energy future and provides a prospective analysis of their influence on the energy landscape in the next decades.

7.1 Decentralized Energy Systems and Microgrids

A significant development in Africa's renewable energy market is the rapid emergence of decentralized energy systems [90], especially in off-grid and rural regions [91]. Mini-grids and standalone solar systems are developing as effective solutions to Africa's energy access concerns when expanding the national grid is neither practical nor economically viable [92].

Mini-grids, powered by solar, wind, or modest hydropower, are essential in combating energy poverty in isolated areas. Nations such as Nigeria, Kenya, and Tanzania are using mini-grid initiatives to expedite rural electrification [93]. Kenya's Community Mini-Grid Program has provided dependable power to nearly 150,000 individuals, enabling energy access to areas that hitherto depended on diesel generators [49]. By 2030, the mini-grid sector in sub-Saharan Africa is projected to expand to more than 12,000 functioning mini-grids, catering to millions of families and enterprises [6].

The emergence of Pay-as-You-Go (PAYG) solar systems is a notable development [18], enabling users to purchase solar energy via manageable [16], incremental payments using mobile money networks. Firms such as M-Kopa Solar in Kenya and BBOXX in Rwanda have given millions of families access to solar energy via PAYG models [94], adeptly integrating technology and finance to surmount initial cost obstacles [6]. This trend is anticipated to proliferate, establishing decentralized solar systems as a fundamental component of Africa's energy future [95].

7.2 Hybrid Renewable Energy Systems

The amalgamation of several renewable energy sources, referred to as hybrid systems, is an emerging idea that aims to improve energy stability and efficiency in Africa [96]. Hybrid systems often integrate solar, wind, and hydropower with energy storage options, therefore guaranteeing a more consistent electricity supply despite fluctuations in renewable output.

7.2.1 Hybrid Solar-Wind Initiatives

A prominent advancement in this domain is the creation of hybrid solar-wind initiatives, which use Africa's varied renewable resources. The Gulf of Suez Hybrid Project in Egypt aims to use both solar and wind energy, using the area's elevated sun irradiance and steady wind velocities [97]. This hybrid methodology may diminish dependence on fossil fuels [98] and alleviate the intermittency challenges linked to singular renewable initiatives [6].

7.2.2 Solar-hydro Synergies

In Africa, hydropower facilities are progressively integrated with solar photovoltaic (PV) systems to enhance the dependability of energy supply [99], especially during arid seasons when hydropower production diminishes [100]. The Koysha Dam in Ethiopia exemplifies the consideration of solar photovoltaic technology as a supplementary energy source to the hydroelectric facility [101]. The integration of renewable resources will be essential for maximizing Africa's energy potential and guaranteeing a continuous electricity supply throughout the year.

7.3 Sophisticated Energy Storage Solutions

Energy storage technologies are essential for addressing intermittency concerns and guaranteeing a consistent supply of renewable energy [102]. Africa is starting to adopt sophisticated battery storage systems [103], which are crucial for grid stabilization [104], improving off-grid solutions [105], and incorporating more renewable energy sources into the energy portfolio [106].

The declining cost of lithium-ion batteries has made them more feasible for extensive energy storage initiatives across Africa [107]. The Kathu Solar Park in South Africa utilizes a battery energy storage system (BESS) to retain surplus energy produced during the day for nighttime consumption, ensuring a consistent power supply to the grid [6]. The use of BESS technology across Africa is anticipated to increase markedly, enhancing the dependability of both grid-connected and off-grid renewable energy systems [108].

Hydrogen is becoming recognized as a viable alternative for long-term energy storage [109] and decarbonization [110], surpassing traditional batteries. Green hydrogen, generated by electrolysis using renewable energy [111], is attracting interest as a possible transformative force for Africa's energy sector [112]. Morocco and Namibia are at the forefront of Africa's green hydrogen production initiatives, implementing large-scale projects designed for the export of green hydrogen to Europe and other international markets [6]. Hydrogen technologies have the capacity to meet seasonal energy storage requirements [113] and elevate Africa to a prominent position in renewable energy exports worldwide [113].

7.4 Digitalization and Intelligent Grid Technologies

Digital technologies are transforming the monitoring [114], management [115], and optimization of energy systems across Africa [116]. The use of smart grids, digital meters, and artificial intelligence (AI) in energy management facilitates the more effective utilization of renewable resources [117], minimizes energy waste, and enhances system stability [118].

African nations are investing in smart grid technology to enhance system resilience and integrate a greater proportion of renewable energy [119]. South Africa's Eskom is investigating smart grid systems to incorporate dispersed solar and wind energy into the national grid, minimize transmission losses, and enhance real-time energy delivery [6]. Smart grids provide enhanced demand-side management [120], enabling utilities to modify power supply in accordance with consumption patterns, thereby augmenting total energy efficiency.

The amalgamation of Artificial Intelligence (AI) and artificial of intelligence (IoT) in energy management is becoming prevalent throughout Africa [113]. These technologies provide predictive maintenance [121], load forecasting [122], and real-time monitoring of energy systems [123], therefore simplifying the balance of supply and demand [124]. The AI-driven grid management solution created by Powerhive has reduced downtime [125] and enhanced energy dependability for off-grid solar installations in rural Kenya [5]. The ongoing digitization of energy systems will be essential in optimizing the effectiveness of renewable energy expenditures [126].

7.5 Financing Innovations and Sustainable Bonds

Finance continues to be a substantial obstacle to the expansion of renewable energy initiatives throughout Africa. Innovative financing structures, including green bonds [127], impact investments, and blended finance, are facilitating the closure of the funding gap [128] and drawing money into the renewable energy industry [79].

Green bonds, intended to fund ecologically sustainable initiatives, have gained prominence across Africa [129]. In 2017, Nigeria became the first African nation to issue a sovereign green bond, securing \$29 million to finance solar energy initiatives [6]. South Africa has engaged in green bond issuing, with the City of Cape Town securing financing for renewable energy and climate resilience initiatives. Green bonds are anticipated to be essential in funding Africa's energy transformation [89], providing a sustainable financial framework for extensive renewable energy projects [87].

Blended finance, integrating public and private resources, is becoming a potent mechanism to mitigate risks associated with renewable energy projects and stimulate private sector participation. The Sustainable Energy Fund for Africa (SEFA), overseen by the African Development Bank, has effectively used blended financing to facilitate projects like the Benban Solar Park in Egypt, one of the biggest solar installations globally [6]. The introduction of additional blended financing methods is expected to enhance investment in Africa's renewable energy industry, facilitating the expedited implementation of clean energy initiatives [118].

7.6 Regional Integration and Transnational Electricity Commerce

Projects like the African Continental Free Trade Area (AfCFTA) and the African Power Pools are accelerating regional energy collaboration and transnational electricity commerce in Africa. These programs seek to establish linked energy markets that facilitate the cross-border sharing of renewable energy resources [129], hence optimizing efficiency and minimizing costs [126].

The West African Power Pool (WAPP) exemplifies how cross-border energy commerce may enhance the incorporation of renewable energy into national systems. The WAPP seeks to establish a cohesive power market for the 15 ECOWAS member states, enabling countries with surplus renewable resources to sell excess electricity to adjacent nations. This regional integration would allow nations such as Nigeria and Ghana to harness their solar and wind capabilities to satisfy regional energy requirements [6].

The Eastern Africa Power Pool (EAPP) is facilitating the integration of renewable energy from Ethiopia's extensive hydropower resources into adjacent nations, including Kenya, Sudan, and Djibouti. As regional power pools evolve, they will be essential in stabilizing electricity supply, lowering prices, and promoting the widespread use of renewable energy across the continent [52].

8. CONCLUSIONS

Africa's energy landscape is at a pivotal moment as the region confronts increasing energy needs while addressing the necessity for sustainable and dependable power sources. This research has shown the considerable potential of solar, wind, and hydropower as foundational elements of Africa's renewable energy transformation. Solar energy, abundant across the continent, has significant potential, especially in areas with high irradiation levels. Recent technical developments, together with declining prices, are making solar power more accessible to a broader demographic. Wind energy, despite its geographical concentration, is increasingly gaining momentum, particularly in the Horn of Africa and coastal locations where wind velocities are conducive to extensive projects. Hydropower, a fundamental component of Africa's energy production, is essential for delivering reliable baseload power while encountering problems associated with environmental issues and the effects of climate change.

The effective implementation of these renewable energy sources will mostly rely on the creation of strong regulatory and policy frameworks. Governments must cultivate a climate that promotes investment, innovation, and public-private partnerships while guaranteeing fair access to renewable energy solutions in all areas. Policy measures that promote decentralized energy systems, foster the development of smart grids, and include energy storage technologies will be crucial for securing a sustainable renewable energy future.

Africa is poised for an energy change due to advancements in energy storage, enhanced grid infrastructure, and regional collaboration. These factors will alleviate the intermittency issues linked to renewables and realize the whole potential of cross-border energy commerce. As Africa progresses down this path, it will not only fulfill its energy requirements but also establish itself as a global leader in renewable energy innovation, building a paradigm for sustainable development and climate resilience globally.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Enhancing Cybersecurity in Energy Infrastructure: Strategies for Safeguarding Critical Systems in the Digital Age

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In the digital age, energy infrastructure faces unprecedented cybersecurity challenges that threaten the stability and reliability of critical systems. This paper explores the current threat landscape, detailing prevalent cyber threats such as malware, ransomware, and phishing that target energy systems. It examines the technical, organizational, and regulatory challenges in securing these infrastructures, highlighting issues like legacy systems, lack of cybersecurity awareness, and stringent compliance requirements. The paper proposes comprehensive strategies for enhancing cybersecurity, emphasizing the implementation of advanced technologies such as artificial intelligence, machine learning, and blockchain. Best practices, including regular security audits, incident response planning, and employee training, are also discussed. Furthermore, the importance of collaborative efforts, such as public-private partnerships and information sharing networks, is underscored. The paper concludes with recommendations for energy organizations to strengthen their cybersecurity posture, ensuring the protection of critical systems and the continuity of operations in the face of evolving cyber threats.

Keywords: Cybersecurity; Energy Infrastructure; Advanced Technologies; Threat Landscape; Public-Private Partnerships; Incident Response

Introduction

In the modern digital age, energy infrastructure forms the backbone of economic stability and societal functionality. Power grids, oil pipelines, and gas distribution networks are integral to the daily operations of industries, governments, and households [1]. As these systems become increasingly digitized, their efficiency and interconnectivity improve, exposing them to significant cybersecurity risks. Energy infrastructure security is paramount because a successful cyber attack can disrupt power supplies, damage physical assets, and pose serious national security threats. Ensuring robust cybersecurity measures is essential to maintaining the integrity and reliability of these critical systems, which are fundamental to both economic and national security [2].

The energy sector is facing an escalating wave of digital threats that are becoming more sophisticated and damaging. Cyber attackers, including state-sponsored actors, hacktivists, and cybercriminals, continuously develop advanced methods to breach

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security defenses [3]. These threats manifest in various forms, such as malware, ransomware, phishing, and Distributed Denial of Service (DDoS) attacks, each posing unique challenges to energy infrastructure. For instance, malware can be used to infiltrate control systems, leading to operational disruptions. Ransomware can lock critical data and systems, demanding hefty ransoms for restoration. Phishing attacks can deceive employees into disclosing sensitive information, providing an entry point for cyber attackers. DDoS attacks can overwhelm network resources, rendering essential services unavailable [2].

The proliferation of the Internet of Things (IoT) within energy systems has further expanded the attack surface. IoT devices, often with inadequate security, are being integrated into grid management, metering, and monitoring systems, creating new vulnerabilities. Moreover, the convergence of Information Technology (IT) and Operational Technology (OT) networks has increased the complexity of securing these environments [4]. Traditionally isolated OT systems, responsible for controlling physical processes, are now interconnected with IT networks, which manage data and communication. This integration enhances operational efficiency and means that a breach in IT systems can potentially impact OT operations, making comprehensive cybersecurity strategies indispensable [5].

This paper explores the strategies necessary for safeguarding energy infrastructure in the face of evolving digital threats. It will provide an in-depth analysis of the current threat landscape, identify the primary challenges in securing energy systems, and propose effective cybersecurity strategies. The goal is to offer a comprehensive understanding of enhancing cybersecurity measures to protect critical energy systems from cyber attacks.

The scope of this paper includes an examination of both the technical and organizational aspects of cybersecurity in the energy sector. Technical aspects will cover the advanced technologies and best practices that can be implemented to bolster defenses. Organizational aspects will address the importance of cybersecurity awareness, policies, and regulatory compliance. Additionally, the paper will highlight the role of collaborative efforts, such as public-private partnerships and information-sharing networks, in enhancing cybersecurity resilience. By the end of this paper, readers will gain valuable insights into the importance of cybersecurity in energy infrastructure, the nature of the threats it faces, the challenges involved in securing these systems, and the strategies that can be employed to mitigate these risks. The recommendations provided will guide energy organizations seeking to strengthen their cybersecurity posture and protect their critical assets from cyber threats.

Current Threat Landscape

Analysis of Prevalent Cybersecurity Threats Facing Energy Infrastructure

The energy sector is increasingly becoming a prime target for cyber-attacks due to its critical importance to national security, economic stability, and public safety. As energy infrastructure continues to modernize and integrate digital technologies, the complexity and interconnectedness of these systems also increase, making them more vulnerable to cyber threats. The convergence of Information Technology and Operational Technology has further complicated the security landscape, creating new vulnerabilities that cyber attackers are eager to exploit [2].

One of the most significant challenges in this domain is the evolving nature of cyber threats. Cyber attackers continually develop new tactics, techniques, and procedures (TTPs) to breach security defenses. State-sponsored actors, hacktivists, and cybercriminals have different motives and methods, ranging from espionage and sabotage to financial gain and ideological objectives. The energy sector, with its mix of legacy systems and cutting-edge technologies, presents a broad attack surface that is attractive to these malicious actors [6].

Types of Cyber Attacks Commonly Targeting Energy Systems

Energy infrastructure faces a variety of cyber attacks, each with distinct characteristics and potential impacts. Understanding these types of attacks is crucial for developing effective cybersecurity strategies.

a) **Malware:** Malware is a general term for malicious software designed to infiltrate, damage, or disable computer systems. In the context of energy infrastructure, malware can disrupt operations, steal sensitive information, or gain control of critical systems. A notable example is the Stuxnet worm, which specifically targeted supervisory control and data acquisition (SCADA) systems and caused significant damage to Iran's nuclear program. This attack demonstrated the potential for malware to be used in state-sponsored sabotage of critical infrastructure [7].

b) **Ransomware:** Ransomware is malware that encrypts a victim's data and demands a ransom for its release. Energy companies are particularly vulnerable to ransomware attacks due to the critical nature of their operations. An attack can halt production, disrupt services, and cause financial losses. For instance, the Colonial Pipeline ransomware attack in 2021 led to widespread fuel shortages across the eastern United States, highlighting the significant impact such attacks can have on society.

c) **Phishing:** Phishing attacks involve tricking individuals into revealing sensitive information, such as login credentials or financial data, by masquerading as trustworthy in electronic communications. These attacks are often the entry point for more sophisticated cyber intrusions. In the energy sector, phishing can be used to access corporate networks, enabling attackers to deploy malware or exfiltrate data. The success of phishing attacks often relies on exploiting human vulnerabilities, making employee training and awareness crucial components of cybersecurity [8].

d) **Distributed Denial of Service (DDoS) Attacks:** DDoS attacks aim to overwhelm a target's network or servers with a flood of internet traffic, rendering the services unavailable. In the energy sector, DDoS attacks can disrupt customer service portals, billing systems, and even operational controls. While these attacks do not typically result in data breaches, they can cause significant operational disruptions and financial losses [9].

e) **Zero-Day Exploits:** Zero-day exploits target vulnerabilities in software or hardware that are unknown to the vendor or not yet patched. These exploits can be particularly dangerous for energy infrastructure, as they can be used to bypass traditional security measures. Attackers can use zero-day exploits to gain control of critical systems, disrupt operations, or steal sensitive information. The complexity of modern energy systems makes them an attractive target for such sophisticated attacks [10].

f) **Supply Chain Attacks:** Supply chain attacks target the interconnected networks of suppliers and service providers that support the energy sector. Attackers can infiltrate the primary target's network by compromising a supplier or contractor. This method was notably used in the SolarWinds attack, where attackers inserted malicious code into a

software update, affecting numerous organizations, including those in the energy sector. Such attacks underscore the importance of securing the entire supply chain to protect critical infrastructure [11, 12].

g) **Advanced Persistent Threats (APTs):** APTs are prolonged and targeted cyber attacks designed to infiltrate and remain within a system for an extended period. These attacks are typically conducted by state-sponsored actors with significant resources and expertise. APTs often aim to gather intelligence, disrupt operations, or prepare for future attacks. In the energy sector, APTs can compromise sensitive operational data, disrupt energy production and distribution, and undermine national security [13].

h) **Insider Threats:** Insider threats involve individuals within an organization who intentionally or unintentionally compromise security. These threats can come from disgruntled employees, contractors, or other insiders with access to critical systems. Insider threats are particularly challenging to detect and mitigate because they involve legitimate users with access to sensitive network areas. Implementing strict access controls, monitoring, and employee training are essential to mitigate these risks [14].

In conclusion, energy infrastructure's current threat landscape is diverse and constantly evolving. Cyber attackers employ a variety of methods to target these critical systems, each with the potential to cause significant disruption and damage. Understanding the types of cyber attacks commonly targeting energy systems is the first step in developing comprehensive cybersecurity strategies to protect these vital assets. As the energy sector continues to modernize and integrate digital technologies, staying ahead of these threats through proactive measures, advanced technologies, and robust policies is essential to safeguarding the future of energy infrastructure.

Challenges in Securing Energy Infrastructure

Technical Challenges

One of the foremost technical challenges in securing energy infrastructure is the prevalence of legacy systems. Many energy facilities, including power plants and distribution networks, rely on outdated technology that has not been designed with cybersecurity in mind. These legacy systems often lack the necessary security features to protect against modern cyber threats, making them vulnerable to attacks [15]. Updating or replacing these systems can be prohibitively expensive and technically challenging, particularly when considering the need to maintain continuous operations. The incompatibility of old and new systems further complicates efforts to enhance cybersecurity, as integrating advanced security solutions with legacy infrastructure often requires significant customization and adaptation.

Another critical technical challenge is the integration of Information Technology and Operational Technology networks. Traditionally, OT systems, which control physical processes like electricity generation and distribution, operated in isolation from IT networks, which manage data and communication. However, the push for greater efficiency and real-time data analytics has led to the convergence of IT and OT systems [16]. While this integration offers significant operational benefits, it also expands the attack surface. Cyber vulnerabilities in IT systems can now directly impact OT operations, potentially leading to physical disruptions in energy supply. Ensuring robust cybersecurity in such integrated environments requires comprehensive strategies that address the unique security needs of both IT and OT systems [17].

Additionally, the increasing adoption of Internet of Things (IoT) devices in energy infrastructure presents another layer of technical challenges. IoT devices, used for monitoring and controlling various aspects of energy systems, often come with inadequate security features. These devices can serve as entry points for cyber attackers if not properly secured. The sheer number and diversity of IoT devices in energy infrastructure make it difficult to enforce uniform security standards, further complicating efforts to protect these critical systems [15].

Organizational Challenges

Organizational challenges are equally significant in securing energy infrastructure. One of the primary issues is the lack of cybersecurity awareness among employees. Human error remains one of the leading causes of cybersecurity breaches. Employees may inadvertently expose systems to risks by clicking on phishing emails, using weak passwords, or failing to follow security protocols. Building a culture of cybersecurity awareness within energy organizations is crucial for mitigating these risks. This involves regular training programs, awareness campaigns, and implementing policies that encourage vigilant behavior among all staff members [18, 19].

Inadequate cybersecurity policies also pose a substantial organizational challenge. Many energy companies lack comprehensive cybersecurity frameworks that address their operations' specific threats and vulnerabilities. Effective cybersecurity policies should encompass risk assessment, incident response, data protection, and continuous monitoring. However, developing and enforcing such policies requires significant resources and expertise, which may be lacking in some organizations. Additionally, ensuring these policies are consistently followed and updated in response to evolving threats is an ongoing challenge [20].

Another organizational issue is the difficulty in attracting and retaining skilled cybersecurity professionals. The demand for cybersecurity expertise far exceeds the supply, leading to a talent shortage that affects many industries, including the energy sector. Energy companies must compete with other sectors to hire qualified professionals, often offering high salaries and benefits to attract top talent. The scarcity of skilled cybersecurity professionals can leave energy organizations vulnerable to attacks, as they may lack the expertise to implement and maintain robust security measures [6, 21].

Regulatory and Compliance Challenges

Meeting regulatory and compliance requirements presents a significant challenge for securing energy infrastructure. The energy sector is subject to a complex web of industry standards, government regulations, and compliance mandates designed to ensure the security and reliability of energy systems. These regulations vary by region and can be highly detailed, requiring organizations to implement specific security measures and undergo regular audits.

One major challenge is keeping up with the ever-changing regulatory landscape. As cyber threats evolve, regulatory bodies frequently update their requirements to address new risks. Energy companies must stay informed about these changes and adapt their security practices accordingly. This can be resource-intensive and requires a proactive approach to compliance management [22, 23].

Additionally, compliance with regulatory standards does not necessarily equate to comprehensive cybersecurity. While regulations set minimum security requirements, they may not cover all potential threats or vulnerabilities specific to an organization's

infrastructure. Therefore, energy companies must go beyond compliance to develop robust cybersecurity strategies addressing their unique risks [24].

The enforcement of regulatory requirements can also pose challenges. Regulatory bodies may impose fines or other penalties for non-compliance, adding financial and operational pressures on energy organizations. Moreover, the process of demonstrating compliance through audits and reporting can be time-consuming and complex, diverting resources from other critical security activities.

International energy companies face the added complexity of navigating different regulatory frameworks across multiple jurisdictions. Ensuring compliance with diverse and sometimes conflicting regulations requires a coordinated effort and a deep understanding of each region's legal requirements. This can strain resources and complicate cybersecurity efforts, particularly for smaller companies with limited capacities [25].

Strategies for Enhancing Cybersecurity

Implementation of Advanced Cybersecurity Technologies

In the face of escalating cyber threats, energy infrastructure must adopt advanced cybersecurity technologies to protect critical systems. Artificial Intelligence and machine learning (ML) are at the forefront of this technological evolution. These technologies enable developing sophisticated threat detection systems that can identify and respond to anomalies in real-time. AI-driven security systems can analyze vast amounts of data to detect patterns indicative of cyber attacks, such as unusual network traffic or unauthorized access attempts. Machine learning algorithms can adapt to new threats by learning from previous incidents, thereby continuously improving the defense mechanisms. By implementing AI and ML, energy companies can enhance their ability to predict, detect, and mitigate cyber threats before they cause significant damage [26].

Blockchain technology also offers promising applications for cybersecurity in energy infrastructure. Blockchain's decentralized and immutable nature makes it highly resistant to tampering and fraud. Using blockchain, energy companies can secure transactions, protect data integrity, and ensure the authenticity of communications between different energy grid components. For instance, blockchain can be used to secure communication between smart meters and control centers, preventing hackers from manipulating energy consumption data. Additionally, blockchain can enhance the transparency and traceability of energy transactions, reducing the risk of cyber attacks on financial systems associated with energy trading [27, 28].

Best Practices for Securing Energy Infrastructure

Adopting best practices is crucial for enhancing the cybersecurity of energy infrastructure. Regular audits are essential to identify vulnerabilities and ensure compliance with security standards. These audits should encompass all aspects of the energy system, including hardware, software, and network configurations. By conducting regular security assessments, energy companies can proactively address weaknesses before attackers exploit them. Moreover, audits help maintain regulatory compliance, which is vital for avoiding penalties and ensuring the overall security of energy operations [29].

Incident response planning is another critical best practice. Energy companies must develop and regularly update comprehensive incident response plans to effectively manage cyber attacks when they occur. These plans should outline procedures for identifying, containing, and mitigating cyber incidents and protocols for communication and coordination among different teams. A well-defined incident response plan enables energy companies to respond swiftly and efficiently to cyber threats, minimizing the impact on operations and reducing recovery time.

Employee training is a fundamental aspect of cybersecurity best practices. Human error remains a significant factor in many cyber incidents, making it imperative to cultivate a culture of cybersecurity awareness among employees. Regular training programs should educate staff on recognizing phishing attempts, using strong passwords, and following security protocols. Additionally, conducting simulated cyber attack exercises can help employees practice their response to real-world threats, enhancing their preparedness and resilience. Energy companies can significantly reduce the risk of human-related security breaches by investing in continuous cybersecurity education [30].

Collaborative Efforts

Enhancing cybersecurity in energy infrastructure requires collaborative efforts between public and private sectors. Public-private partnerships (PPPs) are vital in fostering cooperation and sharing resources to address common security challenges. Governments can provide regulatory frameworks, funding, and intelligence to support private energy companies' cybersecurity efforts. In return, private companies can share their expertise, innovations, and real-time threat information with public agencies. This collaboration helps create a unified front against cyber threats, leveraging the strengths of both sectors to enhance overall security [31].

Information sharing networks are also crucial for effective collaboration. Cyber threats evolve rapidly, and timely access to threat intelligence can significantly improve an organization's ability to defend against attacks. Energy companies should participate in industry-specific information sharing and analysis centers (ISACs) to exchange threat data, best practices, and mitigation strategies with their peers. These networks facilitate a collective defense approach, allowing energy companies to learn from each other's experiences and stay ahead of emerging threats. Furthermore, information sharing enhances situational awareness, enabling energy companies to detect and respond to threats more quickly and effectively.

Standardizing cybersecurity practices across the industry is another important collaborative strategy. Establishing common security standards and protocols ensures that all energy companies adhere to a baseline level of security. Industry associations and regulatory bodies can play a pivotal role in developing and promoting these standards. By aligning their cybersecurity practices, energy companies can collectively raise the security bar, making it more difficult for attackers to exploit vulnerabilities. Standardization also facilitates interoperability between different systems and technologies, enhancing the overall resilience of the energy infrastructure [32].

Conclusion and Recommendations

Conclusion

The critical nature of cybersecurity in the energy sector cannot be overstated, given the growing reliance on digital technologies to manage and operate complex energy systems. The analysis reveals that energy infrastructure faces many cyber threats, including sophisticated malware, ransomware attacks, and phishing schemes, which target both the IT and OT environments. These threats pose significant risks to the stability and reliability of energy supplies, potentially leading to severe economic and societal disruptions.

The challenges in securing energy infrastructure are multifaceted. Technical hurdles such as outdated legacy systems and the integration of IT and OT present significant vulnerabilities. Organizational issues, including a general lack of cybersecurity awareness and inadequate policies, further complicate the security landscape. Additionally, regulatory and compliance requirements add another layer of complexity, as energy companies strive to meet stringent industry standards and government regulations.

The strategies for enhancing cybersecurity in energy infrastructure are equally comprehensive. Adopting advanced technologies like AI, machine learning, and blockchain provides robust defenses against emerging threats. Best practices such as regular security audits, incident response planning, and employee training are essential for maintaining a strong security posture. Collaborative efforts, particularly through public-private partnerships and information-sharing networks, enhance the collective ability of the energy sector to defend against cyber attacks.

Recommendations

Based on the insights gathered, several recommendations can be made for energy organizations aiming to bolster their cybersecurity measures. Firstly, energy companies should prioritize the integration of advanced cybersecurity technologies. Implementing AI and machine learning can significantly enhance threat detection and response capabilities. These technologies should be leveraged to monitor network activity in real-time, identify anomalies, and predict potential threats based on historical data. Blockchain technology should also be explored to secure transactions and ensure the integrity of data exchanges within the energy grid.

Secondly, establishing a culture of cybersecurity awareness is crucial. This involves continuous training programs for employees to effectively recognize and respond to cyber threats. Regular cybersecurity drills and simulations can help prepare staff for real-world scenarios, minimizing the risk of human error. Fostering a vigilance and accountability culture can ensure that all employees, from executives to frontline workers, are committed to maintaining robust security practices.

Thirdly, energy organizations must develop and regularly update comprehensive incident response plans. These plans should outline clear procedures for detecting, reporting, and mitigating cyber incidents. Regular testing and updating of these plans are necessary to adapt to the evolving threat landscape. By being prepared with a well-defined incident response strategy, energy companies can minimize downtime and recover more quickly from cyber attacks. Moreover, energy organizations should engage in collaborative efforts with both the public and private sectors. Participating in industry-specific ISACs and other information sharing networks can provide valuable insights into emerging threats and effective mitigation strategies. Public-private partnerships can facilitate the exchange of critical threat intelligence and resources, enhancing the overall resilience of the energy infrastructure. Finally, energy organizations should strive to meet

and exceed regulatory and compliance standards. Adhering to established cybersecurity frameworks, such as the NIST Cybersecurity Framework or ISO/IEC 27001, can provide a solid foundation for a robust security posture. Regular audits and compliance checks are essential to ensure that all security measures are up-to-date and effective.

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CONFLICTS OF INTEREST

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Multi-Parameter Based Models for Estimating Global Solar Radiation in Selected Locations in Ebonyi State, Southeastern Nigeria

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This study aims to develop hybrid empirical models for estimating global solar radiation in selected locations across Ebonyi State, Nigeria, to enhance photovoltaic energy generation and support climate change mitigation and adaptation. The research is designed to create empirical models for calibrating and modeling global solar radiation using meteorological parameters at Alex Ekwueme Federal University Ndufu-Alike, Ebonyi State University Abakaliki and Akanu Ibiam Federal Polytechnic Unwana, all in Ebonyi State, Southeastern Nigeria. The long term monthly mean daily global solar radiation on the horizontal surface, sunshine hours, relative humidity, minimum and maximum temperature at 2 m height for the period of 1984-2019 for the selected stations were obtained from the National Aeronautics and Space Administration (NASA) atmospheric science data centre. A multi-parameter based model was used to estimate the global solar radiation in each of these locations using Angstrom-Prescott-Page Model. Model performance was evaluated using statistical metrics, including Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Mean Percentage Error (MPE). Additionally, the correlation coefficient (r) and coefficient of determination (r^2) were calculated. Results indicate that the developed empirical models demonstrate a high level of accuracy in estimating daily global solar radiation. Comparisons with existing models in the literature show that the locally calibrated models perform better on monthly and yearly timescales. Therefore, these models can be applied for solar radiation forecasting across Ebonyi State. However, routine recalibration is recommended, as climate variability over time may affect model stability and performance.

Keywords: Global solar radiation; Multi-parameter models; Meteorological parameters; Statistical performance indicators; Ebonyi State Nigeria

1. Introduction

1.1 Background

Global solar radiation is a vital parameter necessary for most ecological models and serves as input for different photovoltaic conversion systems. Hence it is of economic importance to renewable energy alternative. The solar radiation reaching the earth's

surface depends upon climatic conditions of a location which is essential to the prediction and design of a solar energy system [1]. Although solar radiation data are available in most meteorological stations, many stations in developing countries such as Nigeria experience a shortage of facilities required for solar radiation measurements. As a result, we resort to estimation of the solar radiation to provide the information where measured data are not available. This paper aims to develop regression line equations based on Angstrom-Page model that correlate mean daily global solar radiation on horizontal surface in three selected locations in Ebonyi State (Alex Ekwueme Federal University Ndufu-Alike (AE-FUNAI), Ebonyi State University Abakaliki (EBSU) and Akanu Ibiam Federal Polytechnic Unwana (AIFPU) Southeastern Nigeria, using three meteorological parameters namely, maximum air temperature, relative humidity and relative sunshine hours.

Wide range of solar energy applications including modeling, design of solar crop dryers and photovoltaic system sizing require robust knowledge of global solar radiation whose intensity is normally among the variables collected by weather stations. The important role played by knowledge sharing on the subject of solar radiation and its subsequent exploitation have necessitated the need to develop ways of predicting the incident solar radiation in the interest of the regions of the globe like tropical Africa, where routine measurements are lacking in spite of the huge availability of solar energy in the region. As the fossil fuel reserves suffer severe depletion coupled with environmental concerns, it becomes imperative that alternative energy resources should be explored and utilized with high conversion efficiency to help bridge the wide gap between energy supply and energy demand [2].

For sub-Saharan African countries such as Nigeria, the economic and efficient utilization of solar energy has become inevitable because of the abundance and reliability of solar energy resource. Augustine and Nnabuchi [3] estimated about 3,000 hours of annual sunshine in Nigeria. This, however, depends on the location and the time of the year. In spite of this huge amount of solar energy, Nigeria with a dominant rural population still has her residents suffering deprivation from conventional energy due to poor infrastructural facilities and subsequent unreliability in energy supply. Having vast knowledge of the distribution of solar energy at a geographical location is significant for the creation and advancement of new solar energy devices with improved efficiency. Data on solar radiation is a basic requirement for conducting feasibility studies with respect to solar energy systems. Augustine and Nnabuchi [4] opined that knowledge of solar energy acquired over a long period ought to be applicable not only to the site where the radiation data was collected but also to other locations with similar climate.

Nigeria is located between Latitude 4°N and 14°N . This vantage position enables the country to receive a vast amount of solar energy throughout the year. Solar radiation data can be accessed in a variety of forms depending on choice and application. Several scholars have emphasized the importance of solar radiation data in the design and operation of efficient solar energy devices which are anchored on accurate and detailed information of solar radiation climatology. Countless empirical models based on the Angstrom-Prescott-Page type model and other modified models such as exponential form, logarithm form, second order, third order and power form etc have been applied across the globe for estimating global solar radiation in the literature. The temperature-based computing models are especially interesting due to their needed input data (air temperature) which is easily measured globally. Hargreaves and Samani [5] firstly developed a temperature-based model for estimating global solar radiation using

maximum and minimum temperature, and extraterrestrial solar radiation as input parameters and obtained an empirical coefficient of 0.17 using Eq. 1. Since then, it has been recognized as one of the famous, simplest and accurate temperature model for estimating global solar radiation and can be employed for short-term forecasting of global solar radiation. Ohunakin *et al.* [6] recorded a coefficient of 0.1141 in Osogbo while Adaramola [7] obtained a coefficient of 0.1945 at Akure, Nigeria.

$$\frac{H}{H_o} = AHC(T_{\max} - T_{\min})^{0.5} \quad 1$$

where $T_{\max}$ is the maximum temperature, $T_{\min}$ is the minimum temperature with the value of AHC of 0.17 for arid and semi-arid regions. However, calibrations are site-specific and cannot be extrapolated to other sites where weather conditions are different; also some calibrated Hargreaves-Samani (HS) models are more complicated compared to the original HS model. However, routine calibration of this computing model should be carried out to guarantee good performances over subsequent years because the historical data used to calibrate HS model directly ignores the ever-changing climate over the time; when data set extends, instability of the calibrated HS model may appear. Therefore, this present study is aimed at developing hybrid parameter-based models for calibrating HS empirical coefficient in three locations in Ebonyi State, Southeastern Nigeria (AE-FUNAI, EBSU and AIFPU), using 35 years data (1984–2019). This would improve the applicability of HS model for accurate global solar radiation estimation in the Nigerian environment.

1.2 Scope and Significance of the Study

The study is designed to use the monthly mean daily data of global solar radiation, minimum temperature, maximum temperature and relative humidity for the period of thirty-five years (1984-2019) to evaluate the original Hargreaves-Samani coefficient in the three locations in Ebonyi State, Nigeria. The accuracy of the original and calibrated Hargreaves-Samani models was evaluated using the Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Mean Percentage Error (MPE) statistical indicators. The performance of the original and the calibrated Hargreaves-Samani models in the three locations were compared using statistical indicators. With the increased application of Empirical methods in estimating global solar radiation in Nigeria, it has become important to study and compare the relevance of empirical models for global solar radiation over other methods. Therefore, this research is intended to calibrate and model the global solar radiation using the conventional empirical models in AE-FUNAI, EBSU and AIFPU in Ebonyi State, Nigeria.

1.3 Fundamental Parameters

The fundamental parameters of sunshine duration fraction and daily extraterrestrial radiation on the horizontal surface are significant for the estimation of global solar radiation. Sunshine duration fraction is the ratio of actual sunshine duration to maximum possible sunshine duration expressed mathematically by Yaniktepe and Genc [8] as:

$$S_o = \frac{2}{15} \cos^{-1}(-\tan \phi \tan \delta) \quad 2$$

$$\delta = 23.45 \sin \left[\frac{360(n + 284)}{365} \right] \quad 3$$

where ϕ is the latitude, δ is the solar declination given by Yaniktepe and Genc [8] and n , the number of days of the year starting from first January. The daily extraterrestrial solar radiation is the solar radiation intercepted by horizontal surface during a day without the atmosphere expressed theoretically as given by Yaniktepe and Genc [8]:

$$H_o = \frac{24}{\pi} I_{SC} \left(1 + 0.033 \cos \frac{360n}{365} \right) \times \left(\cos \phi \cos \delta \sin \omega_s + \frac{2\pi \omega_s}{360} \sin \phi \sin \delta \right) \quad 4$$

where the mean sunrise hour angle (ω_s) can be evaluated as:

$$\omega_s = \cos^{-1} [\tan \delta \tan \phi] \quad 5$$

I_{SC} is the solar constant and other symbols retain their usual meaning.

1.4 Empirical models

An empirical model in the present context relates global solar radiation with other easily measureable variables such as sunshine duration, temperature, relative humidity, dew point temperature, precipitation and cloud cover by employing concise mathematical functions. As a result of its simplicity and high operability, the empirical model is much more convenient for engineering applications. Several empirical models have been reported in literature for estimating global solar radiation on the Horizontal surface (H) either on Daily mean Basis (DB) or Monthly mean Daily basis (MB) in Nigeria. In this review, the global solar radiation models are classified according to the basis of their input parameters applied in correlating with the clearness index. The clearness index (k_t) indicates the percentage depletion by the sky of the incoming solar radiation and therefore gives both the level of availability of solar radiation and changes in the atmospheric condition in a given environment [9, 10]. Mathematically, clearness index is the ratio of horizontal global solar radiation (often measured and collected from Nigeria Meteorological Station (NIMET), International Institute of Tropical Agriculture (IITA), National Aeronautics and Space Administration (NASA) atmospheric science data center by researchers in Nigeria) to the extraterrestrial solar radiation (H_o) on daily or monthly basis as found in literature expressed as [11-13]:

$$k_t = \frac{H}{H_o} \quad 6$$

It has been accepted that global solar radiation is relatively affected by meteorological parameters, astronomical factors, geographical factors, and geometrical factors [14,15]. This could be attributed to the uniqueness of local climate in determining the meteorological and atmospheric parameters that best fit that particular locality. The availability of input meteorological/atmospheric parameter(s) that a given radiometric station or an individual is capable of measuring routinely affects the quality of the solar radiation predictive model. Thus the accuracy of the resulting model is impacted by the input parameter at the disposal of the researcher for predicting global solar radiation in a location. Thus, in Nigeria, many models have been developed for estimating global solar radiation (*e.g.*, Nwokolo *et al.*, [16], Nwokolo *et al.*, [17], Nwokolo and Amadi, [11], Akpabio and Etuk, [18], Burari and Sambo, [1], Awachie and Okeke, [19], etc.).

2. Study Area

Ebonyi State has a tropical climate with wet and dry seasons. Two distinct wet seasons are observed: the more intense season is observed from April to July whereas a less intense one occurs from September to November. Ebonyi state experiences a dry season (when rain falls less than two days in a month) in August, as well as from December to March. This second part of dry season is accompanied by Harmattan winds which originate from the Sahara Desert and have their peak from December to early February. Ebonyi State has a fair small temperature range, generally between a 33°C and 21°C. The hottest month is March, when the mean diurnal temperatures reach about 29°C. July is the coldest month with a mean temperature of about 25°C [20]. The map showing the locations under study is shown in Figure 1.

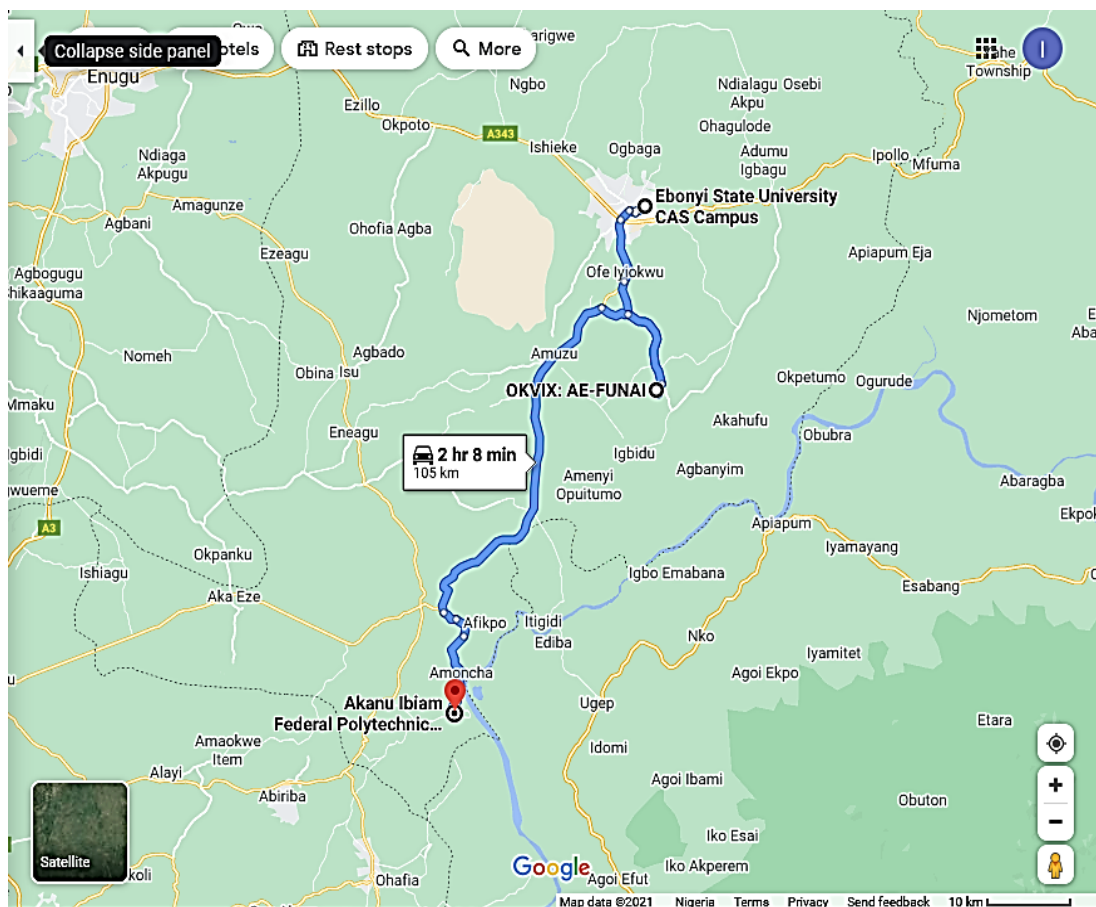


Figure 1. Map showing the locations and relative positions of Alex Ekwueme Federal University Ndufu-Alike, Ebonyi State University Abakaliki and Akanu Ibiam Federal Polytechnic Unwana

3 Materials and Method

3.1 Climate and Meteo-Solar Datasets

A set of historical climate data such as monthly mean solar radiation, average minimum and maximum air temperature, and relative humidity were obtained from the

NASA database (<http://power.larc.nasa.gov/data-access>), and are used in this study. The records of sunshine duration were obtained from the International Institute of Water Management (<http://www.iwmi.cgiar.org/>). The topographical features of the weather stations used in this study are presented in Table 1.

Table 1. Geographical, climatological and meteorological details of the selected locations

Location	Lat. [°N]	Long. [°E]	Ele [m]	Data Range	S	So	S/So	H	Ho	H/Ho	RH	T _{min}	T _{max}	ΔT
AIFPU	5.829	7.927	107m	1984 – 2019	4.832	12.12	0.4000	16.78	35.67	0.4701	84.52	22.22	29.04	6.83
AEFUNAI	6.066	8.083	55m	1984 – 2019	4.99	12.12	0.4133	18.25	35.58	0.5083	82.84	22.12	29.35	7.25
EBSU	6.395	8.014	72m	1984 – 2019	4.99	12.12	0.4100	17.94	35.46	0.5083	82.84	22.12	29.35	7.24

H represents the monthly mean daily global solar radiation ($\text{MJm}^{-2}/\text{day}^{-1}$), H_o represents monthly mean daily extraterrestrial solar radiation ($\text{MJm}^{-2}/\text{day}^{-1}$), k_t is a dimensionless parameter known as monthly mean daily clearness index, S/S_o is a dimensionless parameter known as the monthly mean daily sunshine fraction, S is the monthly mean sunshine hours (in hours), S_o is the monthly mean maximum sunshine hours (in hours), RH is the monthly mean relative humidity (in %), $T_{\min}$ is the monthly mean minimum temperature (in °C), $T_{\max}$ is the monthly mean maximum temperature (in °C), ΔT is the difference between the monthly mean maximum and minimum temperature (in °C).

3.2 Evaluation of Meteo-Solar Parameters

Models based on sunshine hours were selected from among other types of models that are considered to estimate global solar radiation on a horizontal surface in EBSU, AIFPU and AE-FUNAI. The correlation of the datasets between monthly mean global solar radiation (H) and extraterrestrial solar radiation (H_o) often expressed as H/H_o or clearness index (k_t) was considered due to their simple functional form and rigid calculation skills. On this basis, calculations were made on the maximum monthly average solar length and extraterrestrial solar radiation. Therefore, the average extraterrestrial solar radiation is considered as [8, 12, 13, 16]:

$$H_o = \frac{24}{\pi} I_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) \times \left(\cos \varphi \cos \delta \sin \omega + \frac{2\pi\omega}{360} \sin \varphi \sin \delta \right) \quad 7$$

$$\delta = 23.45 \left[\frac{360(n+284)}{365} \right] \quad 8$$

$$\omega = \cos^{-1}[-\tan \delta \tan \varphi] \quad 9$$

The solar declination angle (δ) was calculated using equation (8) and the mean sunrise hour angle (ω) was evaluated using equation (9). n is the number of days of the year starting from first January, and (φ) is the latitude of the location. The monthly mean maximum sunshine period is evaluated as:

$$S_o = \frac{2}{15} \omega \quad 10$$

Equations 7 – 9 were used to evaluate the monthly mean meteorological solar radiation input and output parameters for EBSU, AIFPU and AE-FUNAI.

3.3 Development and Selection of Empirical Models

Consequent upon the need for empirical models to estimate global solar radiation in order to quantify the global solar radiation present in many remote and developing parts of Ebonyi State in the absence of an instrumentation network or measurement structures, six new empirical models were developed for statewide application of a similar correlation procedure classified as models based on sunshine, temperature, relative humidity, and hybrid parameter models using IBM SPSS version 22 software, as presented in Table 4. The sets of monthly average data were divided into training and test sets. 75% of the data set for the period from January 1984 to December 2010 were used for sample training and the remaining 25% of the data set for the period from January 2011 to December 2019 were used for testing. To validate the applicability of the proposed six models, two solar radiation models commonly applied by solar energy estimators were applied, as presented in Table 4. The two single parameter-dependent models were intentionally selected to confirm that the hybrid modeling are much better suited for estimating global solar radiation and for wider application for Ebonyi State locations with varying geographical and climatic conditions.

4. Results and Discussion

4.1 Descriptive Statistics of Meteo-Solar Parameter

Table 2. Descriptive statistics of meteo-solar parameters

Location	Statistic	Meteo-Solar Parameters									
		H	Ho	kt	Tmax	Tmin	ΔT	RH	So	S	S/So
EBSU	Range	6.37	4.92	0.221	3.31	4.83	5.61	21.79	0.73	3.16	0.28
	Minimum	14.34	32.58	0.39	27.92	19	5.41	68.03	11.8	2.96	0.24
	Maximum	20.71	37.5	0.611	31.24	23.82	11.03	89.83	12.5	6.12	0.52
	Mean	18.06	35.68	0.508	29.32	22.07	7.26	82.79	12.1	4.83	0.4
	Std. Error	0.63	0.46	0.021	0.35	0.44	2.07	2.33	0.08	0.33	0.029
	Std.deviation	2.19	1.58	0.074	1.21	1.54	12	8.07	0.27	1.13	0.099
AIFPU	Range	14.05	6.63	0.386	5.16	10.02	8.59	33.39	0.67	6.17	0.528
	Minimum	9.7	31.07	0.283	26.93	14.99	4.65	58.61	11.8	1.77	0.144
	Maximum	23.75	37.7	0.669	32.09	25.01	13.24	92	12.5	7.95	0.673
	Mean	16.78	35.81	0.47	29.05	22.22	6.83	84.49	12.1	4.83	0.4
	Std. Error	2.61	1.4	0.08	1.1	1.53	1.76	7.18	0.23	1.27	0.11
	Std.deviation	6.83	1.97	0.006	1.2	2.34	3.08	51.53	0.05	1.61	0.012
AE-FUNAI	Range	13.6	9.28	0.362	5.98	10.45	9.48	40.3	0.69	3.28	0.29
	Minimum	10.64	28.51	0.333	27.02	14.67	4.71	51.44	11.8	3.08	0.25
	Maximum	24.24	37.79	0.695	33	25.12	14.19	91.74	12.5	6.36	0.54
	Mean	18.06	35.68	0.508	29.36	22.12	7.25	82.79	12.1	4.99	0.413
	Std. Error	0.11	0.08	0.004	0.06	0.08	0.1	0.41	0.07	0.34	0.029
	Std.deviation	2.39	1.72	0.077	1.28	1.76	2.17	8.54	0.25	1.17	0.102

The histogram diagram shown in Figures 2-4 indicate that the amplitude variations of the meteo-solar parameters such as the clearness index (k_t), the hours of sunshine (S), the fraction of sunshine (S/S_o) and the maximum temperature (T_{max}). Response for strong insolation in AE-FUNAI, EBSU, and AIFPU recorded a similar

stable normal curve corresponding to that of global solar radiation on a horizontal surface (H). It can be observed that the AIFPU site reported a higher normal curve for meteorological parameters such as relative humidity, minimum temperature, maximum duration of the sunshine and extraterrestrial solar radiation compared to the EBSU and AE-FUNAI sites. Therefore, the AIFPU site recorded lower global solar radiation than EBSU and AE-FUNAI. This indicates that the greater the amplitude curvature of these meteorological sites, the lower the monthly average global solar radiation of the ground recorded in EBSU, AIFPU and AE-FUNAI, as well as in other geographic and climatic locations similar to those of Nigeria as presented in Table 2.

4.2 Diurnal Fluctuations of Meteorological Parameters

Values of monthly and annual meteorological parameters observed as global solar radiation on a horizontal surface (H), extraterrestrial solar radiation (H_o), clearness index (k_t), maximum hour of daylight (S_o), sunlight hours (S), sunlight fraction (S/S_o), relative humidity (RH), maximum temperature (T_{max}) and minimum temperature (T_{min}), for EBSU, AIFPU and AE-FUNAI are presented in Table 3 and Figure 5. Diurnal fluctuations in solar-meteorological parameters in response to seasonal changes of the year due to Earth's rotation around the Sun brought about observable changes in the monthly and annual datasets. During the rainy season months (April to October), meteorological parameters such as global solar radiation on a horizontal surface (H), the clearness index (k_t), hours of sunshine (S), fraction of sunlight (S/S_o) and maximum temperature (T_{max}) values are lower than in the dry season (from November to March) as presented in Table 3 and Figure 5. On the contrary, the meteorological-solar parameters such as relative humidity, minimum temperature, maximum solar duration and extraterrestrial solar radiation record the highest values in the rainy season months (April to October) compared to the dry season (November to March) as presented in Table 3 and Figure 5. High values of global solar radiation on a horizontal surface (H), clearness index (k_t), hours of sunshine (S), fraction of sunlight (S/S_o) and maximum temperature (T_{max}) obtained during the dry season can be as a result of low relative humidity and cloud cover, low absorption of diffuse solar radiation and near-infrared radiation in the solar spectrum, long dry season with associated latitude and widespread cloud and atmospheric humidity associated with the movement of Hadley cell circulation system along the equatorial path during this period on Ebony State and its environs, thus improving these meteorological parameters obtained for EBSU, AIFPU and AE-FUNAI. However, the low values of these meteorological parameters obtained during the rainy season may be due to relatively higher cloud cover, relative humidity, long rainy season and greater diffuse and near-infrared radiation absorption in the solar spectrum, resulting in a low global solar radiation received at the site. These trends are similar to the report of some solar energy researchers in the region of tropical rainforest and semi-arid climates of Nigeria (Nwokolo and Ogbulezie [20] for 23 locations sparsely selected in Nigeria; Maduekwe and Chendo [21] for Lagos; Fagbenle [22] for Ibadan; Adaramola [7] for Akure; Ohunakin *et al.* [6] for Osogbo; Okundamiya *et al.* [23] for Ibadan). Maximum and minimum values of the daily average duration of the sunshine occurred in December and August at these three locations respectively as shown in Table 3 and Figure 5. For instance, EBSU recorded maximum of 6.36 hours of sunshine hours and minimum of 3.08 hours with corresponding overall annual average value of 4.99 hours. AIFPU recorded a maximum of 6.13 sunshine hours and a minimum of 2.95 hours with corresponding average values of 4.83 hours.

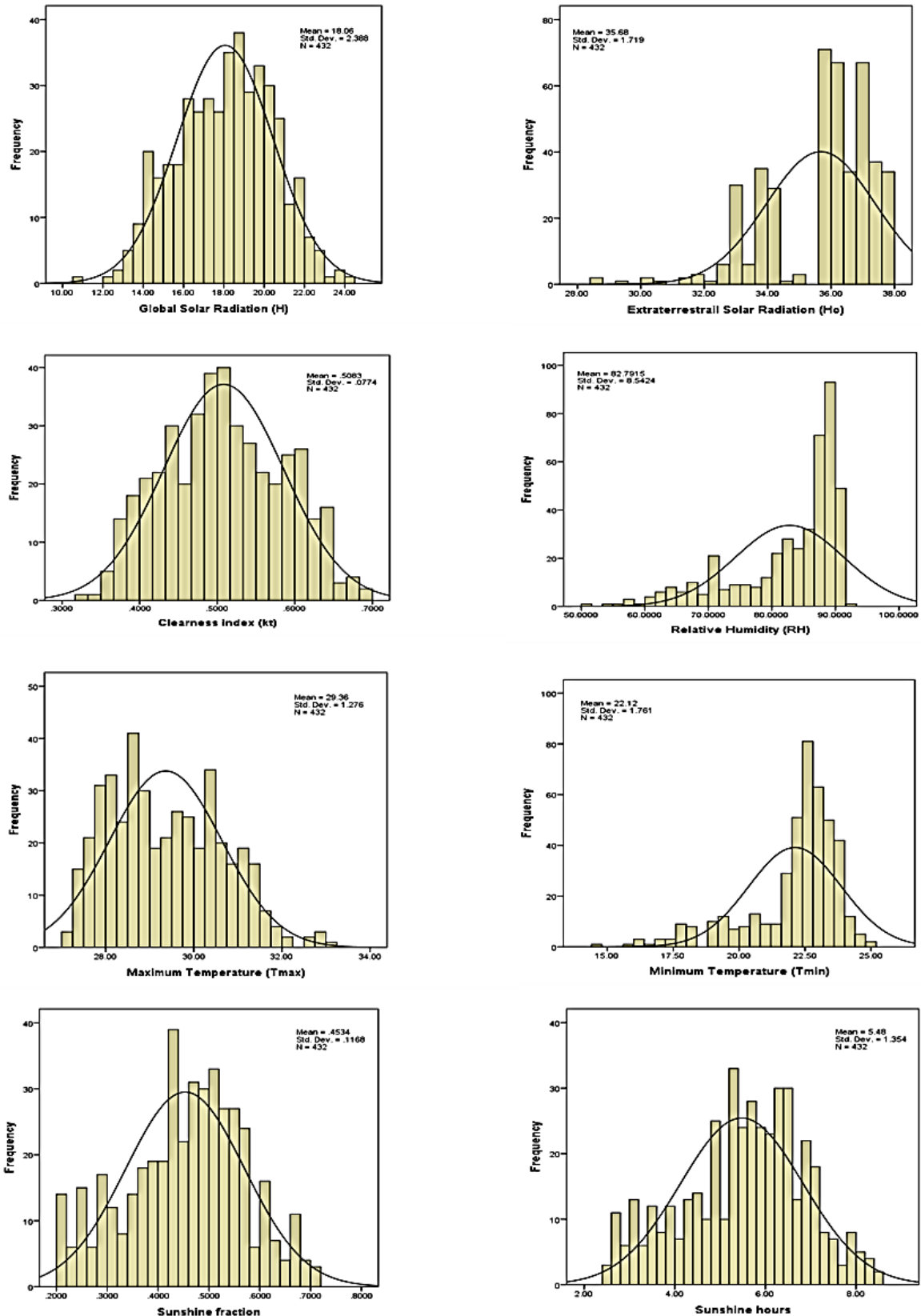


Figure 2. Descriptive statistics for AE-FUNAI

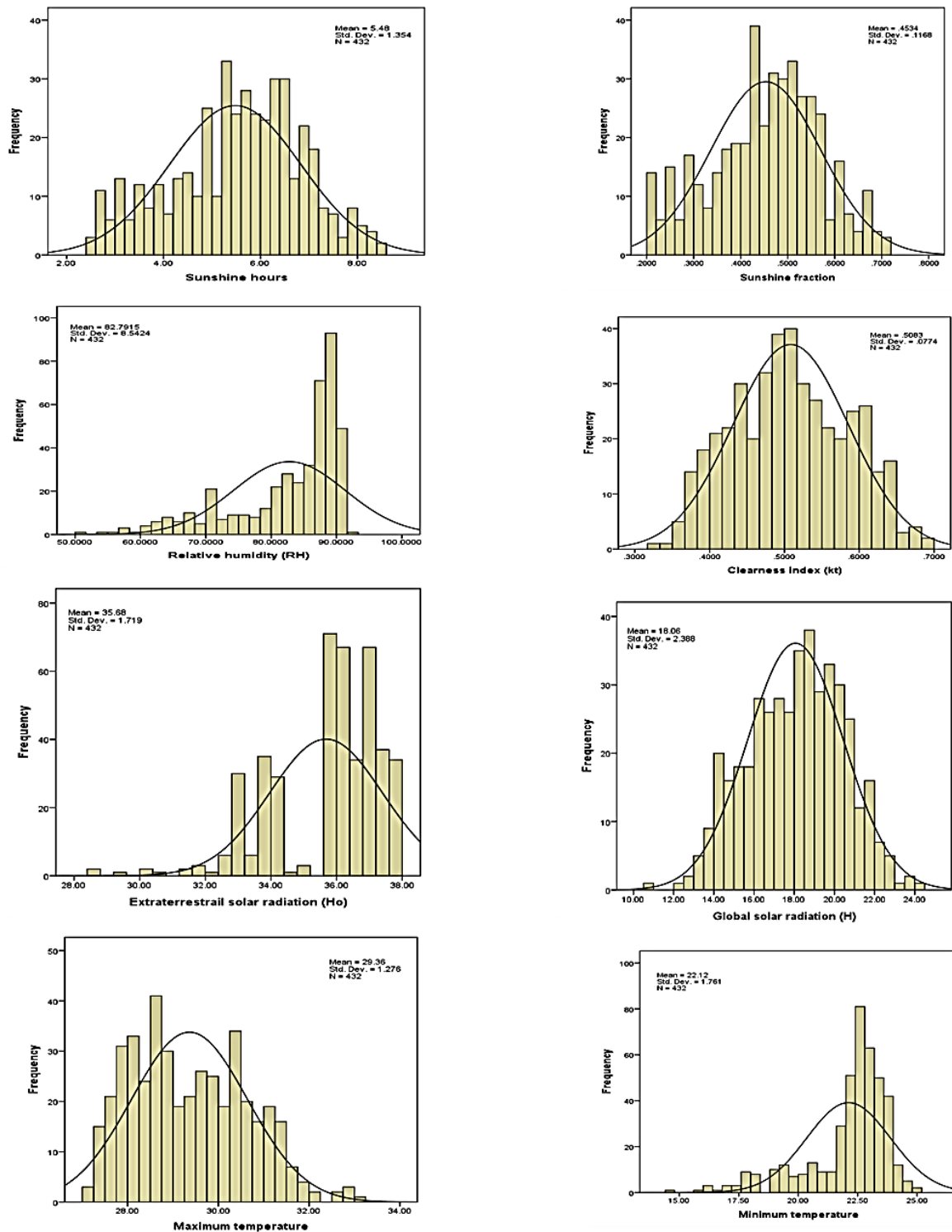


Figure 3. Descriptive statistics for EBSU

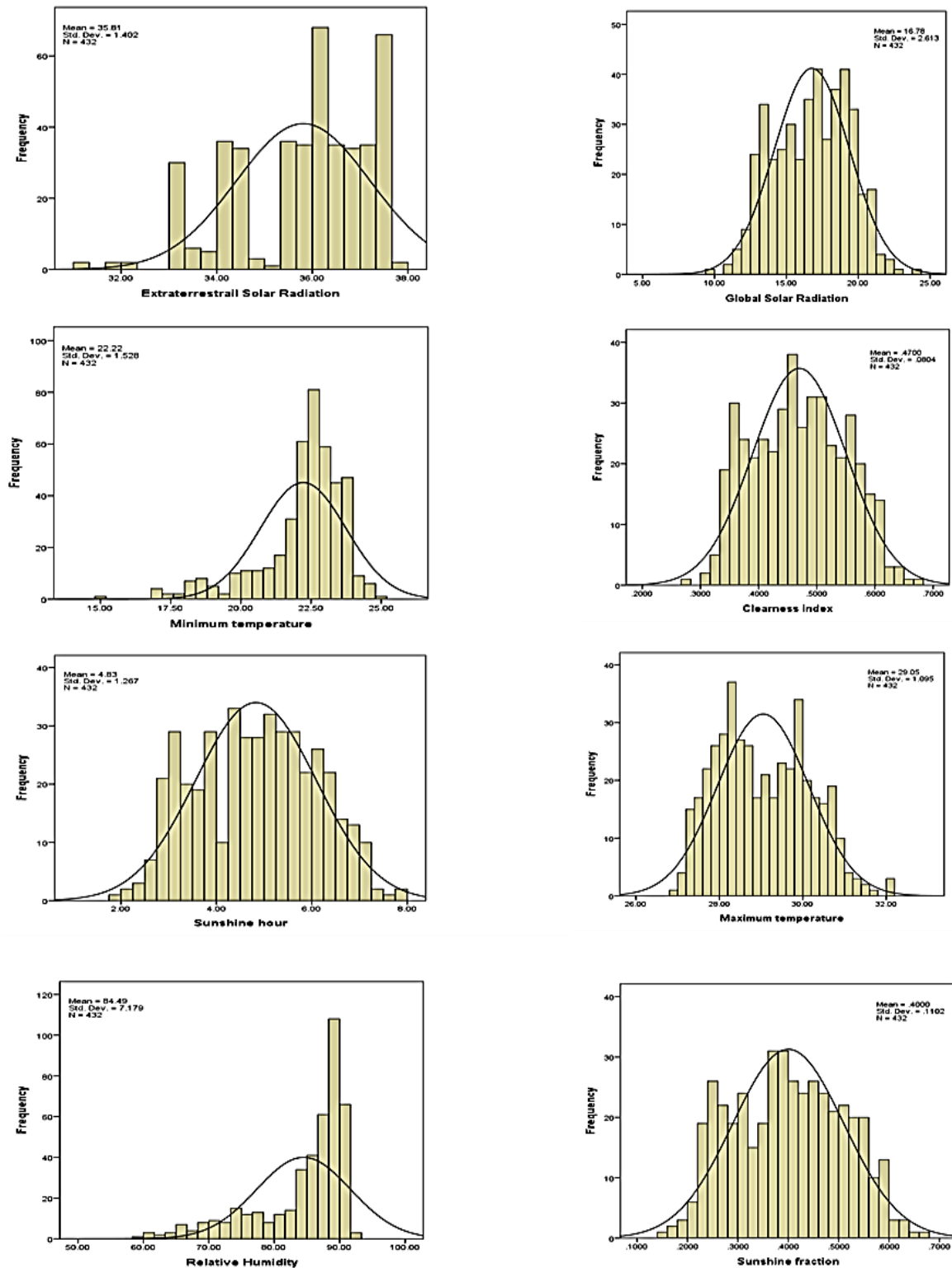


Figure 4. Descriptive statistics for AIFPU

The monthly maxima and minima of the monthly global solar radiation averages occurred in February and August respectively at these three locations as shown in Table 3 and Figure 5. For instance, EBSU recorded $20.71 \text{ MJm}^{-2}\text{day}^{-1}$ for maximum global solar radiation and $14.34 \text{ MJm}^{-2}\text{day}^{-1}$ for the minimum, with a corresponding annual average value of $17.94 \text{ MJm}^{-2}\text{day}^{-1}$. Other details can be found in Table 3. The results validate the results of several authors around the world that meteo-solar parameters such as solar hours, latitude, maximum temperature, relative humidity and other atmospheric parameters influence global solar radiation as reported nationally, Nwokolo and Ogbuluezie, [9]; regional, Nwokolo and Ogbuluezie, [10]; and global review [15].

4.3 Meteo-Solar Classification

4.3.1 Sunshine Fraction

The fraction of monthly sunshine is the ratio of the actual duration of the sun to the maximum possible sunshine duration which varies from one month to another due to the movement of the earth as shown in Table 3. Based on the World Meteorological Organization classification namely: (1) cloudy sky ($0 \leq S/S_o < 0.3$), (2) sky with scattered clouds ($0.3 \leq S/S_o < 0.7$) and (3) clear skies ($0.7 \leq S/S_o \leq 1.0$), sunshine conditions at the three locations (EBSU, AIFPU and AE-FUNAI) are mostly Type 2 sky conditions, except in the months of July to September when this can be viewed as the state of the cloudy sky. These proportions are comparable to the values recorded in the literature in the same warm semi-arid climatic region of Nigeria [18, 24].

4.3.2 Clearness Index

The monthly average clearness index designates the percentage of depletion by the sky of the incoming global solar radiation and therefore indicates both the level of availability of solar radiation and the changes in atmospheric conditions in a given location. The prevailing clearness index ranged between 0.39 - 0.51 for EBSU; 0.36 - 0.49 for AIFPU and 0.40 - 0.51 for AE-FUNAI between the months of April to October in the rainy season and 0.54 - 0.61 for EBSU; 0.50 - 0.58 for AIFPU and 0.55 - 0.62 for AE-FUNAI between the months from January-March to November-December in the dry season with an annual value of 0.51 for EBSU, 0.47 for AIFPU and 0.51 for AE-FUNAI as shown in Table 3. Using the meteorological classification proposed by Iqbal [25] which are: (1) heavily cloudy weather ($k_t \leq 0.4$); (2) partially cloudy weather ($0.4 \leq k_t \leq 0.6$); and (3) clear weather ($k_t \geq 0.7$), Ebonyi's prevailing weather conditions fall within the partially cloudy weather. These indicate that the notable features of Ebony State are the predominance of partially cloudy weather. It has been observed from Table 3 that global solar radiation increases as the clearness index increases and then increases rapidly as heavy cloudy weather becomes lighter. This reveals that the global solar radiation is optimally controlled by the clearness index except during August in EBSU and AE-FUNAI and July to September for the AIFPU sites when the weather conditions can be considered as heavily cloudy weather in Ebonyi State, Nigeria. Meteorological conditions predominant for the three locations within the maximum intensity of solar radiation which occurred in December-January for EBSU (0.61), 0.58 in December-January for AIFPU and 0.62 in January for AE-FUNAI fall within the partially cloudy weather. Predominant weather conditions for Ebonyi within the minimum intensity of solar radiation occurring in August for EBSU (0.39), AIFPU (0.36) and AE-FUNAI (0.40) fall within heavily overcast weather. It is appropriate to state emphatically that the month in which the minimum clearness index occurs (August) represents the peak cloudiness in

which persistent precipitation occurs sandwiched by some days of sunshine, otherwise known as little dry season (LDS) or "August Break" in the local parlance. From Table 3, it can be seen that the EBSU and AE-FUNAI localities recorded respectively 0.39 and 0.40 values in the month of August representing only heavily cloudy weather while the AIFPU recorded values of the clearness index of 0.37, 0.36 and 0.38 in the months of July, August and September respectively in the peak of the months of the rainy season. This indicates that AIFPU's location is more turbid than EBSU and AE-FUNAI due to perhaps, peculiar land-river characteristics, relatively higher cloud cover, relative humidity, prolonged rainy season, and increased absorption of diffuse and near infrared radiation in the spectrum solar radiation, resulting in low global solar radiation received at the site compared to EBSU and AE-FUNAI. In general, it can be concluded that, as the prevailing weather conditions are sampled in parts of EBSU, AIFPU and AE-FUNAI from different parts of Ebonyi State, the skies are mostly clear. This suggests that various photovoltaic solar technologies such as mono-silicon, hybrid silicon, amorphous silicon, cadmium telluride, and poly-silicon can function properly in the State, especially in the EBSU and AE-FUNAI sites.

4.4 Fittings Performance Evaluation

Hybrid regression technique and single parameter were used to estimate monthly average global solar radiation (H) at EBSU, AIFPU and AE-FUNAI representing various institutions of higher education in the Ebonyi State. Consequently, for each institution selected in this study, performance analyses were performed using the adjusted empirical models EM1 -EM6 presented in Table 4. Table 4 presents the regressive functional empirical forms with their respective coefficients, as well as the HS temperature model and the Angstrom-Prescott (AP) sunshine model selected from the literature. The AP model represents the conventional empirical model of the sunshine hour parameter from which at least other linear and non-linear regression techniques are developed using meteo-solar parameters. As a result, HS adopted the AP functional form to develop the temperature model as a power function. It can be seen that the HS model was the first empirical model to calculate the global solar radiation (H) using the temperature parameter, and Angstrom was the first researcher to introduce the linear idea of Kimball [26] in linear functional form correlated with the application of the solar eclipse fraction with H in the clear sky in the convenient functional form that is currently used worldwide as an empirical reference model to estimate H. This technique was instilled to compare the fitted models in this study with the famous HS and AP models because most solar testers often used these models as a reference model to develop other models based on sunshine and temperature parameters for solar systems in order to compare HS and AP coefficients, since models based on temperature and sunshine parameters are the best empirical models available in Nigeria (Nwokolo and Ogbulezie, [20]; India, Makade *et al.* [27]; China, Feng *et al.*, [28]; West Africa, Nwokolo and Ogbulezie, [10], global, Besharat *et al.*, [15]). The error metrics for the training and testing data sets of the six regression models are presented in Table 5. Figures 6 - 8 show the relative performance of the three distinct models (AE-FUNAI, EBSU and AIFPU respectively) comparing the observed and estimated global solar radiation for the three selected higher education institutions sites, using models based on individual parameters and on the training and suitability test categories.

Table 3. Monthly and annual diurnal variability of meteo-solar parameters

PARAMETER	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Ebonyi State University (EBSU)													
RH	67.99	70.97	80.57	84.98	87.33	88.63	89.00	89.07	89.75	89.68	83.37	72.14	82.84
Tmin	19.06	21.15	23.28	23.84	23.69	23.01	22.36	22.25	22.53	22.79	22.09	19.36	22.12
Tmax	30.10	31.24	31.04	30.51	29.66	28.66	28.00	27.98	28.02	28.21	29.40	29.53	29.35
Ho	33.46	35.66	37.30	37.50	36.44	35.73	35.95	36.77	37.01	35.92	33.83	32.58	35.46
H	20.44	20.71	20.16	19.28	18.12	16.78	15.08	14.34	15.71	17.36	18.97	19.84	17.94
Kt	0.61	0.58	0.54	0.51	0.50	0.47	0.42	0.39	0.42	0.48	0.56	0.61	0.51
S	5.79	5.85	5.32	5.64	5.57	4.49	3.23	3.08	3.52	4.80	6.28	6.36	4.99
So	11.82	11.93	12.10	12.25	12.38	12.47	12.43	12.32	12.15	12.00	11.85	11.78	12.12
S/So	0.49	0.49	0.44	0.46	0.45	0.36	0.26	0.25	0.29	0.40	0.53	0.54	0.41
Akanu Ibiam Federal Polytechnic, Unwana (AIFPU)													
RH	71.89	74.90	83.07	86.30	88.09	89.31	89.56	89.50	90.25	90.18	85.44	75.36	84.52
Tmin	19.67	21.58	23.34	23.76	23.59	22.88	22.22	22.07	22.43	22.75	22.36	19.99	22.22
Tmax	29.64	30.63	30.46	30.11	29.41	28.44	27.86	27.90	27.90	28.07	29.02	29.16	29.04
Ho	33.98	35.99	37.38	37.40	36.29	35.50	35.71	36.68	37.11	36.20	34.32	33.17	35.67
H	19.69	19.73	18.75	18.19	16.98	15.25	13.34	13.22	13.94	15.61	17.54	19.10	16.70
Kt	0.58	0.55	0.50	0.49	0.47	0.43	0.37	0.36	0.38	0.43	0.51	0.58	0.47
S	5.56	5.73	5.19	5.50	5.45	4.36	3.11	2.95	3.40	4.56	6.05	6.13	4.83
So	11.82	11.93	12.08	12.23	12.38	12.45	12.43	12.30	12.15	12.00	11.87	11.78	12.12
S/So	0.47	0.48	0.43	0.45	0.44	0.35	0.25	0.24	0.28	0.38	0.51	0.52	0.40
Alex Ekwueme Federal University Ndufu Alike Ikwo (AE-FUNAI)													
RH	67.91	69.97	80.70	84.91	86.33	89.63	89.57	89.05	89.70	89.64	83.40	72.18	82.75
Tmin	19.08	21.13	23.24	23.86	23.67	23.03	22.34	22.27	22.55	22.76	22.07	19.40	22.12
Tmax	30.15	31.20	31.01	30.53	29.65	28.64	28.01	27.97	28.04	28.23	29.42	29.51	29.37
Ho	33.67	35.81	37.47	37.64	36.69	35.89	36.10	36.92	37.17	36.06	34.07	32.83	35.86
H	20.82	21.19	20.51	19.33	18.17	16.87	15.40	14.69	15.76	17.23	18.97	20.07	18.25
Kt	0.62	0.59	0.55	0.51	0.50	0.47	0.43	0.40	0.42	0.48	0.56	0.61	0.51
S	5.79	5.85	5.32	5.64	5.57	4.49	3.23	3.08	3.52	4.80	6.28	6.36	4.99
So	11.82	11.93	12.10	12.25	12.38	12.47	12.43	12.32	12.15	12.00	11.85	11.78	12.12
S/So	0.49	0.49	0.44	0.46	0.45	0.36	0.26	0.25	0.29	0.40	0.53	0.54	0.41



Figure 5. Monthly diurnal variability of meteo-solar parameters for EBSU, AIFPU & AE-FUNAI

H represents the monthly mean daily global solar radiation ($\text{MJm}^{-2}/\text{day}^{-1}$), H_0 represents monthly mean daily extraterrestrial solar radiation ($\text{MJm}^{-2}/\text{day}^{-1}$), k_t is a dimensionless parameter known as monthly mean daily clearness index, S/S_0 is a dimensionless parameter known as the monthly mean daily sunshine fraction, S is the monthly mean sunshine hours, S_0 is the monthly mean maximum sunshine hours, RH is

the monthly mean relative humidity (%), $T_{\min}$ is the monthly mean minimum temperature ($^{\circ}\text{C}$), $T_{\max}$ is the monthly mean maximum temperature ($^{\circ}\text{C}$).

From Table 5, it can be understood that the six regression models used in the different locations accurately estimated the observed average global solar radiation based on the error metric evaluations. The EM6 model classified as a hybrid model based on parameters with input of sunshine fraction shows variation between maximum and minimum temperature, maximum sunshine hours and relative humidity shows better performance in terms of training and test error measures compared to EM1 - EM5 using the difference between maximum and minimum temperature (EM1 and EM2), fraction of sunshine duration (EM3), variation between maximum and minimum temperature and maximum parameters of sunshine (EM4) and relative humidity (EM5) in EBSU, AIFPU and AE-FUNAI. To universally apply the applicability of the AP solar model (EM8) and HS temperature model (EM7) to the HS type models (EM1) and AP (EM3) developed by this study as presented in Table 4, error metrics are presented in Table 5. It may be noted that EM1 and EM3 developed in EBSU, AIFPU and AE-FUNAI performed better than the original AP (EM8) model and the HS model (EM7). This could be attributed to the geographical and climatic factors used to obtain the coefficients of the model EM8 (AP) and the model EM7 (HS). North American meteo-solar parameter is completely different from three meteo-solar parameters used in this study. To test the applicability of the universally applied AP (EM8) sunshine model and the HS (EM7) temperature model to the best performing hybrid (EM6) in the three locations, the metrics indicate that rates of applied error EM6 was better than EM7 (HS) and EM8 (AP) as presented in Table 5. This could be attributed to the geographic and climatic factors used to obtain the coefficients of the EM8 (AP) model and the EM7 (HS) model. North American meteo-solar parameter is completely different from three solar-meteorological parameters in the locations used in this study.

Table 4. Developed models in this study together with frequently employed models for estimating global solar radiation using various meteorological parameters in AIFPU, AE-FUNAI and EBSU in Nigeria

S/N	Algebraic Equation	Parameter	Station/Country	Study	Model #
1	$\frac{H}{H_o} = 0.181703(\Delta T)^{0.5}$	Temperature	AIFPU, Nigeria	Present	EM1
2	$\frac{H}{H_o} = -0.058 + 0.204(\Delta T)^{0.5}$	Temperature	AIFPU, Nigeria	Present	EM2
3	$\frac{H}{H_o} = 0.264 + 0.464\left(\frac{S}{S_o}\right)$	Sunshine	AIFPU, Nigeria	Present	EM3
4	$\frac{H}{H_o} = 0.238 + 0.415\left(\frac{\Delta T}{S_o}\right)$	Hybrid	AIFPU, Nigeria	Present	EM4
5	$\frac{H}{H_o} = 1.234 - 0.899\left(\frac{RH}{100}\right)$	Relative humidity	AIFPU, Nigeria	Present	EM5
6	$\frac{H}{H_o} = -0.249 + 0.709\left(\frac{S}{S_o}\right) - 0.509\left(\frac{S}{S_o}\right)^2 + 0.357(\Delta T)^{0.5} - 0.470\left(\frac{\Delta T}{S_o}\right) - 0.177\left(\frac{RH}{100}\right)$	Hybrid	AIFPU, Nigeria	Present	EM6
1	$\frac{H}{H_o} = 0.19059(\Delta T)^{0.5}$	Temperature	FUNAI, Nigeria	Present	EM1
2	$\frac{H}{H_o} = 0.070 + 0.164(\Delta T)^{0.5}$	Temperature	FUNAI, Nigeria	Present	EM2
3	$\frac{H}{H_o} = 0.299 + 0.464\left(\frac{S}{S_o}\right)$	Sunshine	FUNAI, Nigeria	Present	EM3
4	$\frac{H}{H_o} = 0.311 + 0.326\left(\frac{\Delta T}{S_o}\right)$	Hybrid	FUNAI, Nigeria	Present	EM4
5	$\frac{H}{H_o} = 1.118 - 0.739\left(\frac{RH}{100}\right)$	Relative humidity	FUNAI, Nigeria	Present	EM5

6	$\frac{H}{H_o} = -0.275 + 0.814 \left(\frac{S}{S_o}\right) - 0.643 \left(\frac{S}{S_o}\right)^2 + 0.218(\Delta T)^{0.5} - 0.360 \left(\frac{\Delta T}{S_o}\right) - 0.435 \left(\frac{RH}{100}\right)$	Hybrid	FUNAI, Nigeria	Present	EM6
1	$\frac{H}{H_o} = 0.191588(\Delta T)^{0.5}$	Temperature	EBSU, Nigeria	Present	EM1
2	$\frac{H}{H_o} = 0.053 + 0.172(\Delta T)^{0.5}$	Temperature	EBSU, Nigeria	Present	EM2
3	$\frac{H}{H_o} = 0.298 + 0.469 \left(\frac{S}{S_o}\right)$	Sunshine	EBSU, Nigeria	Present	EM3
4	$\frac{H}{H_o} = 0.306 + 0.340 \left(\frac{\Delta T}{S_o}\right)$	Hybrid	EBSU, Nigeria	Present	EM4
5	$\frac{H}{H_o} = 1.127 - 0.744 \left(\frac{RH}{100}\right)$	Relative humidity	EBSU, Nigeria	Present	EM5
6	$\frac{H}{H_o} = -0.301 + 0.707 \left(\frac{S}{S_o}\right) - 0.529 \left(\frac{S}{S_o}\right)^2 + 0.207(\Delta T)^{0.5} - 0.081 \left(\frac{\Delta T}{S_o}\right) + 0.124 \left(\frac{RH}{100}\right)$	Hybrid	EBSU, Nigeria	Present	EM6

Frequently employed models from Literature

1	$\frac{H}{H_o} = 0.17(\Delta T)^{0.5}$	Temperature	North America	Hargreave-Samani	EM7
2	$\frac{H}{H_o} = 0.25 + 0.54 \left(\frac{S}{S_o}\right)$	Sunshine	North America	Angstrom-Preseccott	EM8

Table 5. Statistical metrics of empirical models developed for EBSU, AIFPU and AE-FUNAI, Nigeria

Study	Country	Method	Model No	Training					Testing				
				MBE	MPE	RMSE	RRMSE	R ²	MBE	MPE	RMSE	RRMSE	R ²
Present	EBSU, Nigeria	Empirical	EM1	-0.0022	-0.0227	0.1540	0.9979	0.4159	-0.0001	-0.0021	0.0635	1.1727	0.6503
Present	EBSU, Nigeria	Empirical	EM2	-0.0027	-0.0263	0.1498	0.9821	0.4109	-0.0002	-0.0031	0.0618	1.1571	0.6427
Present	EBSU, Nigeria	Empirical	EM3	0.0015	0.0044	0.1212	0.7357	0.5864	0.0017	0.0069	0.0853	1.4733	0.3534
Present	EBSU, Nigeria	Empirical	EM4	-0.0022	-0.0239	0.1493	0.9773	0.4058	-0.0001	-0.0024	0.0634	1.1818	0.6277
Present	EBSU, Nigeria	Empirical	EM5	-0.0038	-0.0334	0.1577	1.0320	0.3578	0.0000	-0.0023	0.0664	1.2282	0.5946
Present	EBSU, Nigeria	Empirical	EM6	0.0000	-0.0011	0.0457	0.8372	0.7979	-0.0015	-0.0135	0.1074	0.6758	0.6989
HS	North America	Empirical	EM7	0.0163	0.0842	0.2026	1.2169	0.4159	0.0063	0.0329	0.1207	2.1053	0.6503
AP	North America	Empirical	EM8	-0.0037	-0.0280	0.1311	0.8242	0.5575	-0.0001	-0.0034	0.0855	1.5116	0.3285
Present	AIFPU, Nigeria	Empirical	EM1	0.0001	-0.0031	0.0713	1.4559	0.6238	0.0029	-0.0364	1.5307	11.3552	0.4675
Present	AIFPU, Nigeria	Empirical	EM2	0.0001	-0.0026	0.0707	1.4323	0.6297	-0.0026	-0.0328	1.5235	11.2107	0.4754
Present	AIFPU, Nigeria	Empirical	EM3	-0.0001	-0.0048	0.0908	1.7495	0.3452	0.0059	-0.0489	1.5181	10.6077	0.5561
Present	AIFPU, Nigeria	Empirical	EM4	0.0001	-0.0036	0.0723	1.4636	0.6191	0.0032	-0.0367	1.5040	11.1184	0.4831
Present	AIFPU, Nigeria	Empirical	EM5	-0.0001	-0.0036	0.0718	1.4419	0.6235	0.0053	-0.0494	1.5730	11.6136	0.4835
Present	AIFPU, Nigeria	Empirical	EM6	0.0001	-0.0013	0.0521	1.0362	0.7890	-0.0029	-0.0255	1.0533	7.4179	0.7739
HS	North America	Empirical	EM7	0.0034	0.0170	0.0946	1.7915	0.6238	0.0069	0.0256	1.7333	11.9041	0.4675
AP	North America	Empirical	EM8	0.0023	0.0179	0.1027	2.0297	0.3551	0.0126	-0.0885	1.7852	12.6083	0.5728
Present	AE-FUNAI, Nigeria	Empirical	EM1	0.0035	-0.0297	1.4369	9.3590	0.5735	0.0001	-0.0028	0.7296	13.5724	0.4567
Present	AE-FUNAI, Nigeria	Empirical	EM2	-0.0032	-0.0296	1.4027	9.2546	0.5631	0.0001	-0.0032	0.6954	13.1496	0.4473
Present	AE-FUNAI, Nigeria	Empirical	EM3	0.0015	0.0044	1.2116	7.3568	0.5854	0.0012	0.0037	0.8960	15.7531	0.3228

Present	AE-FUNAI, Nigeria	Empirical	EM4	- 0.0024	- 0.0254	1.3956	9.2324	0.5500	0.0003	-0.0010	0.7198	13.4796	0.4208
Present	AE-FUNAI, Nigeria	Empirical	EM5	- 0.0025	- 0.0259	1.5621	10.1624	0.5693	0.0000	-0.0026	0.6933	12.9603	0.3578
Present	AE-FUNAI, Nigeria	Empirical	EM6	- 0.0031	- 0.0219	1.1031	6.8804	0.7447	- 0.0002	-0.0026	0.5370	9.9125	0.6876
HS	North America	Empirical	EM7	0.0143	0.0732	1.8343	11.0012	0.5735	0.0059	0.0307	1.1758	20.6347	0.4564
AP	North America	Empirical	EM8	- 0.0021	- 0.0191	1.2639	7.9053	0.5537	0.0000	-0.0038	0.8995	16.1253	0.2992

5. Conclusion and Recommendations

5.1 Conclusion

The present study found that the locally simulated empirical model performed better for global solar radiation on a monthly and annual time scale in AE-FUNAI, EBSU and AIFPU due to the performance evaluation metrics obtained in the error metric evaluation in Table 5. Based on these, the models proposed for AE-FUNAI, EBSU and AIFPU (model numbers EM6 in Table 4) can be judged as an efficient empirical approach to estimate H. Therefore, the simulated models could be largely applied to the monthly forecast of global solar radiation in AE-FUNAI, EBSU and AIFPU as follows:

For AE-FUNAI,

$$\frac{H}{H_o} = -0.275 + 0.814 \left(\frac{S}{S_o}\right) - 0.643 \left(\frac{S}{S_o}\right)^2 + 0.218 (\Delta T)^{0.5} - 0.360 \left(\frac{\Delta T}{S_o}\right) - 0.435 \left(\frac{RH}{100}\right) \quad 11$$

For EBSU,

$$\frac{H}{H_o} = -0.301 + 0.707 \left(\frac{S}{S_o}\right) - 0.529 \left(\frac{S}{S_o}\right)^2 + 0.207 (\Delta T)^{0.5} - 0.081 \left(\frac{\Delta T}{S_o}\right) + 0.124 \left(\frac{RH}{100}\right) \quad 12$$

For AIFPU,

$$\frac{H}{H_o} = -0.249 + 0.709 \left(\frac{S}{S_o}\right) - 0.509 \left(\frac{S}{S_o}\right)^2 + 0.357 (\Delta T)^{0.5} - 0.470 \left(\frac{\Delta T}{S_o}\right) - 0.177 \left(\frac{RH}{100}\right) \quad 13$$

However, these models are open to adjustment and calibration, since numerous meteorological parameters can be incorporated into the empirical model. However, the proposed numerical models (equations 11, 12 and 13) can be used to estimate H in any part of Ebonyi State with similar climatic conditions as AE-FUNAI, EBSU and AIFPU respectively, since it has the mathematical capabilities and the necessary coefficients to function as a statistical model sufficiently and efficiently. Equations 11, 12 and 13 are the model numbers EM6 for each of the stations: AE-FUNAI, EBSU and AIFPU respectively as vividly presented in Table 4. They are the best performing hybrid models as demonstrated by the statistical key performance metrics presented in Table 5 for each of the model numbers EM6 of the individual stations. These results are further corroborated by the plots in Figure 4, Figure 5 and Figure 6 for AE-EUNAI, EBSU and AIFPU respectively.

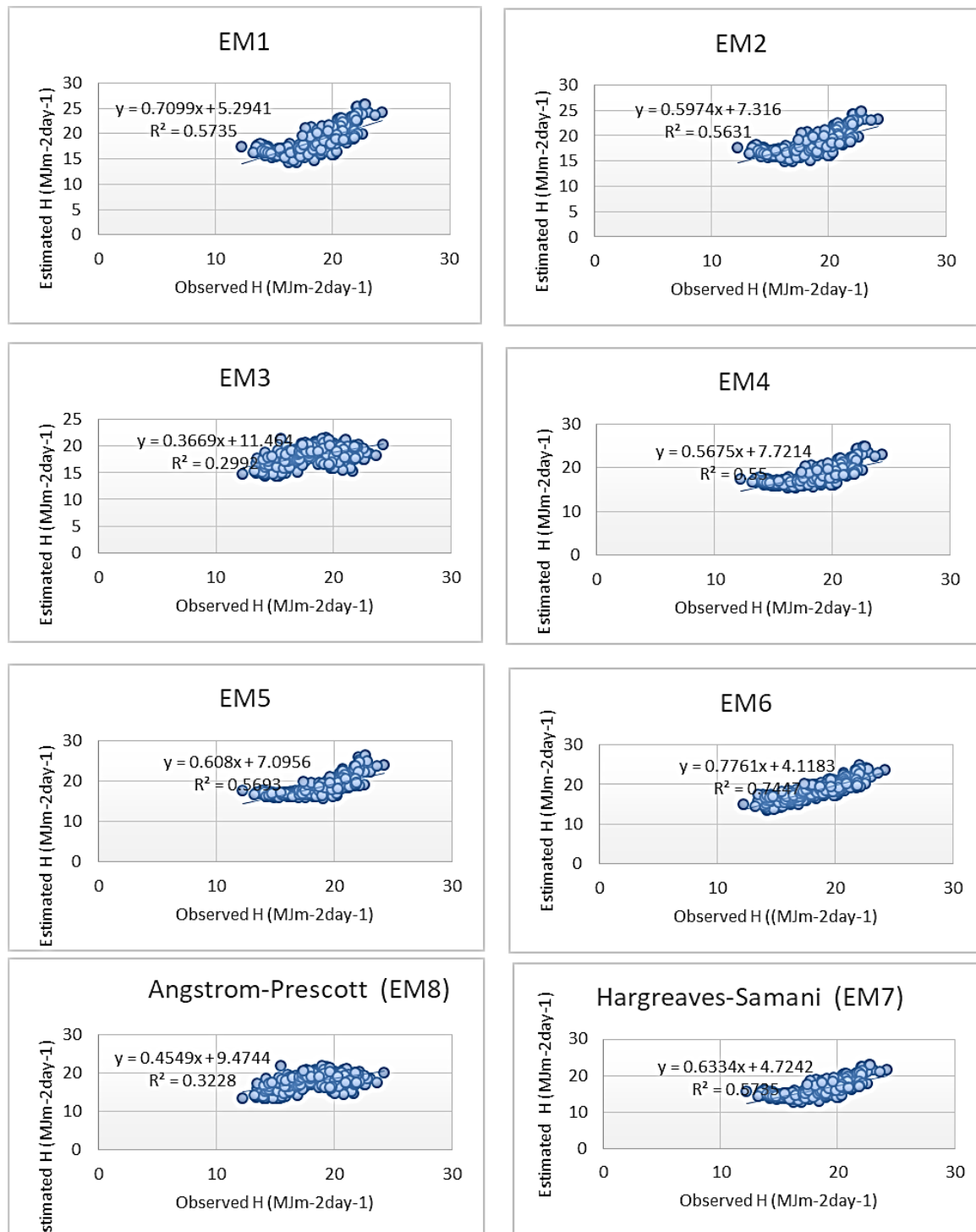


Figure 6. Comparison between observed and estimated for AE-FUNAI

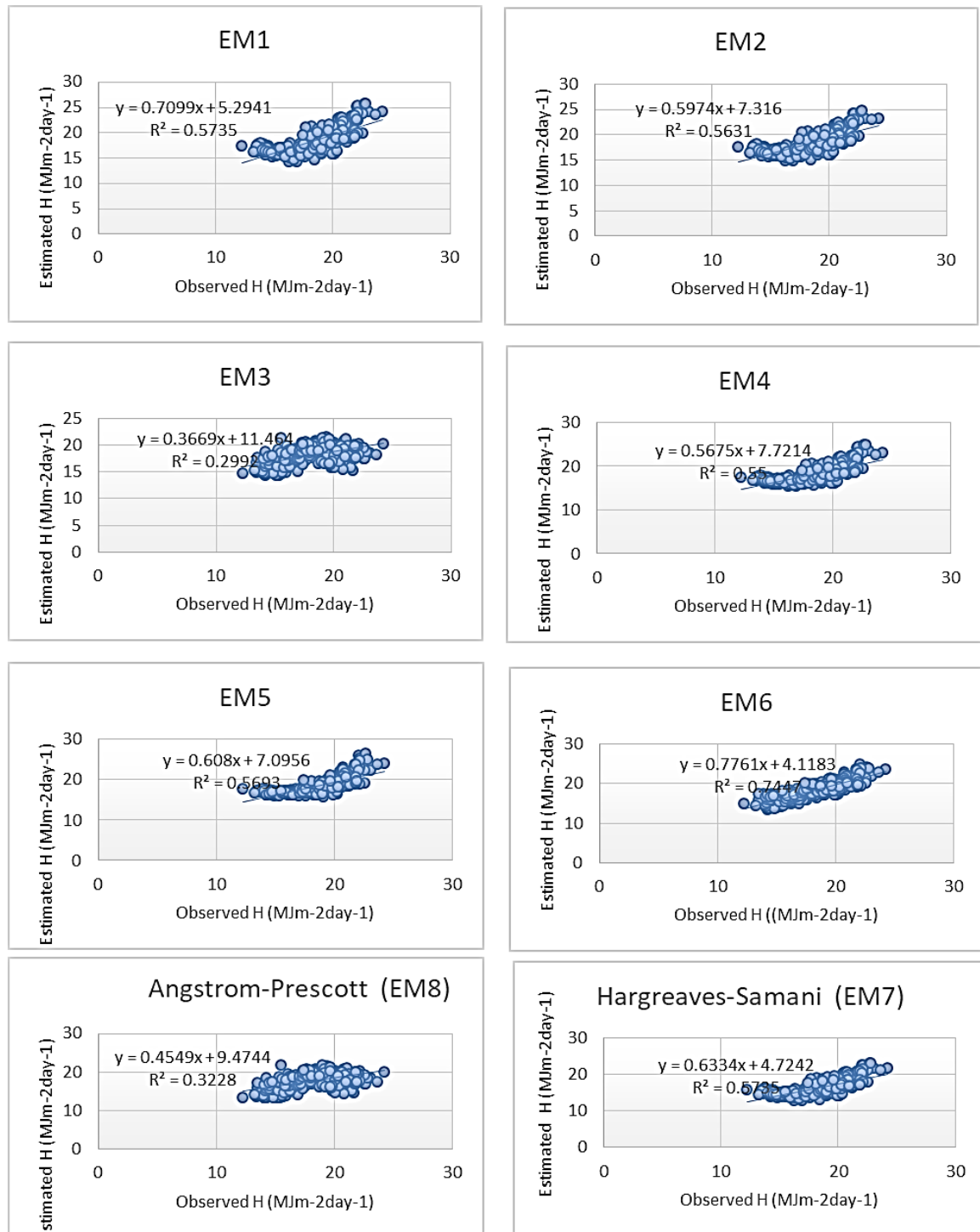


Figure 7. Comparison between observed and estimated for EBSU

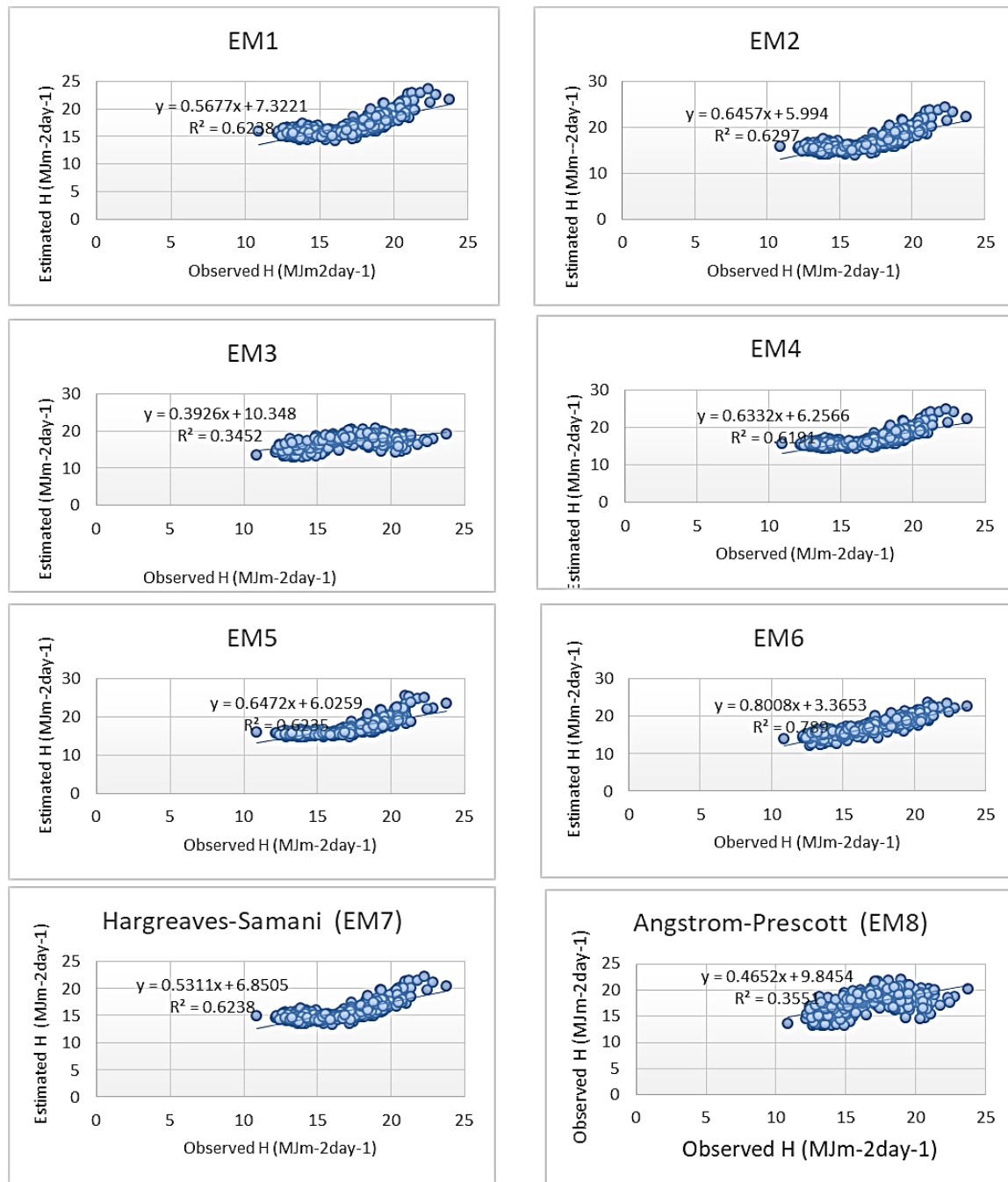


Figure 8. Comparison between observed and estimated for AIFPU

5.2 Recommendations

The researcher recommends routine calibration of the various computational models developed in this study (equations 11 - 13). This is because the historical data used to calibrate the models directly ignores the ever-changing climate over time, which may achieve the good performance of the calibrated models in the calibration years, but as the dataset stretches, the instability of the calibrated models can be seen. The researcher also recommends that the stimulated model coefficients for the evaluation of global solar radiation be regularly calibrated for the remaining municipal towns and

remote villages in order to obtain a local coefficient applicable throughout the state of Ebonyi in order to facilitate the evaluation of the global solar radiation data easily without a network of instrumentation that would otherwise be needed.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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The Impact of Operating Frequencies and Neural Network Training Program Properties on the Performance of Neural Network Topology Generator Methodology

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Until now, Neural Network Topology Generator Methodology (NNTGM) has been theoretically proposed so that its generated overhead low-voltage broadband over power lines topologies (NNTGM OV LV BPL topologies) may populate the existing OV LV BPL topology classes. With reference to the OV LV BPL topology class maps, which are defined by the graphical combination of ACA and RMS-DS of the OV LV BPL topologies, and the NNTGM OV LV BPL topology footprints for given indicative OV LV BPL topologies, the impact on the relative position and the size of the NNTGM OV LV BPL topology footprints has been assessed for a number of factors that affect the preparation of the Topology Identification Methodology (TIM) OV LV BPL topology database being used during the NNTGM operation. In this companion paper, the effect of the operating frequencies and the Neural Network (NN) training program properties on the relative position and the size of the NNTGM OV LV BPL topology footprints is here examined. The effect study is supported by suitable Graphical Performance Indicators (GPIs).

Keywords: Smart Grid; Broadband over Power Lines (BPL) networks; Power Line Communications (PLC); Distribution and Transmission Power Grids; Neural Networks; Simulation; Modeling

Introduction

Overhead Low-Voltage (OV LV) power lines, originally not intended for data transmission, exhibit varying line lengths, impedance, and noise, which can degrade signal quality if not properly managed. By accurately classifying and updating these OV LV Broadband over Power Lines (OV LV BPL) topologies, network operators can optimize signal propagation and minimize interference based on real-time grid conditions, which is especially important as grids incorporate renewable energy and smart technologies [1]. Detailed topology information may enhance channel modeling and routing algorithms, improving network reliability and scalability of smart grids. Populating OV LV BPL topology classes with appropriate OV LV BPL topologies has become a critical task in modern BPL networks since machine learning (ML) techniques can also benefit from the data, enabling predictive and automated grid management as power networks evolve in complexity [2].

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Neural Network Topology Generator Methodology (NNTGM), which has been theoretically proposed in [3] and numerically tested in [4], addresses the need for generating appropriate virtual OV LV BPL topologies (NNTGM OV LV BPL topologies) that can populate OV LV BPL topology classes. Based on the topological characteristics of the indicative OV LV BPL topologies of the topology classes, NNTGM OV LV BPL topologies of each examined topology class maintain the topological characteristics of its indicative one but with similar virtual channel attenuation behavior. Actually, NNTGM, which is the last member of the neural network identification methodology (NNIM)-based family products, achieves to generate similar channel attenuation behaviors for given OV LV BPL topological characteristics by procedurally reversing the network identification methodology for the line length approximation (NNIM-LLA) [5-7]. Exploiting artificial intelligence (AI), ML and neural network (NN) features, the ability of NNTGM to create NNTGM OV LV BPL topologies that imitate the characteristics of the real-world OV LV BPL topologies has been demonstrated on OV LV BPL topology class maps, which are based on the graphical representation at the same plot of the average theoretical channel attenuation (ACA) and the root mean square delay-spread (RMS-DS) [4].

Based on the OV LV BPL topology class maps and the corresponding graphical performance indicators (GPIs), the impact of the parameters of the NNTGM operation settings on the relative position and the size of the NNTGM virtual topology footprints have first been assessed in [4] and are further examined in this paper. In accordance with [3, 4], NNTGM OV LV BPL topologies lie close to their indicative OV LV BPL topologies thus defining the respective NNTGM virtual topology footprints. To assess the relative position and the size of the NNTGM virtual topology footprints with respect to the corresponding OV LV BPL topology class borderlines, two GPIs have been applied in [4]; say, the percentage of the NNTGM OV LV BPL topologies that remain inside the OV LV BPL topology class of their respective indicative OV LV BPL topology and the percentage of the NNTGM OV LV BPL topologies that remain inside specific ACA / RMS-DS limits with respect to their indicative OV LV BPL topology. According to [3, 4], the impact of the following parameters of the NNTGM operation settings on the NNTGM virtual topology footprints have been recognized and benchmarked, namely: (i) The inclusion or not of the examined indicative OV LV BPL topology in the Topology Identification Methodology (TIM) OV LV BPL topology database during the NNTGM operation;

(ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments. In this paper, with reference to the NNTGM default operation settings of [3], the impact of the following parameters of the NNTGM operation settings on the NNTGM virtual topology footprints and GPIs are further assessed, namely: (i) The operating frequencies (i.e., frequency range and flat-fading subchannel frequency spacing); and (ii) the participation percentages of the three phases (training, validation and testing) of the MATLAB NN training program of NNTGM [8, 9]. The findings of this paper are combined with the ones of [4] so that a more extended populating strategy for the OV LV BPL topology class can be available.

The rest of this paper is organized as follows: Section 2 synthesizes the class maps and GPIs of the indicative OV LV BPL topologies of [3] when the NNTGM default operation settings of [3] are adopted. Section 3 analyzes the impact of the aforementioned parameters of the NNTGM operation settings on the NNTGM virtual topology footprints and GPIs. Section 4 concludes this paper.

NNTGM Default Operation Settings, OV LV BPL Topology Class Maps and GPIs

In this Section, NNTGM has been proposed in [3]. In order to assess NNTGM performance when various parameters of its operation settings change, NNTGM default operation settings are briefly reported in this Section. Also, the channel attenuation metrics of ACA and RMS-DS and the occurring OV LV BPL topology class maps for the indicative OV LV BPL topologies of [3] with their respective NNTGM virtual OV LV BPL topologies are also given in this Section for benchmark purposes. Finally, GPIs, which have first been demonstrated in [4] and assessed the impact of the parameter changes of the NNTGM operation settings on the relative position and the size of the NNTGM virtual topology footprints of the OV LV BPL topology classes, are also given in this Section.

NNTGM Definition and NNTGM Default Operation Settings

NNTGM procedurally reverses NNIM-LLA by exploiting its same main components; say, the TIM OV LV BPL topology database and the MATLAB NN training program [5-7]. In fact, TIM OV LV BPL topology database acts as the big data pool for the NNTGM operation while it contains the following fields: (i) the ID number p of the OV LV BPL topology when the number of all OV LV BPL topologies in the TIM OV LV BPL topology database is equal to P ; (ii) the actual number of branches N of the OV LV BPL topology; (iii) the actual lengths of the distribution lines of each OV LV BPL topology; (iv) the actual lengths of the branch lines of each OV LV BPL topology; and

(v) the theoretical coupling scheme channel transfer function values with respect to the frequency. In contrast with the preparation of the TIM OV LV BPL topology database for the other NNIM-based family products, TIM OV LV BPL topology database for NNTGM should be filtered so as to contain only OV LV BPL topologies with the lengths of their distribution and branch lines to remain close to the respective values of the examined indicative OV LV BPL topology, as it has been defined in [3]. Therefore, NNTGM virtual topologies are expected to present theoretical channel attenuation behaviors that can remain close to the one of the examined indicative OV LV BPL topology but this can be further adjusted by the change of the parameters of the NNTGM operation settings as it has been shown in [4].

With reference to [4], the NNTGM default operation settings support NNTGM virtual topology footprints that remain close to the examined indicative OV LV BPL topology in each scenario with extents that confine NNTGM virtual topology footprints to remain inside the class of the examined indicative OV LV BPL topology in the vast majority of the cases. As it has previously been mentioned, the NNTGM default operation settings are based on the database representativeness principle of [5], namely:

- For given examined indicative OV LV BPL topology, its number of the branches and its actual lengths of the distribution and branch lines are assumed to be known thus the OV LV BPL topologies that are going to be included in the TIM OV LV BPL topology database are defined by eqs. (4)-(8) of [3] in each case.

- For given examined indicative OV LV BPL topology, the total number of the OV LV BPL topologies that are added in the TIM OV LV BPL topology database is given in eq. (9) of [3] with the inclusion of the indicative OV LV BPL topology in the TIM OV LV BPL topology database that is the default option of the parameter. As the default operation setting values are concerned, the length of the distribution and branch line segments are assumed to be equal to 1m and 1m, respectively, while the number of the distribution and branch line segments are assumed to be equal to 1 and 1, respectively. It is clear that the aforementioned NNTGM default operation setting parameter selection focuses on generating NNTGM virtual topology footprints that derive from the examined indicative OV LV BPL topology in each scenario while higher values of the aforementioned parameters are expected to relax the position and the extent of the NNTGM virtual topology footprints.
- The total distribution line length is assumed to be equal to 1,000m in all the OV LV BPL topologies of the TIM OV LV BPL topology database. Also, the terminations of all the OV LV BPL topologies of the TIM OV LV BPL topology are assumed to be open-circuit ones in a similar way to the indicative OV LV BPL topologies of Table 1 of [3]. With reference to [10, 11], the applied coupling scheme is the WtG¹ one.
- In the TIM OV LV BPL topology database, as its OV LV BPL topologies are concerned the amplitudes of the coupling scheme channel transfer functions are stored in dB with respect to the frequency.
- As the operating frequencies of NNTGM default operation settings are concerned, the frequency range is assumed to be equal to 1-30MHz while the flat-fading subchannel frequency spacing is assumed to be equal to 1MHz. Hence, the number of flat-fading subchannels is equal to 29. In this short paper, the impact of the frequency range and the flat-fading subchannel frequency spacing on the NNTGM virtual topology footprints are going to further be investigated.
- As the NNTGM is based on the MATLAB NN training program of [8, 9], the default participation percentages of its three phases; say, training, validation and testing phases, are assumed to be equal to 70%, 15% and 15%, respectively. In this paper, the impact of the participation percentages of the three phases on the NNTGM virtual topology footprints are going to further be investigated.

Apart from the default operation settings, to assess the performance of NNTGM, the channel attenuation metrics of ACA and RMS-DS, which are exploited for the preparation of the OV LV BPL topology class maps, and the GPIs are briefly presented in the following subsection.

NNTGM Channel Attenuation Metrics, OV LV BPL Topology Class Maps and GPIs

Similarly to the class maps of [12-16], OV LV BPL topology class maps of [3, 4] have been plotted by using channel attenuation metrics for their two axes; say, ACA and RMS-DS. With reference to eqs. (11), (12) of [3], ACA can be calculated for each indicative OV LV BPL topology or NNTGM virtual topology by averaging the amplitudes of the coupling scheme channel attenuations in dB over the flat-fading subchannels while RMS-DS measures the average channel attenuation distance from ACA for the examined OV LV BPL topologies over the same flat-fading subchannels. By

exploiting the pair of ACA and RMS-DS values, each indicative OV LV BPL topology with its NNTGM virtual topologies can graphically define its OV LV BPL topology footprint on the class map. With reference to [3, 4], footprints of the indicative OV LV BPL topologies present graphical origin and proximity to their indicative OV LV BPL topologies while their positions and sizes on the class map depend on the applied NNTGM operation settings.

To demonstrate the OV LV BPL topology class areas on the class maps and examine the behavior of the OV LV BPL topology footprints, two graphical milestones are illustrated on the class maps. First, the two class borderlines are roughly derived as the median lines between the neighboring indicative OV LV BPL topologies of [3] when the NNTGM default operation settings are applied; say, the class borderline (rural-suburban) and the class borderline (suburban-urban). Second, the ACA / RMS-DS box of $\pm 10\%$, which results from the variation of $\pm 10\%$ in the values of ACA and RMS-DS, is defined around each indicative OV LV BPL topology for the applied NNTGM operation settings. With reference to the two previous graphical milestones, two GPIs have been defined in [4] and are going to be applied here in order to evaluate the way of populating the OV LV BPL topology classes with respect to the applied NNTGM operation settings, namely:

- *Inside the class:* This GPI has to do with the percentage of the NNTGM OV LV BPL topologies that remain inside the OV LV BPL topology class of their respective indicative OV LV BPL topology. Note that the class borderlines are the ones of [4] since the changes of the NNTGM operation settings may affect the ACA / RMS-DS position of the indicative OV LV BPL topologies on the class maps of this paper.
- *Inside the box:* The percentage of the NNTGM OV LV BPL topologies that remain inside the ACA / RMS-DS box of $\pm 10\%$ with respect to their indicative OV LV BPL topology. Note that the ACA / RMS-DS box of $\pm 10\%$ is defined for each indicative OV LV BPL topology per each examined scenario and could be differentiated by the respective ACA / RMS-DS boxes of $\pm 10\%$ of [4]. Dashed lines around each examined indicative OV LV BPL topology are going to be used for the ACA / RMS-DS box of $\pm 10\%$.

To evaluate the impact of the applied NNTGM operation settings of this paper on the NNTGM performance, the combined use of class maps and GPIs is going to significantly help towards the assessment.

Class Maps and GPIs for the NNTGM Default Operation Settings

With reference to [4], in Figure 1, the OV LV BPL topology class map with the NNTGM virtual topology footprints of the rural case, suburban case and urban case A of [3] is presented when the NNTGM default operation settings are applied. Each NNTGM virtual topology footprint consists of 100 NNTGM virtual topologies that are related with the indicative OV LV BPL topology of the class and the footprint. Apart from the two class borderlines, the three ACA / RMS-DS boxes of $\pm 10\%$ of the respective three indicative OV LV BPL topologies are also added. The aforementioned GPIs are applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes and are reported in Table 1.

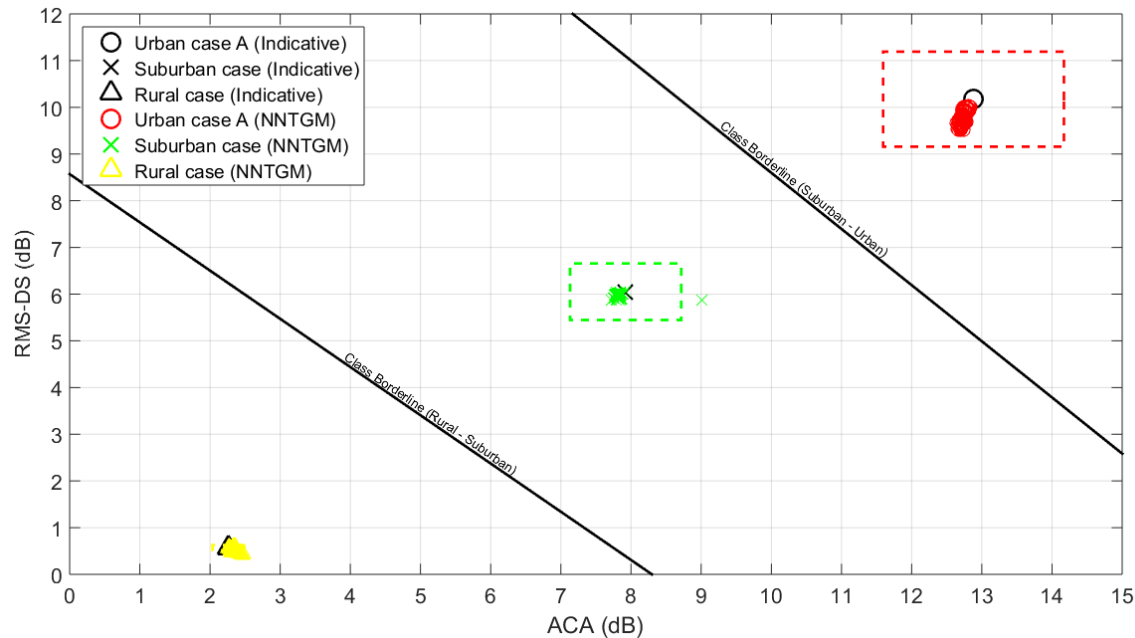


Fig. 1. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied [4].

Table 1. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied) [4]

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	100	100
Inside the box (%)	84	99	100

As already mentioned in [4], the OV LV BPL topology footprints remain significantly close to the respective indicative OV LV BPL topologies when the NNTGM default operation settings are applied. Namely, 100% of the NNTGM OV LV BPL topologies remain inside the borders of their corresponding OV LV BPL topology class while the majority of the NNTGM OV LV BPL topologies (i.e., above 84%) remain inside the ACA / RMS-DS box of $\pm 10\%$ of their corresponding indicative OV LV BPL topology. Therefore, the NNTGM default operation settings allow the creation of strict OV LV BPL topology footprints to their respective indicative OV LV BPL topologies thus locally populating the OV LV BPL topology classes.

Figure 1 and Table 1 act as the benchmark values so that the impact of a number of NNTGM operation setting parameters could be assessed. Until now, the parameters that have been assessed in [4] are: (i) The inclusion or not of the examined indicative OV LV BPL topology in the TIM OV LV BPL topology database during the NNTGM operation; (ii) the length of the distribution / branch line segments; and (iii) the number of the distribution / branch line segments. In the following Section, the impact assessment continues with the following parameters of the NNTGM operation settings, namely: (i) The operating frequencies (i.e., frequency range and flat-fading subchannel frequency spacing); and (ii) the participation percentages of the three phases (training, validation and testing) of the MATLAB NN training program of NNTGM [8, 9].

The Impact of the Different NNTGM Operation Settings on the NNTGM Virtual Topology Footprints

In this Section, the impact of the following parameters of the NNTGM operation settings of [3] on the NNTGM virtual topology footprints and GPIs is going to be investigated, namely: (i) The operating frequencies; and (ii) the participation percentages of the three phases of the MATLAB NN training program of NNTGM.

Operating Frequencies and Their Impact on NNTGM Virtual Topology Footprints and GPIs

As it has already mentioned, when the operating frequencies of NNTGM default operation settings are concerned, the frequency range is assumed to be equal to 1-30MHz while the flat-fading subchannel frequency spacing is assumed to be equal to 1MHz. Hence, the number of flat-fading subchannels is equal to 29. To investigate the impact of operating frequencies on NNTGM virtual topology footprints and GPIs, the frequency range and the flat-fading subchannel frequency spacing should be separately investigated.

As the frequency range is concerned, in Figure 2, the OV LV BPL topology class map with the NNTGM virtual topology footprints of the rural case, suburban case and urban case A of [3] is presented when the NNTGM default operation settings are applied but the frequency range is assumed to be wider; say, the frequency range is equal to 1-88MHz. In Figure 2, the flat-fading subchannel frequency spacing remains the same with the one of NNTGM default operation settings; say, 1MHz. Similarly to Figure 1, each NNTGM virtual topology footprint comprises 100 NNTGM virtual topologies per indicative OV LV BPL topology. The two class borderlines of Figure 1 and the three ACA / RMS-DS boxes of $\pm 10\%$ of the respective three indicative OV LV BPL topologies for the current NNTGM operation settings are also added. The same GPIs of Table 1 are applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes of Figure 2 and are reported in Table 2.

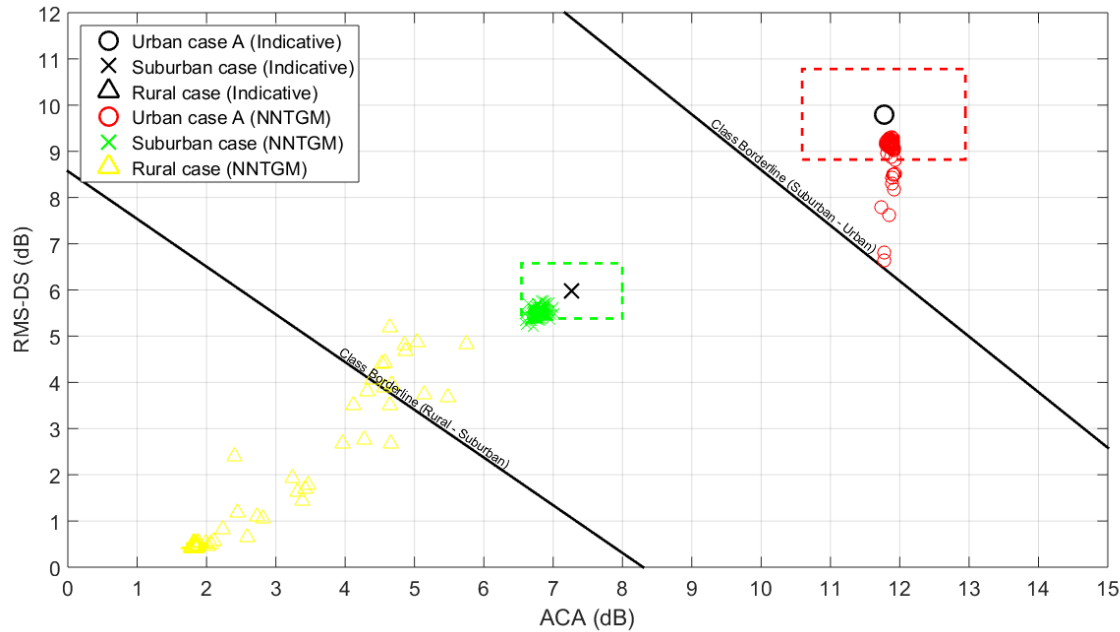


Fig. 2. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but the frequency range is equal to 1-88MHz.

Table 2. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied but the frequency range is equal to 1-88MHz)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	88	100	100
Inside the box (%)	65	90	89

Comparing Figures 1 and 2, the extended frequency range does not significantly affect the position of the three examined indicative OV LV BPL topologies and their ACA / RMS-DS boxes of $\pm 10\%$ on the class map. Anyway, the two class borderlines of Figure 2 are the same with the ones of Figure 1 regardless of the changes of the NNTGM operation settings. As the extent of the NNTGM virtual topology footprints is examined, verifying the observations of the Figures with the data of Tables 1 and 2, the footprints of the indicative rural case and urban case A are primarily and secondarily affected, respectively, whereas the footprint of the indicative suburban case is slightly affected only in the case of their ACA / RMS-DS boxes of $\pm 10\%$. More specifically, the only OV LV BPL topology footprint that exceed the class borderlines is the one of the rural case with 12 NNTGM OV LV BPL topologies while 19, 9 and 11 more NNTGM OV LV BPL topologies now leave the ACA / RMS-DS boxes of $\pm 10\%$ of the rural, suburban and urban case A, respectively, in comparison with the corresponding NNTGM OV LV BPL topologies of the NNTGM default operation settings of Table 1. Exhibiting similar footprint and GPI behaviors with the case of the length increase of the branch line segment of the NNTGM default operation settings as reported in [4], the wider frequency range of 1-88MHz has as a result a wider class populating for the rural case, a slightly

wider class populating for the urban case A but the same class populating behavior for the suburban case and this is due to the fact that the wider 1-88MHz frequency range increases the number of flat-fading subchannels and, thus, the size of the NNTGM generated channel attenuation column vectors of eq. (3) of [3] and the inner big data of the TIM OV LV BPL topology database. The new spectral notches that occur in the newly added 30-88MHz frequency range are numerically described in the NNTGM generated channel attenuation column vectors in the same way that the new spectral notches from the length increase of the branch line segments have been taken into account. From the previous change, the most affected indicative OV LV BPL topology is the rural one since the relatively smaller number of corresponding OV LV BPL topologies in the TIM OV LV BPL topology database with rare spectral notches is critically affected. From the perspective of sparsely populating the OV LV BPL topology classes, the increase of the frequency range mainly supports sparse NNTGM virtual topology footprints for the rural class. Except for the change of the frequency range, the impact of the flat-fading subchannel frequency spacing on the NNTGM virtual topology footprints is also investigated.

As the flat-fading subchannel frequency spacing is concerned, in Figure 3, the OV LV BPL topology class map with the NNTGM virtual topology footprints of the rural case, suburban case and urban case A of [3] is presented when the NNTGM default operation settings are applied but the flat-fading subchannel frequency spacing is assumed to be wider; say, the flat-fading subchannel frequency spacing is equal to 2MHz. In Figure 3, the frequency range remains almost the same with the one of NNTGM default operation settings; say, 1-31MHz instead of 1-30MHz so that the last 2MHz flat-fading subchannel frequency spacing can fit into the frequency range. Similarly to Figures 1 and 2, the same number of 100 NNTGM virtual topologies are generated per indicative OV LV BPL topology while the two class borderlines of Figure 1 are again plotted the same in Figure 3 and the three ACA / RMS-DS boxes of $\pm 10\%$ of the respective three indicative OV LV BPL topologies for the current NNTGM operation settings are also added. The same GPIs of Tables 1 and 2 are applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes of Figure 3 and are reported in Table 3.

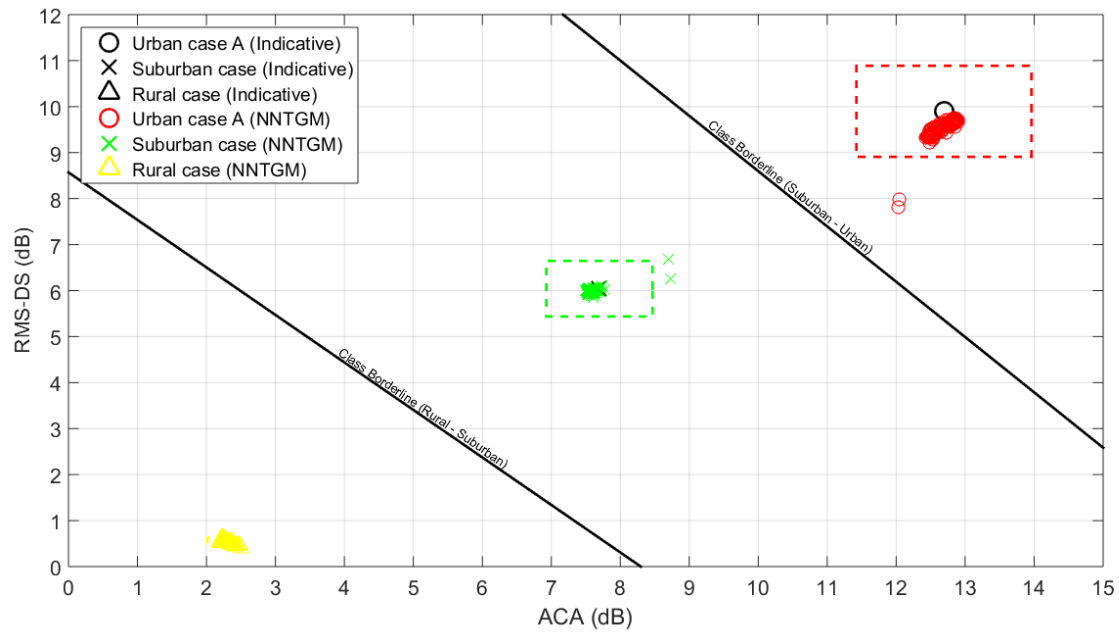


Fig. 3. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but the flat-fading subchannel frequency spacing is equal to 2MHz.

Table 3. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied but the flat-fading subchannel frequency spacing is equal to 2MHz)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	100	100
Inside the box (%)	75	98	98

Comparing Figures 3 with Figures 1 and 2, the extended flat-fading subchannel frequency spacing presents the complementary effect to the increase of the frequency range on the footprints of the class map. First, the position of the three examined indicative OV LV BPL topologies and their ACA / RMS-DS boxes of $\pm 10\%$ remains almost unchanged on the class map with respect to the class borderlines of the NNTGM operation settings. As the extent of the NNTGM virtual topology footprints is examined, verifying the observations of the Figures with the data of Tables 1-3, the footprints of the indicative rural, suburban case and urban case A are shrunk with reference to the respective ones of the NNTGM default operation settings. In fact, all the NNTGM OV LV BPL topologies remain inside the borders of their corresponding OV LV BPL topology classes while the majority of the NNTGM OV LV BPL topologies (i.e., above 75%) remain inside the ACA / RMS-DS box of $\pm 10\%$ of the examined indicative OV LV BPL topologies. Despite the lower values of the inside the box GPI for the footprints of the three indicative OV LV BPL topologies, all the three footprints are more shrunk and located closer to their indicative OV LV BPL topologies in comparison with the respective footprints of the NNTGM default operation settings. In contrast with the increase of the frequency range, the number of flat-fading subchannels decreases given the same frequency range thus reducing the size of the NNTGM generated channel

attenuation column vectors of eq. (3) of [3] and the inner big data of the TIM OV LV BPL topology database. The spectral notches that occur in the 1-31MHz frequency range with 2MHz flat-fading subchannel frequency spacing are less or equal to the ones of 1MHz flat-fading subchannel frequency spacing. From the previous change, all the three indicative OV LV BPL topologies get less affected. From the perspective of densely populating the OV LV BPL topology classes, the increase of the flat-fading subchannel frequency spacing mainly supports dense NNTGM virtual topology footprints that remain close to their indicative OV LV BPL topologies.

Except for the operating frequencies, MATLAB NN training program is a critical module for the operation of all the NNIM-based family products [5-7]. Hence, all the parameters of the MATLAB NN training program may significantly affect the performance of NNTGM and the class maps. In the following subsection, the participation percentages of the three phases of the MATLAB NN training program, which is a fundamental part of the MATLAB training program operation, are further examined.

Participation Percentages of the Three Phases of the MATLAB NN Training Program and Their Impact on NNTGM Virtual Topology Footprints and GPIs

As it has already mentioned, when the participation percentages of the three phases of the MATLAB NN training program of NNTGM default operation settings are concerned [8, 9], the default participation percentages of its three phases; say, training, validation and testing phases, are assumed to be equal to 70%, 15% and 15%, respectively. To investigate the impact of the participation percentages of the three phases on the NNTGM virtual topology footprints and GPIs, three value scenarios are going to be studied, where in each scenario one participation percentage will take an extreme value, say 98%, and the other two participation percentages will balance to 100% with equal values between them, say 1% and 1%. As the operating frequencies and the frequency range are concerned, these are assumed to be unchanged and the same with the ones of NNTGM default operation settings; say, 1-30MHz and 1MHz, respectively.

In Figure 4, the OV LV BPL topology class map with the NNTGM virtual topology footprints of the rural case, suburban case and urban case A of [3] is presented when the NNTGM default operation settings are applied but the training, validation and testing phase participation percentages are assumed to be equal to 98%, 1% and 1%, respectively. The two class borderlines of Figure 1 remain the same in Figure 4 while the three ACA / RMS-DS boxes of $\pm 10\%$ of the respective three indicative OV LV BPL topologies for the current NNTGM operation settings are also added. The same GPIs of Table 1 are applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes of Figure 4 and are reported in Table 4. Same plots with Figure 4 are given in Figures 5 and 6, but for the training, validation and testing phase participation percentage sets being equal to [1%, 98%, 1%] and [1%, 1%, 98%], respectively. Tables 5 and 6 report the GPIs of Table 1 applied to the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes of Figures 5 and 6, respectively.

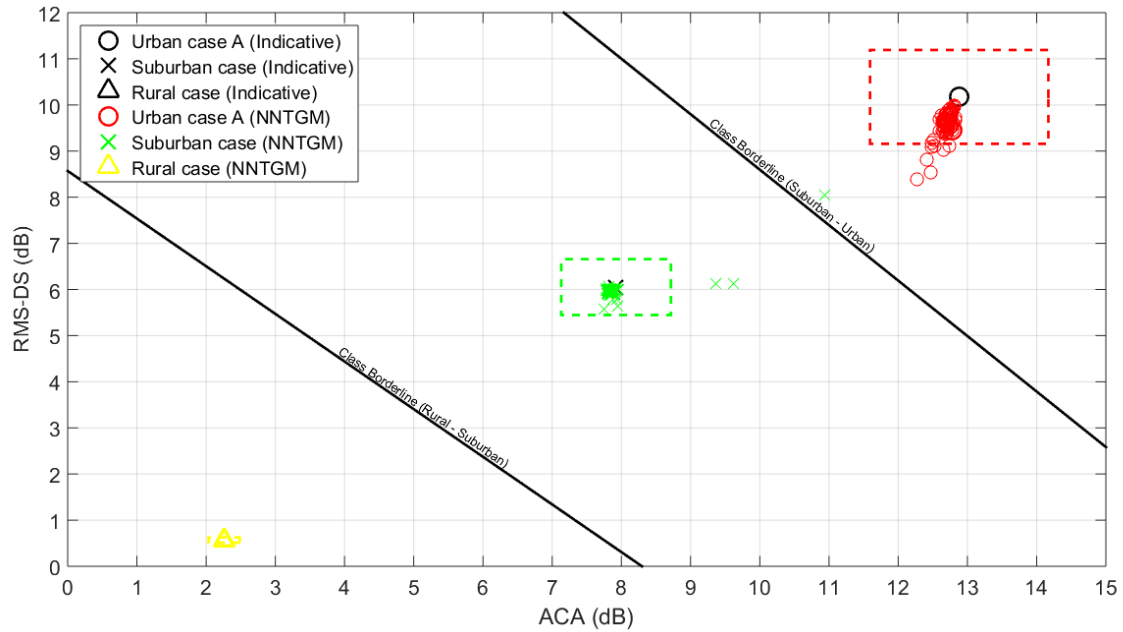


Fig. 4. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but for training, validation and testing phase participation percentages being equal to 98%, 1% and 1%, respectively.

Table 4. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied but the training, validation and testing phase participation percentages are equal to 98%, 1% and 1%, respectively)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	99	100
Inside the box (%)	100	97	93

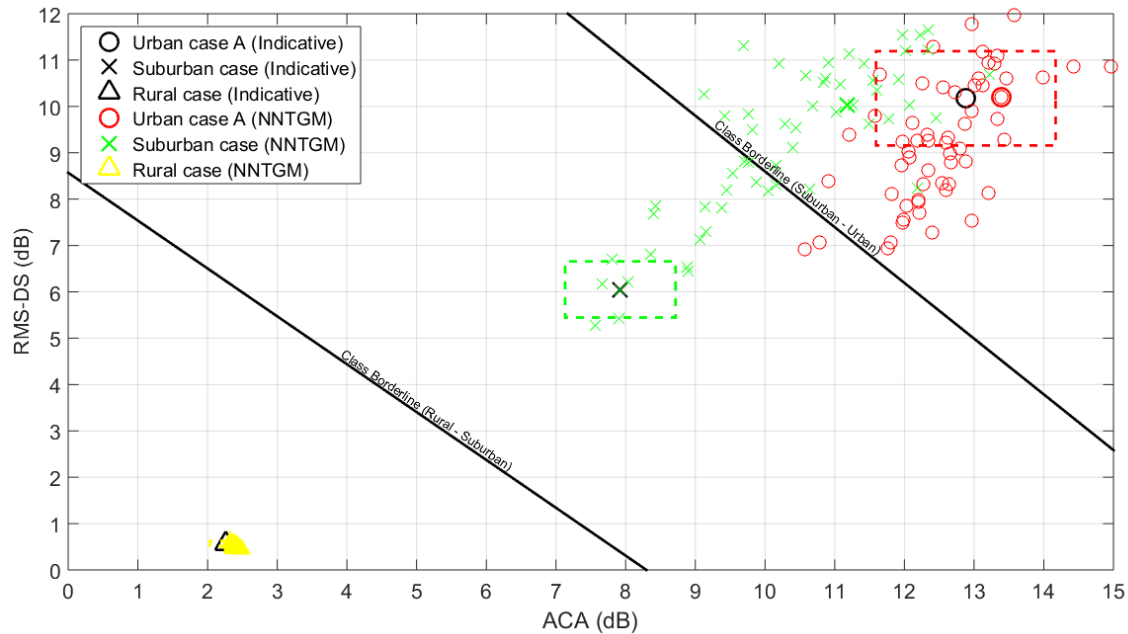


Fig. 5. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but for training, validation and testing phase participation percentages being equal to 1%, 98% and 1%, respectively.

Table 5. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied but the training, validation and testing phase participation percentages are equal to 1%, 98% and 1%, respectively)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	98	23	100
Inside the box (%)	46	4	26

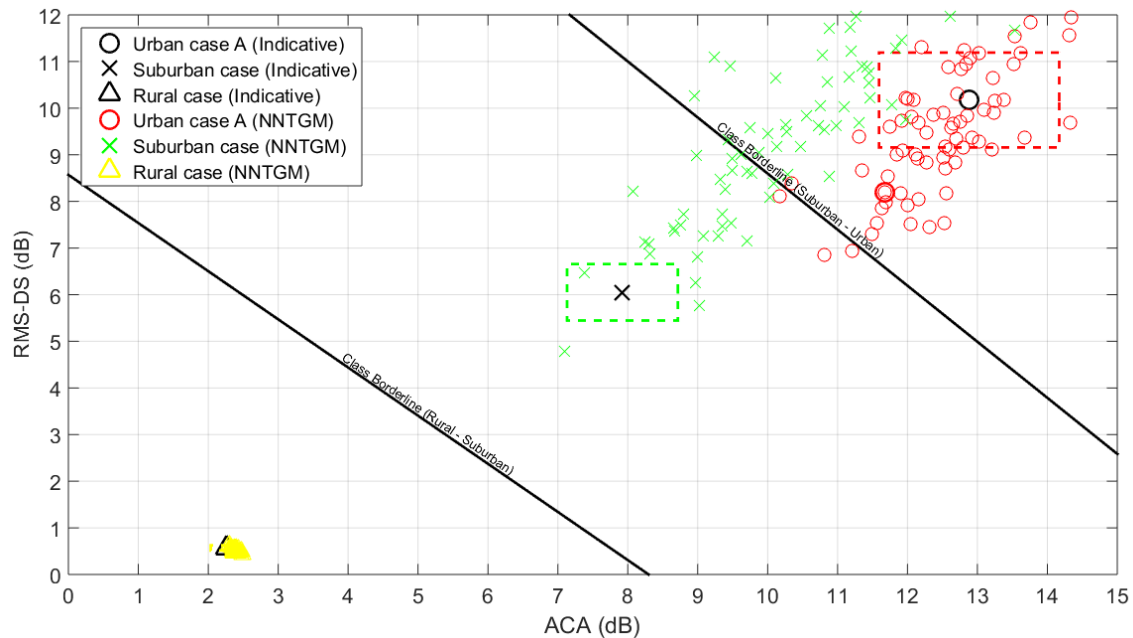


Fig. 6. OV LV BPL topology class map with NNTGM virtual topology footprints of the three indicative OV LV BPL topologies when the NNTGM default operation settings are applied but for training, validation and testing phase participation percentages being equal to 1%, 1% and 98%, respectively.

Table 6. GPIs of the NNTGM OV LV BPL topologies of the three OV LV BPL topology classes (NNTGM default operation settings are applied but the training, validation and testing phase participation percentages are equal to 1%, 1% and 98%, respectively)

GPI	OV LV BPL topology class		
	Rural case class	Suburban case class	Urban case A class
Inside the class (%)	100	29	97
Inside the box (%)	34	1	33

Comparing Figures 4-6 with Figures 1-3, the changes in the training, validation and testing phase participation percentages may support a new sparse populating pattern of the footprints on the class map for the suburban case and urban case A. More specifically:

- With reference to Figure 4, the enhanced training phase participation percentage of 98%, which anyway is the enhanced version of the training phase participation percentage of 70% of the NNTGM default operation settings, force NNTGM virtual topology footprints to be more concentrated to their respective indicative OV LV BPL topologies for all the cases, thus creating a confined populating pattern. Indeed, from Table 4, all the NNTGM OV LV BPL topologies remain inside the borders of their corresponding OV LV BPL topology classes when the vast majority of the NNTGM OV LV BPL topologies (i.e., above 93%) remain inside the ACA / RMS-DS box of $\pm 10\%$ of the examined indicative OV LV BPL topologies. In accordance with NNTGM definition of [3], the enhanced training phase participation percentage of the MATLAB NN training program generates

- NNTGM virtual topologies with low stochasticity that finally remain close to their corresponding indicative OV LV BPL topologies.
- With reference to Figures 5 and 6, the enhanced validation and testing phase participation percentages may support a new populating pattern of the OV LV BPL topology classes for the suburban case and urban case A that is different from all the populating patterns presented until now and in [4]. In fact, the low training phase participation percentage of the MATLAB NN training program generates NNTGM virtual topologies with high stochasticity that further create NNTGM virtual topology footprints of high extents tending to move away from the indicative suburban case and urban case A class borderlines with a significant number of NNTGM virtual topologies presenting higher values for both ACA and RMS-DS. Indeed, as the high validation phase participation percentage is concerned in Table 5, only 4% and 26% of the NNTGM OV LV BPL topologies remain inside the ACA / RMS-DS box of $\pm 10\%$ for the examined indicative suburban case and urban case A, respectively. Similarly, when the high testing phase participation percentage is concerned in Table 6, only 1% and 33% of the NNTGM OV LV BPL topologies remain inside the ACA / RMS-DS box of $\pm 10\%$ for the examined indicative suburban case and urban case A, respectively. In fact, when low participation percentages for the training phase are assumed, MATLAB NN training program fails to learn the meaningful patterns of the OV LV BPL topologies in the TIM OV LV BPL topology database leading to poor generalization and high bias. The inadequate training phase forces the MATLAB NN training program to learn patterns for the validation and testing sets instead of generalizing from the training set thus causing slow or failed convergence.
 - As the NNTGM virtual topology footprint of the rural case is examined, the changes of the participation percentages of the three phases of the MATLAB NN training program does not have any significant effect on the inside the class GPI. In contrast, the low training phase participation percentage of the MATLAB NN training program have almost the same impact on the inside the box GPI of the rural case with the one of the urban case A. Anyway, the absolute extent of the NNTGM virtual topology footprint of the rural case remains significantly lower on the class map in comparison with the NNTGM virtual topology footprint of the urban case A rather indicating a dense populating option.

From the perspective of generating virtual topologies for populating OV LV BPL topology classes, the previous findings concerning the impacts of the participation percentages of the three phases of the MATLAB NN training program on the NNTGM virtual topology footprints may allow the sparse populating when low participation percentages of the training phase are concerned. In this case, the suburban case is characterized by sparse populating either outside the class or outside the box with reference to the corresponding GPIs. As the footprints of the rural case and the urban case A are regarded in the case of the low participation percentages of the training phase, these footprints present sparse populating as the inside the box GPI is examined. Despite the similar values of the inside the class GPIs of the rural case and the urban case A, the footprint extent of the urban case A inside its class borderlines is significantly wide indicating a sparse populating inside the class when low participation percentages of the training phase are applied. In conclusion, the low participation percentages for the training phase lead to a MATLAB NN training program that is highly sensitive to small variations in the data, making it less stable since the MATLAB NN training program

memorizes the OV LV BPL topologies of the TIM OV LV BPL topology database instead of learning general patterns thus sparsely populating the corresponding OV LV BPL topology classes.

Conclusions

In this paper, additional numerical results for populating OV LV BPL topology classes by applying NNTGM are demonstrated and analyzed. In [3], the theory for populating OV LV BPL topology classes by applying NNTGM has been given while the first numerical results and parameter investigation have been given in [4]. With reference to the class maps and the GPIs, the impact of the following NNTGM parameters on the NNTGM virtual topology footprints, whose significance has already been recognized in [3], has been assessed, namely: (i) The operating frequencies (i.e., frequency range and flat-fading subchannel frequency spacing); and (ii) the participation percentages of the three phases (training, validation and testing) of the MATLAB NN training program of NNTGM. First, as the operating frequencies are concerned, the increase of the frequency range with respect to its size in the NNTGM default operation settings given the default flat-fading subchannel frequency spacing mainly supports sparse NNTGM virtual topology footprints for the rural class while the NNTGM virtual topology footprints of the suburban case and urban case A are only affected regarding their position and size with respect to the corresponding ACA / RMS-DS boxes of $\pm 10\%$. In contrast, the increase of the flat-fading subchannel frequency spacing with respect to its value in the NNTGM default operation settings given the default frequency range supports dense NNTGM virtual topology footprints for all the examined indicative OV LV BPL topologies. Generalizing the impact of the operating frequencies on the NNTGM virtual topology footprints, the higher number of operating frequencies introduces more noise and randomness in the TIM OV LV BPL topology database and the MATLAB NN training program of NNTGM, increasing stochasticity while wider flat-fading subchannel frequency spacings provide more global information and reduce local overfitting, decreasing stochasticity. Second, as the participation percentages of the three phases of the MATLAB NN training program are concerned, the main issue regarding the populating mode is the participation percentage of the training phase. In fact, high participation percentages of the training phase, that lie over the default value of 70%, supports dense populating due to the low stochasticity of the generated NNTGM virtual topologies that finally remain close to their corresponding indicative OV LV BPL topologies. When low participation percentages of the training phase are concerned sparse populating is expected for the NNTGM virtual topology footprints of the suburban and urban cases. Concluding this companion paper of [4], five main factors of the NNTGM operation settings have been assessed in total offering a wide portfolio of populating scenarios for the OV LV BPL topology classes by applying NNTGM.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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Design Optimization of Vortex-Induced Vibration Bladeless Wind Turbines for Urban Energy Harvesting

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Urban environments require innovative solutions for clean energy generation, as conventional wind turbines are often limited by space and noise constraints. Vortex-Induced Vibration (VIV) bladeless wind turbines present a promising alternative by converting oscillatory motion into electricity without rotating blades. This study investigates the influence of mast height, upper diameter, and lower diameter on turbine flexibility and performance under the low wind speeds typical of urban settings. Computational fluid dynamics and static structural analysis in ANSYS, combined with Response Surface Methodology (RSM) and Central Composite Design (CCD), were used to develop an optimization model aimed at maximizing mast deflection—a critical factor in energy harvesting efficiency. Results reveal that mast height and upper diameter significantly influence deformation, while lower diameter has a relatively minor impact. The optimal configuration achieved a mast deflection of 9.15 mm, validating the model's predictive accuracy. These findings provide practical design insights for enhancing bladeless wind turbine performance in urban settings, paving the way for more sustainable and space-efficient renewable energy solutions.

Keywords: Bladeless Wind Turbine; Vortex Shedding; Resonance; Static Structural Analysis; Response Surface Methodology

Introduction

The global demand for energy has surged dramatically since the Industrial Revolution, driven by rapid urbanization, population growth, and technological advancements. Historically, this demand has been met primarily through the exploitation of fossil fuels such as petroleum and coal. However, these non-renewable resources are finite and are major contributors to environmental degradation, including global warming, air pollution, acid rain, ozone layer depletion, and disruption of ecosystems [1]. These adverse impacts have heightened public awareness and underscored the urgent need to transition toward sustainable energy solutions. Renewable energy technologies are therefore essential for building a resilient and environmentally responsible future [2].

Recognizing this imperative, the United Nations has established 17 Sustainable Development Goals (SDGs), which provide a comprehensive framework for achieving sustainability across social, environmental, and economic dimensions. Among these, “Affordable and Clean Energy” emphasizes the critical role of clean energy in shaping a sustainable future [3].

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Common renewable energy sources include solar, wind, and hydropower. According to the U.S. Department of Energy, in 2022, wind power generated 10.3% of all U.S. electricity, indicating the importance and potential of wind power [4].

Conventional wind energy systems primarily employ Horizontal-Axis Wind Turbines (HAWTs) and Vertical-Axis Wind Turbines (VAWTs). However, these designs face significant challenges in urban environments. Limited open space, noise restrictions, and complex wind patterns caused by densely packed buildings make large-scale wind farms impractical in cities. Urban wind conditions are characterized by low wind speeds, turbulence, and eddies, which further reduce the efficiency of traditional turbines.

To overcome these limitations, Vortex-Induced Vibration (VIV) bladeless wind turbines (BWTs) have emerged as a promising alternative. Unlike conventional turbines, VIV BWTs generate electricity by converting oscillatory motion induced by vortex shedding into electrical energy, eliminating the need for rotating blades. This design offers advantages such as reduced noise, compact size, and insensitivity to wind direction, making it particularly suitable for urban applications.

The primary contribution of this study is to enhance the performance of VIV BWTs under low wind speed conditions typical of urban settings. Specifically, the research focuses on maximizing mast deflection, which is a critical factor influencing energy harvesting efficiency. To achieve this, a series of three-dimensional simulations were conducted using ANSYS, and the results were analyzed through Response Surface Methodology (RSM) implemented in JASP software.

Literature Review

A vortex-induced vibration (VIV) bladeless wind turbine (BWT) differs fundamentally from conventional bladed wind turbines. It is a type of wind power generator that generates energy by harnessing the wind induced oscillatory mechanical energy caused by wind induced vortex shedding.

When the VIV BWT is exposed to a fluid flow, the mast is primarily subjected to pressure exerted by the flow. It can be calculated by using Eqs. 1 and 2 [5, 6]

$$P=F/A \quad (1)$$

where F is the force experienced by the mast and A is the cross-sectional area.

$$F = 0.5\rho u^3 DLC \quad (2)$$

where F is the dynamic drag force, ρ is the density of fluid, u is the velocity of the fluid, D is the average diameter, L is the height, and C is the coefficient of lift force.

Vortex shedding is a fluid dynamics phenomenon. When a fluid flow passes a bluff body, the pressure of fluid rises to the stagnation pressure from the stream pressure. The fluid pressure remains symmetrical at low flow rates [6], more specifically, when the Reynolds number $Re \leq 40$ [8]. The equation of Reynolds number (Re) characterizes the state of fluid flow and can be estimated by using Eq. 3 [9].

$$Re = \frac{\rho v \phi}{\mu} \quad (3)$$

where Re is the Reynolds number, ρ is the density of the fluid, v is the average velocity of incident wind flow, Φ is the characteristic length, and μ is the fluid viscosity.

However, when the Reynolds number reached the critical value, the pressure on both side of the object becomes unstable. The instability leads to the formation of vortices in the wake region of the object. These vortices result in a periodical alternating pattern called Kármán Vortex Street, creating a fluctuating force perpendicular to the direction of the fluid flow [10]. This transverse force, primarily contributed by the lift force, can be expressed by Eq. 4 [9]

$$F_L = \frac{1}{2} \rho \phi v^2 C_L \sin(2\pi f_v t) \quad (4)$$

where C_L is the lift force coefficient and f_v is the vortex induced vibration/ vortex shedding frequency.

The frequency of vortex shedding can be expressed as Eq. 5 [10]:

$$f = \frac{St \cdot v}{\phi} \quad (5)$$

where St is the constant of proportionality (Strouhal Number) and f is the frequency of vortex shedding

Vortex induced vibration occurs when the frequency of vortex shedding matches or is close to the natural frequency of vibration of the body. This condition induces resonance, amplifying the harmonic vibration of the body. Within the ‘synchronization range’, the vibration amplitude increases significantly [8]. Even when the shedding frequency does not precisely match the natural frequency, the body will still vibrate if the incident velocity falls within the lock-in range, which can be expressed by Eq. 6 [9]

$$v_{lock} \approx \frac{\phi}{St} f \quad (6)$$

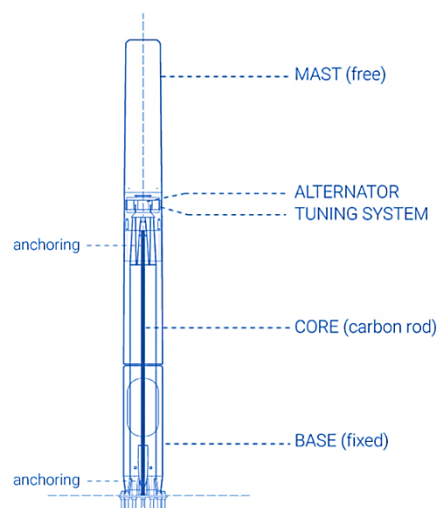


Figure 1. Schematic Diagram of current commercialized VIV BWT [10]

The VIV BWT leverages this phenomenon by using a flexible mast that oscillates due to vortex shedding and the resulting vortex induced vibration (Fig. 1). As the wind flows past the mast, the turbine captures wind energy by harvesting the vibrational kinetic energy of the mast into electrical energy by electromagnetic induction. A combination of a coil and a magnet is employed within the mast, where the relative motion of the magnet with respect to the coil induces an electromagnetic field, generating electrical current as the mast oscillates (Faradays Law) [12]. Thus, during the resonance vibrations, greater the deflection angle that the mast can achieve, greater the energy that can be generated.

In practical applications, a tuning system is also implemented with respect the vibration phenomena (Fig. 1). Although the "lock-in range" enables synchronisation, this range is narrow and cannot accommodate the variations in non-constant wind velocities experienced in real-world conditions. As a result, a tuning system comprising two circular permanent magnets will be installed to the original damped oscillator. The tuning mechanism could dynamically 'adjust' the device's natural frequency by extending the lock-in range and increasing the synchronisation workable range with peak/ near peak performance. The magnetic repulsive force between two permanent magnets is inversely proportional to the square of the average distance between their poles. Consequently, as deflection increases, the gap between the magnets in one side decreases, leading to greater repulsion. The system enables the vibration frequency increases with the degree of deflection during oscillation [11], leading to energy harvesting more frequently and intense. The frequency equation can be given by Eq. 7 [11]

$$f(x) = \frac{1}{2\pi} \sqrt{\frac{(k+k'(x))}{m} - \left(\frac{c}{2m}\right)^2} \quad (7)$$

Currently, VIV BWT only generate 30% of power that conventional wind turbines generate [13]. To improve the turbine performance of wind energy harvesting, two primary approaches are either maximising the vibration frequency or increase the magnitude of the deflection of the mast. Since vortex shedding frequency depends on variables such as incident wind speed — which cannot be continuously controlled to match the natural frequency of the body — this study focuses on maximizing the deflection that the mast can achieve during vibration to improve turbine performance.

As it pertains to vibration of the cylinder in an incident wind flow, vortex formation is significantly different based on the type of cylinder — Uniform cylinder and tapered cylinder, and these significantly affect VIV turbine performance. The current commercially available VIV bladeless (Fig. 2) are primarily designed with nearly uniform cylindrical shapes [11].

From the review articles on various VIV BWT models, the turbine parameters can preliminary be divided into rod (base) height, mast height, and diameter. Tapered cylindrical designs are worth exploring further, as tapered cylinder performs greater degree of deflection under same the same airflow [14].

Reviews were also conducted to explore existing approaches to optimisation problems in wind turbine research. Common methods include computational fluid dynamics (CFD), numerical analysis, metaheuristic algorithms, morphological/ geometric optimisation, *etc.* These approaches are widely used to analyse the dynamic response and fluid flow in both BWT and conventional wind turbines.

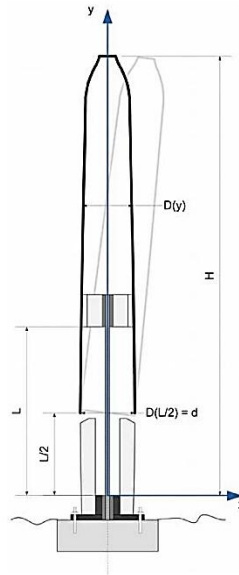


Figure 2. Current BWT design of Vortex Bladeless [10]

The most common and essential approach for studying the stability and performance of wind turbines is CFD and numerical analysis. They enable studies in dynamic response and fluid flow in both BWT and conventional turbines. For instance, past research has employed CFD to examine the stability of vortex-induced vibrations in conventional wind turbines by analysing mode shapes at different inclinations, providing valuable insights into turbine stability [15]. In the context of VIV BWT, CFD has also been employed to explore the effect of separation distance between tandem cylinders on vortex shedding frequency. The airflow passing through the first cylinder generates wakes, and CFD has proven instrumental in determining the optimal separation distance by providing maximum amplitude and frequency of vibration for the downstream one, thus to improve performance and stability of the overall system [16].

Metaheuristic Algorithms are also widely utilised in engineering design for solving complex optimisation problems. These algorithms explore large search spaces to identify global optima. Methods include evolutionary algorithms, particle swarm optimisation, and simulated annealing. They have been applied to a range of wind turbine problems, including blade design and layout optimization [17, 18]. Past research has used this method for investigating the optimal number of turbines in a certain area [19] and the layout of wind farm for maximising energy output. Computational random testing and coding were employed to generate plots and diagrams as shown in references [20]. Furthermore, past research in conventional wind turbine also used this method to address aerodynamic design, structural design, damage detection, optimal onshore and offshore location, control optimisation, and wind energy assessment optimisation problems. One study consolidated and analysed these findings to address various operational and control issues, improving and providing better turbine performance [21].

In the context of VIV BWT, static and modal analyses are commonly used to evaluate performance. These methods are particularly relevant as BWT generates energy through deformation and the vibration dynamic behaviour. Static and modal analyses provide critical information on deformation and resonance, which serve as a foundation for further performance optimization [5, 7].

Methodology

The fundamental principle for vortex induced vibration (VIV) bladeless wind turbine is to harvest the energy of wind induced vibration that occur transverse to the incident airflow. Maximising the degree of deflection of the turbine's mast can enhance the vibrational kinetic energy that can be harvested.

The primary objective is to maximize mast deflection within specified constraints. In urban settings, the size of the turbine is a dominant constrain due to the compact and open/ free space-restricted characteristic of city environments. Optimising the deflection degree then involves finding the best set of parameters that yield the local maximum of deflection while adhering to the size constrains.

To conduct this optimisation analysis, various methods were considered. From the reviewed studies on VIV BWT deflection and vibration optimisation, computational fluid dynamics (CFD), static structural analysis, and modal analysis were commonly employed on their models. These methods provided valuable insights on how changes in different factors influence deformation outcomes. However, these studies typically relied on a small sample size, often examining only few parameter configurations and focusing on a single design shape [7, 22]. Such limited sample sizes and parameter variations are neither systematic nor adequate for developing a comprehensive optimisation model for static deformation or modal analysis.

Repeated testing and plots generation methods used in conventional wind turbine and wind farm analyses have provided inspiration for us to develop a more systematic simulation plan. By combining the common approaches used for analysing VIV BWT with methodologies applied in conventional wind turbine and wind farm studies, design of experiment (DOE) is finally chosen. DOE provides a structured method for planning and conducting experiments, as well as data analysis and interpretation for complex systems [23]. It enables clear identification of relationship between variables and their influence on the outcome.

Response Surface Methodology is selected for doing the optimisation analysis, as it can use wide range of model fitting (first order (linear), second order (quadratic), or even higher order (cubic and quartic). The typical model equation for response surface design, which explains different model terms corresponding to the degree of interactions between the factor levels is shown in Eq. 8 [23]

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_2^2 + \beta_5 X_1 X_2 \quad (8)$$

where Y is the response variable, β_0 is the constant term, β_1 , β_2 are the coefficients of the linear model terms, β_3 , β_4 are the coefficient of quadratic model terms, and X_1 , X_2 are the model terms.

Central composite design (CCD) is chosen for conducting response surface methodology (RSM). It applies a second order (quadratic) model to the response outcome (Fig. 3), extending beyond a first order (linear) factorial design to second order design that capture potential curvatures in the response surface. The inclusion of centre points and axial points within CCD allows for a more accurate estimation of the curvature of the response surface, enabling better optimisation [23].

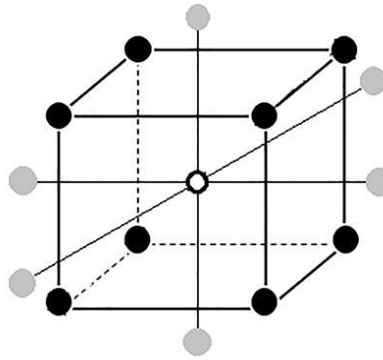


Figure 3. Visualised model of central composite design. The white point is the centre point; grey points are the axial points; black points are the corner points.

For multiple factors involved in this optimisation analysis, CCD and RSM are ultimately chosen as they minimise runs of experiments but can still capture the critical information and the factors and outcome interactions.

The choice of CCD and RSM is based on their ability to balance efficiency and accuracy in optimisation studies involving multiple factors. This method minimise the number of experimental runs required while still capturing critical information about the interactions between variables and their effects on the outcome. A response surface plot can be created at last. By visualising the results, it can make the result and analysis more easy understanding.

In our study, three factors were selected as the primary objectives in CCD: mast height (MH), mast upper diameter (UD), and mast lower diameter (LD), represented as factors X_1 , X_2 , and X_3 , respectively. Consequently, three combinations were formed for conducting the RSM, *i.e.* X_1 and X_2 , X_1 and X_3 , and X_2 and X_3 . Meanwhile, the response variable Y , mentioned in Eq. (8), is the maximum deflection/maximum deformation.

Parameters are being set up with reference to the dimensions of a commercially available vortex-induced vibration bladeless wind turbine developed by Vortex Bladeless. The dimensions of their testing device are used as the centre point in the CCD. To simplify future hardware simulations and ensure scalability, the dimensions have been uniformly reduced by a factor of two. This adjustment maintains the proportional relationships for software simulation in ANSYS while making future possible physical prototyping and simulation more practical and manageable.

Experimental Data and Results

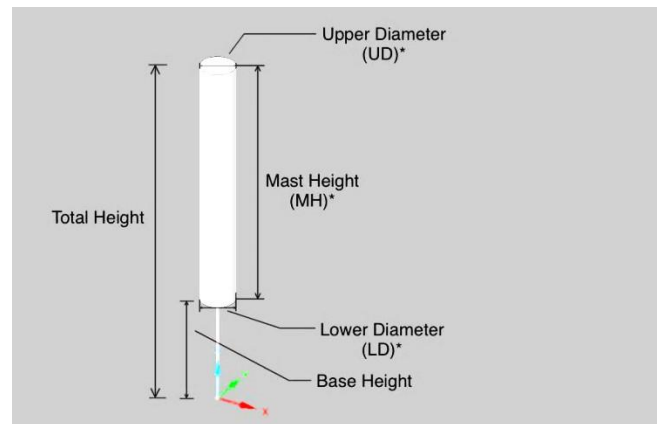
Experimental Data

In the context of harvesting urban wind energy, the velocity of the incident wind flow is a critical factor in ensuring that the simulation results are of practical and reference value. For this study, Central, Hong Kong, a world-class central business district renowned for its densely packed skyscrapers, was selected as the reference location for wind speed data. This typical urban environment provides a realistic basis for evaluating the performance of the VIV bladeless wind turbine under typical urban wind speed.

Table 1. Mean Wind Speed of Selected Site

Mean Wind Speed of Central Pier in 2024 [23]	
Month	Wind Speed (m/s)
January	3.714
February	3.665
March	3.993
April	3.144
May	4.361
June	3.3
July	3.145
August	2.51
September	3.329
November	3.852
December	3.268
Overall Mean	3.439

Considering the wind tunnel effect that may brought by densely packed buildings in urban districts, wind would accelerate between tall buildings and structures. Moreover, the Vortex Bladeless VIV bladeless wind turbine begins generating power at a minimum wind speed of 3 m/s [25]. To reflect realistic operating conditions while ensuring reliable simulation results, a wind speed of 5 m/s (to the positive x direction) was chosen for the ANSYS Fluent computational fluid dynamics (CFD) simulation.

**Figure 4.** Simplified model used for simulation. The labels with “*” are the study objectives.

Parameters analysis is designed to study their effect on the vibration ability of the turbine's mast. As previously mentioned, the dimensions of the testing device from Vortex Bladeless are used as the centre point in the CCD. Three parameters are selected as the study objective (Fig. 4) — Mast Height (MH), Mast Upper Diameter (UD), and Mast Lower Diameter (LD). These parameters collectively represent most of the critical dimensional attributes of the turbine, including mast height, mast upper and lower diameter, rod (base) height, taper ratio. The upper and lower limits for each parameter are set to $\pm 20\%$ of the centre point, with alpha value 1.682 as the axial point. The alpha value is given by this Eq. 9.

$$\alpha = (2^k)^{1/4} \quad (9)$$

where α is the alpha value and k is the number of factors.

This configuration ensures that parameter variations remain within a reasonable range for accurate results, while also allowing for the study of parameter interactions and their influence on turbine's mast deflection.

Table 2. Design Summary Table of CCD

Design Summary	
Variable	Value
Continuous predictors	3
Discrete predictors	0
Base runs	20
Replicates	1
Total runs	20
Centre points in cube	6
Centre points in axial	0
α	1.682

Table 3. Design Table of CCD

Response Surface Design – Central Composite Design				
		Continuous predictors		
Run order	Standard order	A	B	C
1	6	1	-1	1
2	20	0	0	1.682
3	19	0	0	-1.682
4	18	0	1.682	0
5	12	0	0	0
6	1	-1	-1	-1
7	9	0	0	0
8	3	-1	1	-1
9	14	0	0	0
10	11	0	0	0
11	13	0	0	0
12	8	1	1	1
13	16	1.682	0	0
14	17	0	-1.682	0
15	2	1	-1	-1

16	4	1	1	-1
17	5	-1	-1	1
18	7	-1	1	1
19	15	-1.682	0	0
20	10	0	0	0

The raw CCD design generated by JASP (<https://jasp-stats.org/>) is shown in Table 3, where 1 and -1 represent the upper limit and lower limit, respectively.

The reference parameter values for the centre point are derived from a literature paper available on the Vortex Bladeless official website [11]. The testing device described in the literature has a height of 1 m and a diameter of 95 mm. For the purposes of this simulation, these dimensions were scaled down by a factor of two, and our model is then with a height of 0.5 m and a diameter of 0.0475 m. As our study focus is on the mast height, upper mast diameter, and lower mast diameter, the total height of the device is fixed at 0.5 m. This fixation allows us to specifically analyse how variations in mast height influence the outcomes. The mast-to-rod height ratio in the reference device is 2:1 [26], and for simplicity in calculations, the mast height and rod height in centre point were set to 0.35 m and 0.15 m, respectively.

The upper and lower limit for each parameter is set to $\pm 20\%$ of the centre point value. So, for the upper limit (+20%), the MH, UD, and LD would be 0.42 m, 0.057 m, and 0.057 m, respectively; for the lower limit (-20%), the MH, UD, and LD would be 0.28m, 0.038m, and 0.038m, respectively. The CCD experimental plan, incorporating these parameter ranges, generated by JASP, is summarised in Table 4 below:

Table 4. Response Surface Worksheet

<i>Response Surface Design - Central Composite Design</i>				
		Continuous predictors		
Run order	Standard order	Mast Height (m)	Upper Diameter (m)	Lower Diameter (m)
1	10	0.35	0.0475	0.0475
2	12	0.35	0.0475	0.0475
3	11	0.35	0.0475	0.0475
4	5	0.28	0.038	0.057
5	15	0.232	0.0475	0.0475
6	1	0.28	0.038	0.038
7	16	0.468	0.0475	0.0475
8	2	0.42	0.038	0.038
9	8	0.42	0.057	0.057
10	14	0.35	0.0475	0.0475
11	3	0.28	0.057	0.038
12	17	0.35	0.032	0.0475
13	20	0.35	0.0475	0.063
14	6	0.42	0.038	0.057

15	7	0.28	0.057	0.057
16	4	0.42	0.057	0.038
17	18	0.35	0.063	0.0475
18	19	0.35	0.0475	0.032
19	9	0.35	0.0475	0.0475
20	13	0.35	0.0475	0.0475

With the other parameters of the model fixed as follows:

- Total Height: 0.5 m
- Rod Diameter: 0.004 m (4 mm)

This ensures consistency through the whole simulation while only varying the selected study parameters.

Experimental Results

A static structural analysis was performed by selecting carbon fiber as the structural material, with a modulus of 230 GPa. Results from ANSYS Fluent and the static deflection are shown in Table 5. Modal analysis was also conducted, and the results of modal deformation in Y direction (mode shape) and modal frequency are shown in Table 6.

Table 5. Fluent and Static Structural Simulation Result

Run	Total pressure (Pa)(m ²)	C _d	C _l	Maximum Deformation (mm)
1	0.28146781	0.19222508	0.060053516	6.0795
2	0.28146781	0.19222508	0.060053516	6.0831
3	0.28191598	0.19038404	0.072198843	6.2554
4	0.22881341	0.16902544	0.038351499	6.6807
5	0.18260136	0.15215051	-0.031795178	7.0342
6	0.17405874	0.13278225	0.033721399	5.2847
7	0.37378878	0.24677277	0.071273073	1.8531
8	0.24786523	0.19436052	0.040703837	3.3829
9	0.40296264	0.26814913	-0.052038397	5.1753
10	0.28146781	0.19222508	0.060053516	6.0831
11	0.21617909	0.18733908	-0.03952183	8.3022
12	0.22389221	0.16219897	-0.021429441	4.5774
13	0.31739769	0.25221641	0.032131833	7.2835
14	0.31992216	0.24410209	-0.008118619	4.0578
15	0.26402788	0.20574843	0.026202234	8.5333
16	0.32495557	0.22356115	-0.033877016	4.1081
17	0.33065364	0.21953961	-0.084153551	7.3881
18	0.22784349	0.16939196	-0.040941837	5.6533
19	0.28146781	0.19222508	0.060053516	6.241
20	0.28146781	0.19222508	0.060053516	6.0831

Table 6. Modal Analysis Result

Run	Modal deformation (mm)	Modal Frequency (Hz)
1	46.891	0.76562
2	46.895	0.76539
3	46.895	0.76549

4	51.955	0.76074
5	50.945	0.71309
6	61.205	0.89379
7	44.109	1.3572
8	56.481	1.1669
9	37.666	0.77826
10	46.895	0.76539
11	45.874	0.67121
12	60.332	0.9864
13	42.533	0.69738
14	49.422	1.0211
15	40.828	0.60032
16	41.352	0.8541
17	38.177	0.62354
18	51.89	0.84611
19	46.895	0.76539
20	46.895	0.76539

Result Analysis and Interpretation

Static structural analysis involves applying static loads to the structure and studying the corresponding deformation. From our simulations, it serves as a baseline for understanding the dynamic behaviour of the system by providing insight into how the structure responds to static wind pressure. A larger degree of deformation indicates the turbine's potential to deflect under wind stress, which is crucial for amplifying the dynamic effects of resonance during vortex shedding [5].

To optimise the design parameters, analysis of response surface design in JASP was employed. The experimental data has been shown in the previous section. The tables, residues plots, as well as response surfaces, and their corresponding contour plots are shown below.

Table 7. Model Summary Table from JASP

<i>Model Summary</i>			
S	R ²	Adjusted R ²	Predictive R ²
0.196	0.992	0.986	0.936

Table 8. ANOVA Report from JASP

<i>ANOVA</i>					
Source	Sum of squares	df	Mean square	F	p
Model	10.176	9	1.131	29.4	< .001
Linear terms	3.773	3			
Mast Height (m)	2.814	1	2.814	73.162	< .001
Upper Diameter (m)	0.936	1	0.936	24.327	< .001

Lower Diameter (m)	0.024	1	0.024	0.613	0.452
Squared terms	5.181	3			
Mast Height (m) ²	4.89	1	4.89	127.157	< .001
Upper Diameter (m) ²	0.02	1	0.02	0.513	0.49
Lower Diameter (m) ²	0.271	1	0.271	7.055	0.024
Interaction terms	1.222	3			
Mast Height (m) × Upper Diameter (m)	1.146	1	1.146	29.79	< .001
Mast Height (m) × Lower Diameter (m)	0.002	1	0.002	0.043	0.84
Upper Diameter (m) × Lower Diameter (m)	0.075	1	0.075	1.94	0.194
Error	0.385	10	0.038		
Total	10.56	19			

Note. Type III sums of squares.

Table 9. Coded Coefficients Table from JASP

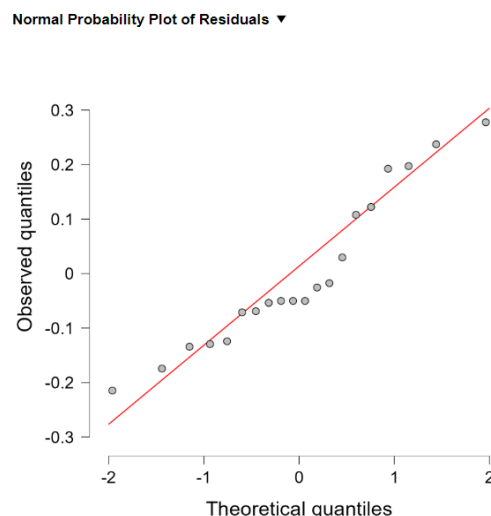
Coded Coefficients							
Alias	Term	Effect	Coefficient	Standard error	t	p	VIF
(Intercept)	(Intercept)		6.133	0.08	76.815	< .001	
A	Mast Height (m)	-5.128	-2.564	0.089	-28.688	< .001	1
B	Upper Diameter (m)	2.767	1.384	0.088	15.784	< .001	1
C	Lower Diameter (m)	1.477	0.738	0.088	8.422	< .001	1
A ²	Mast Height (m) ²	-3.29	-1.645	0.146	-11.276	< .001	
B ²	Upper Diameter (m) ²	-0.206	-0.103	0.144	-0.716	0.49	
C ²	Lower Diameter (m) ²	0.765	0.382	0.144	2.656	0.024	
AB	Mast Height (m) × Upper Diameter (m)	-2.082	-1.041	0.191	-5.458	< .001	1
AC	Mast Height (m) × Lower Diameter (m)	0.079	0.04	0.191	0.207	0.84	1
BC	Upper Diameter (m) × Lower Diameter (m)	-0.514	-0.257	0.185	-1.393	0.194	1

Table 10. Equation to Calculate the Approximate Response Value from JASP

<i>Regression equation in Coded Units</i>
Maximum Deflection = 6.133 (Intercept) - 2.564 A + 1.384 B + 0.738 C - 1.645 A ² - 0.103 B ² + 0.382 C ² - 1.041 AB + 0.04 AC - 0.257 BC

In RSM model summary (Table 7), there are two notations, where S stands for Standard error of the estimation, and R² stands for Coefficient of determination. S represents the average distance that the experimental value apart from the fitted value. S was found to be 0.196, indicating reasonable errors between observed and predicted values. R² was 0.992, demonstrating that 99.2% of the variance in the parameters could be explained by the model, showing a great fit of predictions. Extended from R², the adjusted R² value of 0.986 suggested a tendency for overfitting, meaning the overreliance on preexisting data and low accuracy on new data [27], while the predictive R² of 0.936 confirmed the model's strong predictive capabilities.

The analysis of variance (ANOVA, Table 8) further reinforced the model's reliability, with F-statistic value of 29.400, and p-value <0.001, showing the model is statistically significant (A small p-value (around <0.05) indicates statistical significance). More specifically, among linear terms, mast height (MH) is the most significant predictor (SS = 2.814, F = 73.162, p < 0.001), followed by upper mast diameter (UD) (SS = 0.936, F = 24.327, p < 0.001). Lower mast diameter (LD), however, showed minimal significance (SS = 0.024, F = 0.613, p = 0.452 (statistical insignificant)). Among squared terms, MH (SS = 4.890, F = 127.157, p < 0.001) and LD (SS = 0.271, F = 7.055, p < 0.05) are significant, while UD (SS = 0.02, F = 0.513, p = 0.490) is insignificant. Furthermore, among the interacting terms, only MH×UD (SS = 1.146, F = 29.79, p < 0.001) shows significant interactions, highlighting their combined impact on deflection. Overall, the analysis suggested that MH is the most critical parameter, with both strong linear and quadratic effects. UD also plays an important role, particularly in its linear term and its interaction with MH. LD, however, has a much smaller influence on deflection.

**Figure 5.** Probability Plot of Residuals

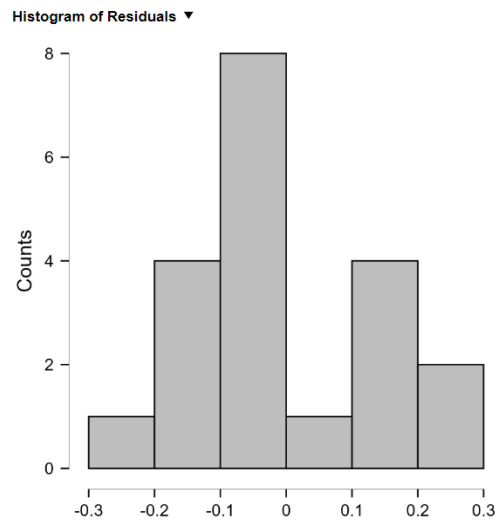


Figure 6. Histogram of Residuals

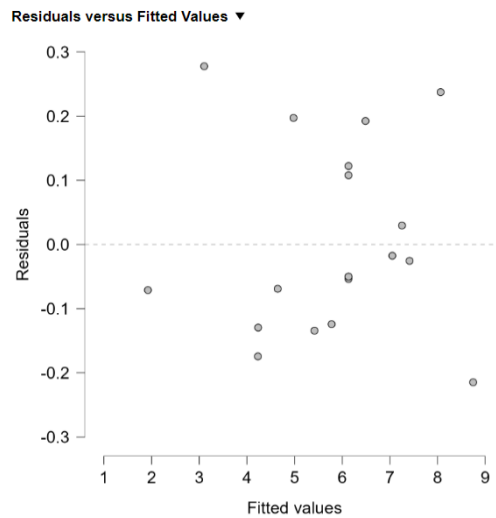


Figure 7. Residuals vs Fitted Values

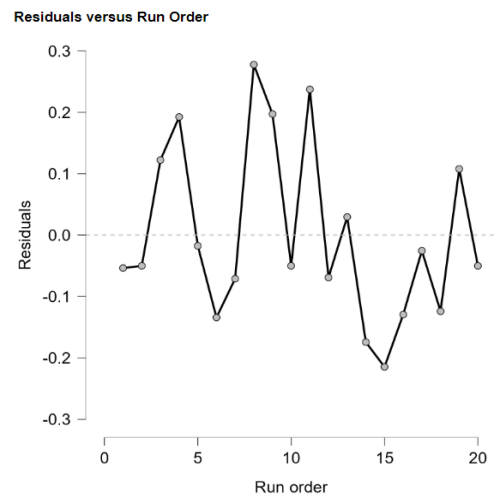
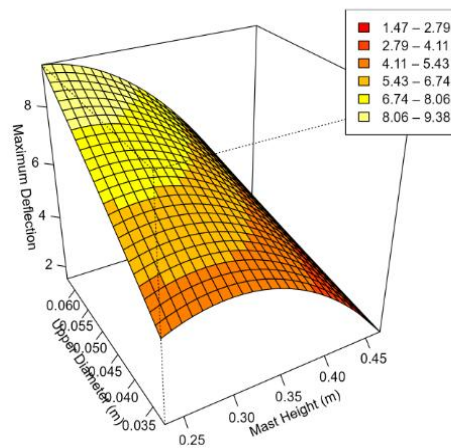


Figure 8. Residuals vs Run Order

In the residuals four in one plot (Figs. 5-8), the normal probability plot (Fig. 5) showed that the residuals were approximately normally distributed, as they fell closely along a straight line. The histogram (Fig. 6) indicated that the residuals were within a small range of ± 0.3 , with most values concentrated between ± 0.2 , confirming the accuracy of the model with reasonable errors. Both the residuals versus fitted values and residuals versus run order plots (Figs. 7-8) showed no discernible patterns, indicating independence and homoscedasticity of the residuals. These observations suggest that the model predictions are robust and free from time-dependent bias.

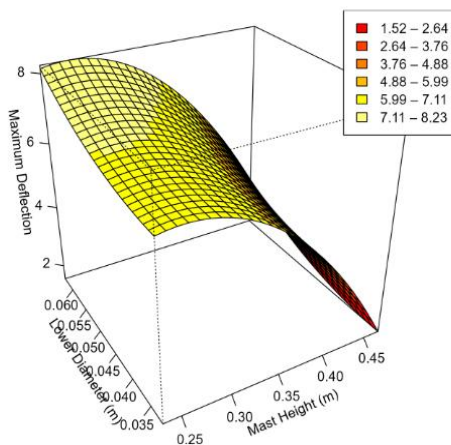
Surface plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)



Slice at Lower Diameter (m) = 0.048

Figure 9. Response Surface of Maximum Deflection vs MH vs UD

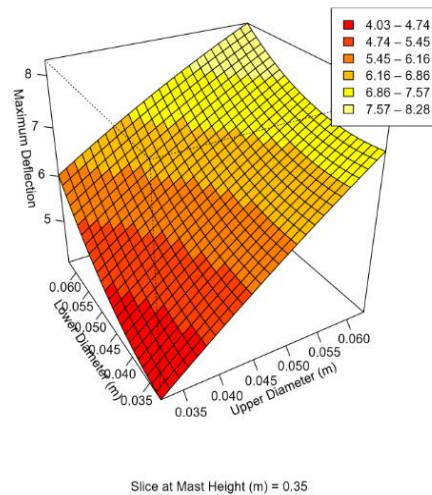
Surface plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)



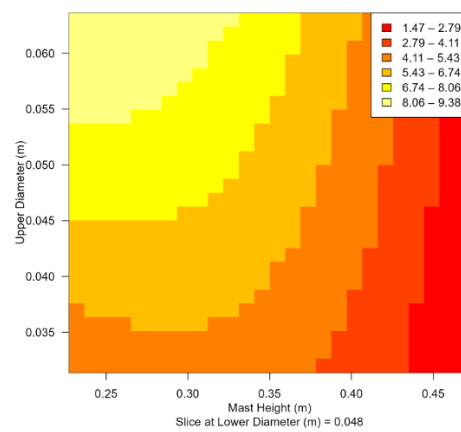
Slice at Upper Diameter (m) = 0.048

Figure 10. Response Surface of Maximum Deflection vs MH vs LD

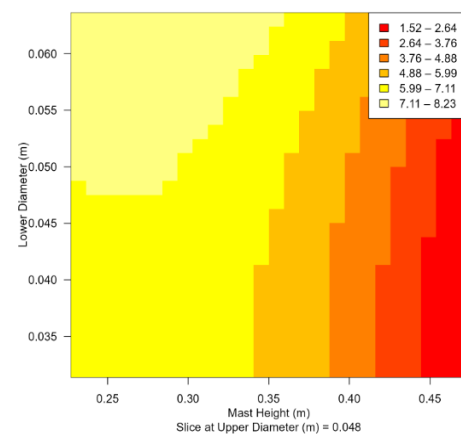
Surface plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)

**Figure 11.** Response Surface of Maximum Deflection vs UD vs LD

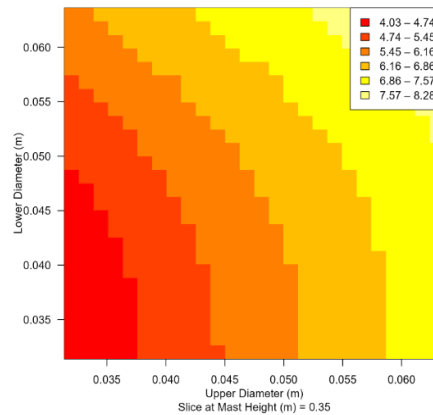
Contour plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)

**Figure 12.** Contour Plot of Fig. 9

Contour plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)

**Figure 13.** Contour Plot of Fig. 10

Contour plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)

**Figure 14.** Contour Plot of Fig. 11

By observing three of the response surfaces (Figs. 9-14), it is observed that the approximate location of the optimal solution, as well as they are sharing the same findings mentioned in the report above. As there are three parameters, the response surfaces were presented in 3D plots, with one parameter held constant at its midpoint value each.

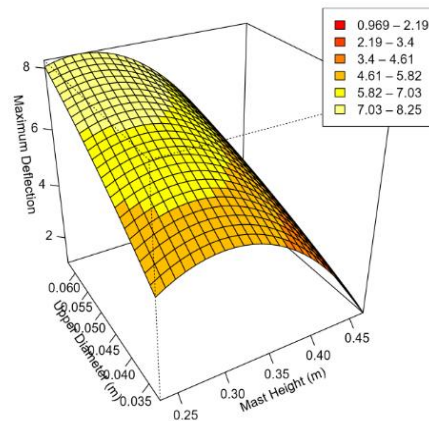
In the Maximum Deflection vs MH vs LD surface plot (Fig. 10) and Maximum Deflection vs MH vs UD surface plot (Fig. 9), it is observed that the shorter the MH, the greater the deflection. This is likely because a shorter mast height raises the system's centre of gravity, making it more prone to deformation under wind stress. We can also observe that LD is playing a less significant role when compared to UD, whereas the dominant parameter is the MH. Similar findings were found in the Maximum Deflection vs LD vs UD plot (Fig. 11). With MH being fixed, the change in UD resulted in a much steeper slope compared to the change in LD. Larger diameter values were associated with greater deflections, which can be attribute to Eq. 1.

To validate the accuracy of the three surfaces, repeated verifications were conducted. For most of the points of verification are fall within a minor and reasonable residual range, two points exhibit significant errors: The two points are:

1. For MH = 0.25 m, UD = 0.06 m, LD = 0.0475 m, the expected deflection was ≥ 8.06 mm, but the observed value was 7.162 mm.
2. For MH = 0.25 m, UD = 0.0475 m, LD = 0.06 m, the expected deflection was ≥ 7.11 mm, but the observed value was 6.3475 mm.

These results represent that in both Maximum Deflection vs MH vs LD surface plot and Maximum Deflection vs MH vs UD surface plot, a downward slope should be presented in the upper left corner instead of the current continuous upward slope. Having considered that two points into our analysis, new response surfaces are generated.

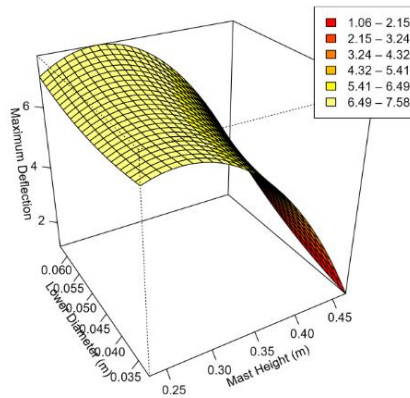
Surface plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)



Slice at Lower Diameter (m) = 0.048

Figure 15. Refined Response Surface of Maximum Deflection vs MH vs UD

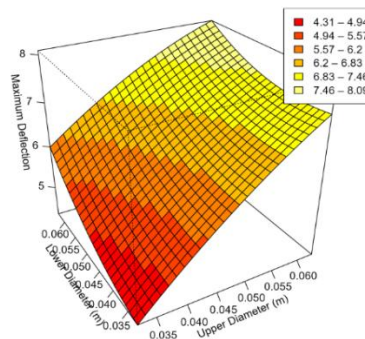
Surface plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)



Slice at Upper Diameter (m) = 0.048

Figure 16. Refined Response Surface of Maximum Deflection vs MH vs LD

Surface plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)



Slice at Mast Height (m) = 0.34

Figure 17. Refined Response Surface of Maximum Deflection vs UD vs LD

Although the adjusted response surfaces still could not precisely predict deflection at these two points, they provided valuable insights into the overall trends and robust zones in the new surfaces. For both plots (Fig. 15, 16), the robust zones for optimal performance were identified as follows:

1. In the Maximum Deflection vs MH vs LD plot (Fig. 15), the optimal region was found at $LD = 0.060$ m and $MH = 0.27\text{--}0.33$ m.
2. In the Maximum Deflection vs MH vs UD plot (Fig. 16), the optimal region was at $UD = 0.060$ m and $MH = 0.27\text{--}0.33$ m.

From the analysis of the three response surface plots, a potential optimal region was identified. The optimal mast height (MH) was observed to lie between 0.27 m and 0.33 m, as indicated from the Maximum Deflection vs MH vs LD (Fig. 16) and Maximum Deflection vs MH vs UD (Fig. 15) surface plots. Furthermore, the optimal values for the lower mast diameter (LD) and upper mast diameter (UD) were found to be 0.060 m, as indicated by the Maximum Deflection vs UD vs LD plot (Fig. 17).

Based on these observations, a potential optimal combination of parameters was tested, with $MH = 0.3$ m, $LD = 0.06$ m, and $UD = 0.06$ m.

The static structural analysis of this configuration achieved the highest response, with a maximum deformation of 9.1497 mm (Fig. 18). This result validates the accuracy and effectiveness of the optimization model in predicting static deformation behavior and confirms the robustness of the identified optimal parameter combination. The results indicate that the optimum ratio of mast height to rod height is approximately 3:2. Additionally, while a larger mast diameter corresponds to greater deflection, the taper ratio does not significantly influence the degree of deflection in static structural analysis (Fig. 17). However, it is likely to play a more critical role in shedding frequency (a dynamic aspect) with reference to past studies [14, 28].

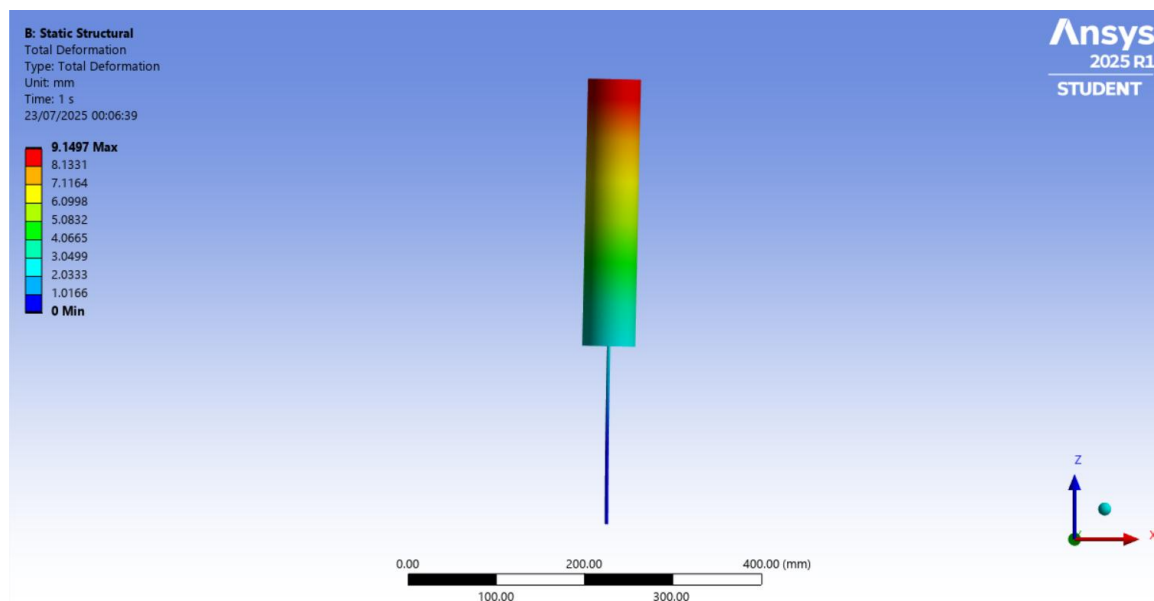


Figure 18. Result of the Optimal Model in Static Structural Analysis

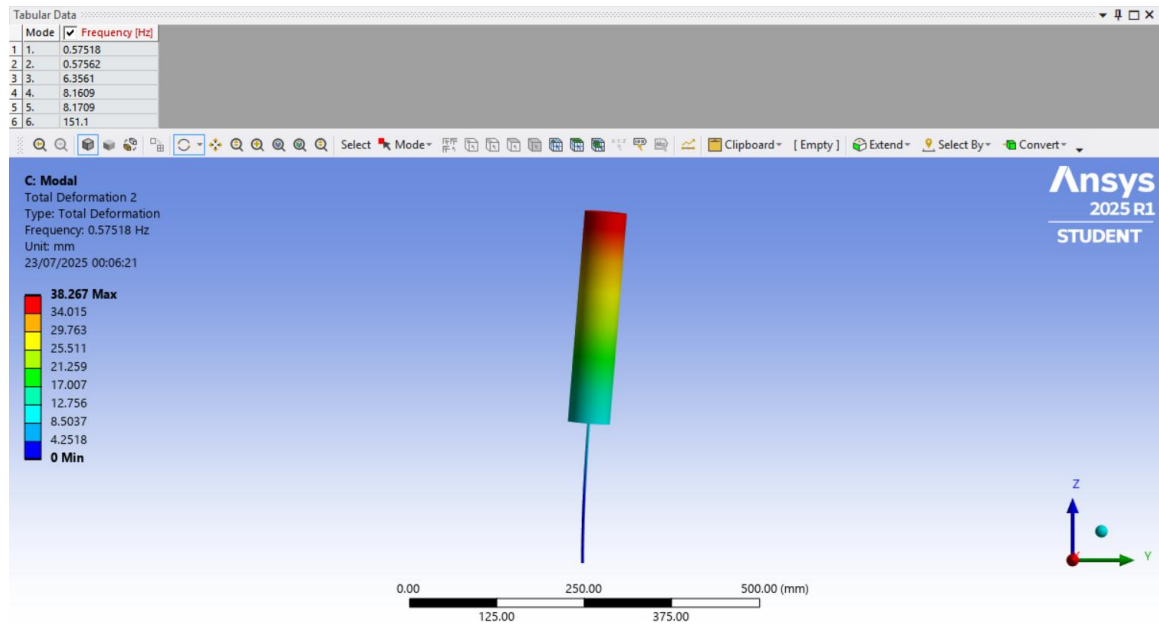


Figure 19. Result of the Optimal Model in Modal Analysis

The results from Table 11 also indicate that, when compared with the findings from the modal analysis, an opposite trend is observed in modal frequency. Specifically, a trend of greater the degree of deformation, the smaller the modal frequency is observed. Structural stiffness plays a critical role in determining both deformation and modal frequency. Lower stiffness allows for greater deformation but also reduces the natural (modal) frequency of the structure [29]. From the static structural analysis, the maximum deflection provides an approximate indication of the relative stiffness between the models. Based on the results, it can be concluded that Run 7 exhibits the greatest stiffness, while Run Max demonstrates the least stiffness, with the other models falling between these extremes under this constant wind speed. Since modal frequency is directly proportional to the stiffness of the structure, (*i.e.*, greater the stiffness greater the frequency), the trend observed in modal frequency is the complete inverse of the trend in maximum deflection obtained from the static structural analysis, which also validates the accuracy of the collected in static structural analysis and reinforces that greater deflection can be achieved under greater flexibility.

While frequency is a key factor in assessing the performance of VIV BWT, it is not the primary focus of this study. For a more comprehensive evaluation in maximising VIV BWT performance, it is necessary to balance both factors. Further research on BWT shedding frequency, including considerations such as material properties, damping, and tuning systems, is required to extend beyond the scope of this study.

Table 11. Comparison Between Static Structural Deflection and Modal Frequency

Run Number	Static Structural – Max. Deflection (mm)	Modal Analysis Frequency [Hz]
Run7	1.8531	1.3572
Run8	3.3829	1.1669
Run14	4.0578	1.0211
Run16	4.1081	0.8541

Run12	4.5774	0.9864
Run9	5.1753	0.77826
Run6	5.2847	0.89379
Run18	5.6533	0.84611
Run1	6.0795	0.76562
Run2	6.0831	0.76539
Run10	6.0831	0.76539
Run20	6.0831	0.76539
Run19	6.241	0.76548
Run3	6.2554	0.76549
Run4	6.6807	0.76074
Run5	7.0342	0.71309
Run13	7.2835	0.69738
Run17	7.3881	0.62354
Run11	8.3022	0.67121
Run15	8.5333	0.60032
Run Max	9.1497	0.57518

Conclusion

This study optimized the design of Vortex-Induced Vibration (VIV) bladeless wind turbines to enhance energy harvesting in urban environments. By applying static structural and modal analyses combined with Response Surface Methodology (RSM), we identified mast height (MH) as the most influential parameter, followed by upper diameter (UD), while lower diameter (LD) had minimal impact. The optimal configuration achieved a maximum static deflection of 9.15 mm, corresponding to an approximate mast-to-rod height ratio of 3:2. Larger mast diameters improved flexibility, whereas taper ratio showed limited effect under static conditions.

These findings provide valuable insights into structural optimization; however, the study primarily addresses static deformation. Future research will address dynamic aspects such as vortex shedding frequency, damping, and tuning mechanisms to achieve a balance between flexibility and resonance. Such advancements are essential for improving the efficiency and reliability of VIV bladeless wind turbines in real-world urban applications. In addition, our future effort will be devoted to the robust design of VIV bladeless wind turbines under uncertainties and disturbance [30-31].

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