

Overcoming Challenges in Carbon Credit Verification for Solar PV Projects in Nigeria: An ICT-Driven Approach

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Abstract: The feasibility of carbon credits for solar photovoltaic (PV) projects in Nigeria is faced with major setbacks, including data inaccuracy, high verification costs, limited transparency, and inadequate institutional capacity. These challenges affect project developers from adequately examining carbon markets and undermine the reliability of emissions reduction claims. This study analyzes an ICT-driven method to manage these barriers, emphasizing on the mobilization of digital monitoring, reporting, and verification (MRV) systems to suit the Nigerian context. By incorporating Internet of Things (IoT) devices, blockchain technology, and cloud-based platforms, the suggested solution improves data trustworthiness, decreases transaction fees, and impacts stakeholder trust. Case studies of already operating solar PV programs in Nigeria are assessed to find the feasibility and effect of such technological solutions. The study concluded that capitalizing on ICT can tremendously refine carbon credit verification processes, improve scalability of renewable energy (RE) projects, and allow wider inclusion in global carbon markets. Recommendations are suggested for policymakers, builders, and investors to aid the use of ICT tools for sustainable carbon finance in Nigeria's energy sector.

Keywords: Photovoltaic; Carbon Credit; Digital Registry; Solar Energy; ICT; Blockchain.

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I. INTRODUCTION

Carbon credits are central to contemporary climate finance, they provide a tradable unit representing a quantified reduction, avoidance, or removal of one tonne of CO₂-equivalent (CO₂e) and are used by companies and governments to meet mitigation commitments or net-zero targets. The global voluntary carbon market attained a projected value of \$4billion in 2024, up from initial \$2.1billion of 2021, although trading volumes contracted by nearly 61% in 2023, mainly due to concerns over 'credit integrity' (Trottier and Narassimhan, 2024; World Bank, 2024). From 2019 to 2022, over 1.7billion carbon credits were issued globally, but independent investigations revealed that almost 94% of rainforest-based credits under certain

procedures failed to represent genuine emission reductions. These fluctuations shows both the risks and opportunities inherent in carbon finance as an apparatus for supporting climate action.

Solar photovoltaic (PV) projects are among the most lucrative sources of carbon credits as they give rise to measurable, near-term reductions in conventional fuel use. Solar PV plays an increasingly central role in the energy transition strategy in Nigeria. The nation's total electricity generation capacity is approximately 13GW, but only 4.5GW is typically available as a result of gas shortages and infrastructural bottlenecks (World Bank, 2023). From this estimation, solar PV contributes less than 0.4GW, which is roughly 3% of all installed RE capacity (IRENA, 2023).

IRENA (2023) projected 0.386GW of installed PV in 2023, while GOGLA (2023) accounted that more than 1.3million off-grid solar residential systems were sold between 2019 and 2022, constituting an annual growth rate of 22%. The Nigeria nation with a population of over 220million still faces alarming access challenges, with about 85 million people (about 43%) lacking reliable electric power supply, making the country the largest energy access shortfall in sub-Saharan Africa, according to World Bank (2023). This deficit has sparked investments in mini-grids, with over 100 operational solar hybrid mini-grids serving almost 50,000 residential facilities as of 2022. The government and private developers additionally announced interests and commitments exceeding \$0.5billion to deploy over a thousand new mini-grids by 2030.

In spite of these positive developments, the integrity of carbon credits tied to Nigeria's solar PV projects faces recurring verification challenges. These challenges are classified either as institutional, technical, or lifecycle categories. Monitoring and measurement remain difficult due to lean infrastructure. Olaniyi et al. (2023) claimed that less than 30% of distributed solar PV systems in Nigeria are connected to smart meters efficient in providing reliable performance data. Even with the existence of meters, studies show that about 15% of devices are prone to illegal recalibration, leading to under-reporting and data gaps (Awerbuch and Yang, 2022). Baseline emission factors also vary: while Nigeria's national grid emits an average of 0.46 kgCO₂/kWh, diesel generators, used by 60% of households and 80% of businesses, emit about 2.7 kgCO₂/kWh, creating a wide range of possible crediting outcomes depending on assumptions (IEA, 2023). Double counting and additionality are also critical issues. Nigeria received over USD 2.3 billion in climate-related donor funding between 2015 and 2020, raising concerns that some solar projects credited as "additional" were already subsidized by international aid. According to the Paris Agreement Article 6 framework, Renewable Energy (RE) deployment recorded in Nigeria's Nationally Determined Contribution (NDC) could be double-counted if also registered in voluntary market(s). In Cames and Harthan (2023)'s analyses, double-counting has affected up to 20 percent of credits issued in African renewable projects from 2016 through 2021.

Permanence and lifecycle effects offer another layer of complexity. PV systems are long-lived but not permanent solutions, and their end-of-life (EoL) management is crucial. Global projections predicted PV wastes will attain 78 million tonnes by 2050, with Africa accounting for about 10% of the waste, or 7 to 8 million tonnes (IRENA, 2022). Nigeria has no dedicated PV recycling facility presently, and informal e-waste recycling is associated with environmental contamination risks and up to 30% material loss (IEA, 2023). Without structured recycling, the long-term overall climate benefit of PV deployment could be jeopardised.

Governance and verification cost further constrain project development. Third-party verification costs can reach USD 40,000 to 60,000 per project cycle (Olaniyi et al., 2023), which is disproportionately high for small-scale mini-grids

that typically generate only 1,000–3,000 credits per year. This cost-to-revenue imbalance ridicules community level participation in carbon markets. Moreover, the Nigerian Electricity Regulatory Commission (NERC) lacks standardized carbon credit protocols, leaving developers dependent on international standards like Verra and Gold Standard, which may not corresponds with local realities. Studies show that verification delays average 18 months for African projects compared to less than 9 months for projects in Asia and Europe (Trottier and Narassimhan, 2024).

These verification challenges can be managed through ICT-driven solutions. Smart inverters and internet of Things (IoT) sensors can provide real-time energy data at a relatively lower cost per unit, that can be significantly cheaper than traditional metering infrastructure (Olaniyi et al., 2023). Blockchain-based registries have been piloted in Ghana and Kenya, reducing transaction times by 35 percent and lowering verification costs by nearly 20 percent (Anagba and Oyeбанjo, 2024). Satellite imaging has as well proven effective in validating project locations, with studies showing well over 92% accuracy in detecting small-scale PV installations across West Africa (Awerbuch and Yang, 2022). Nigeria is faced with digital infrastructure challenges due to the fact that only 55% of rural areas have mobile broadband coverage, and cybersecurity occurrence in the energy sector have increased by 14% annually since 2019 (World Bank, 2023). This study examines the verification barriers that restrict credible carbon credit issuance for solar PV projects in Nigeria and evaluates a suite of ICT-driven solutions to address those barriers. However, high verification costs and weak monitoring processes prevent many renewable projects in Nigeria from fully benefitting from carbon markets. The aim is to identify measurable interventions that reduce uncertainty, lower transaction costs, and improve transparency and credibility in carbon market by increasing trust in solar PV credits so that carbon finance can more reliably support Nigeria's energy transition. In view of achieving this aim, the paper will:

- Quantify where possible the material scale of verification-relevant factors (deployment, metering coverage, expected EoL volumes, market valuations etc);
- Review existing ICT pilots and comparable international practice for digital MRV;
- Propose an actionable governance-aware ICT architecture, secure data aggregation, combining low-cost sensing, transparent registries, and verification workflows that matches Nigeria's institutional and market realities;
- Assess the challenges RE projects face in validating and measuring carbon reductions, and
- Design and pilot a ICT-based or blockchain prototype platform for carbon credit tracking.

II. LITERATURE REVIEW

➤ Carbon Credit Mechanisms and Solar PV Projects

Carbon credit generation from solar PV projects is based on the principle of avoided-emissions. In conventional power facilities, electricity is largely generated from fossil fuels which emit large volumes of greenhouse gases

(GHGs). In Nigeria, about 76% of electricity generation comes from gas-fired plants, with an emissions factor of nearly 0.62 tons of CO₂ per megawatt-hour (MWh) of electricity generated (IEA, 2023). By replacing conventional fuel-based generation with solar PV, which generates zero direct emissions during operation, measurable reductions in emissions of GHG are achieved. These reductions, expressed in carbon dioxide equivalents (tCO₂e), form the basis for issuing tradable carbon credits. World Bank (2022) claims that a 1 MW grid-connected solar PV system operating at 20% capacity factor can generate around 1,752 MWh annually, avoiding roughly 1,086 tCO₂e each year in Nigeria's grid context.

Various research approaches have shown how smart grid technologies can be merged into carbon credit trading systems. Real-time ICT-enabled data collection can enhance the transparency and accuracy of emission reductions, thereby, improving the credibility and integrity of carbon credit verification systems. The process of generating carbon credits typically involves three stages: establishing baseline scenario, project implementation and monitoring actual reductions. The baseline scenario indicates what emissions would have been experienced in the absence of the solar PV installations, usually continuous fossil-fuel reliance. Once operational, clean electricity of the project displaces the

baseline emissions, and these reductions are then monitored, reported, and verified under internationally recognized procedures.

According to Cames and Harthan (2023), various procedures under the Clean Development Mechanism (CDM) and voluntary schemes like the Verified Carbon Standard (VCS) and Gold Standard are applicable to solar PV projects. These procedures require detailed Project Design Documents (PDDs), continuous monitoring of energy output, and intensive third party verification. Verra (2023)'s methodology for RE projects provides step-by-step guidance for quantifying emission reductions and guaranteeing integrity in carbon accounting. The importance of accurate monitoring and verification cannot be overemphasized. Past concerns of "non-additional" projects (projects that would have occurred without carbon finance) have challenged the credibility of carbon markets (Greenpeace, 2021). Digital technologies such as remote sensing, smart meters, and blockchain are increasingly being adopted to address these concerns, ensuring real-time data collection and transparency (Olaniyi, et al. 2023). By including ICT-enabled solutions in Nigeria's solar PV carbon credit system, the country can strengthen both investor confidence and environmental credibility. Figure 1 shows the impact of ICT tools on verification costs.

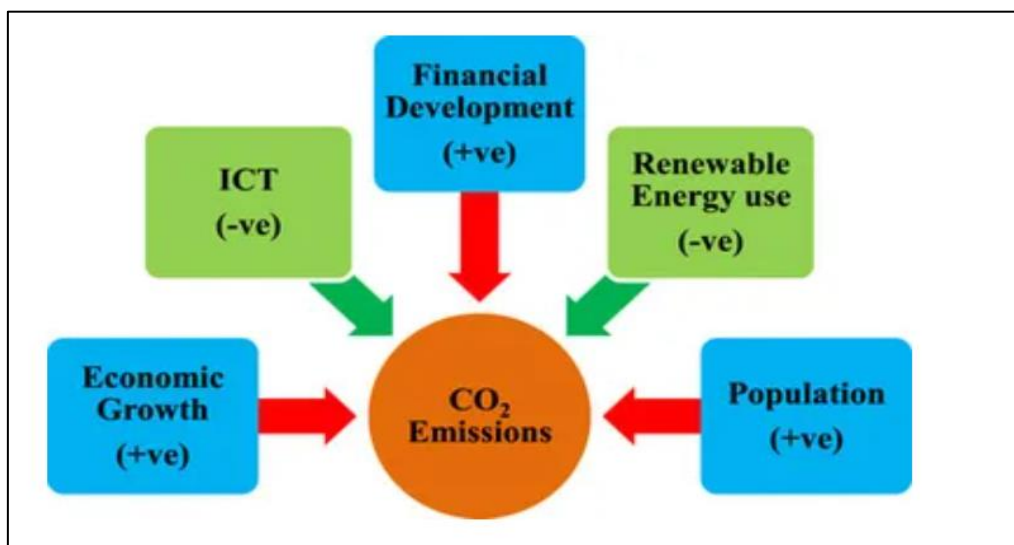


Fig 1 Impact of ICT Tools on Verification Costs (Adapted from Yuzhao et.al., 2022)

➤ Relevant Carbon Markets and Standards

Carbon markets exist in two main forms: compliance markets and voluntary markets. Solar PV projects are eligible for participation in both forms, provided they meet set standards. Under the Kyoto Protocol, the Clean Development Mechanism (CDM) was one of the first global compliance systems that enabled developing countries in generating Certified Emission Reductions (CERs). Between 2005 and 2020, over 8,100 projects were already registered under CDM, but the African continent accounted for less than 3% of them, with Nigeria having fewer than 20 (UNFCCC, 2020). Although there was a decline in CDM activity after the Paris Agreement, its methodologies maintained influence in shaping the standard of carbon accounting.

In the voluntary carbon market (VCM), standards such as the Verified Carbon Standard (VCS) and the Gold Standard dominate RE certification. The Gold Standard, launched in 2003 by the World Wide Fund for Nature (WWF), emphasises sustainable development co-benefits and emissions reductions (Trottier and Narassimhan, 2024). VCS, managed by Verra, represents almost 70% of the voluntary carbon credit supply globally, with over 1 billion credits issued by 2022 (Ecosystem Marketplace, 2023). Both standards provide procedures specifically tailored to solar PV projects, making them suitable frameworks for Nigeria's RE expansion.

Article 6 of the Paris Agreement has in recent times created new opportunities for internationally transferred mitigation outcomes (ITMOs), which can allow Nigeria to participate in emerging compliance-styled markets (World Bank, 2024). However, operationalising the article requires strong governance frameworks to avoid double-counting of emission reductions, and to ensure environmental integrity. The credibility of carbon markets is a recurring issue. Investigations into forestry offsets have projected risks of over-crediting, and questioned their real climate impact. In contrast, RE projects, particularly solar PV, offer more measurable and verifiable results. Nigeria's ability to align its solar projects with credible standards such as VCS or Gold Standard will be important to building trust in its carbon credit portfolio.

➤ *Nigeria's Position in the Global and Regional Carbon Market*

Historically, Nigeria's carbon market participation has been limited, but recent trends suggest a rising recognition of its potential. The country contributes only about 0.3 percent of global GHG emissions yet faces high vulnerability to climate change, thereby making carbon finance a lucrative strategy for both adaptation and mitigation (ECN, 2022). Under CDM, Nigeria registered projects such as the "Lagos State Bus Rapid Transit", and small-scale RE initiatives, but overall impact was marginal as compared to countries like China or India (UNFCCC, 2020). With the rise of voluntary carbon markets, new opportunities have emerged. As of 2023, the global voluntary carbon market was valued at nearly \$2billion, with projections that it could grow to \$50billion by 2030 (McKinsey et. al. 2021). Nigeria has started to position itself to attract a share of this market through solar mini-grid projects that serve the nearly 92million Nigerians without access to electric power. Such projects generate not only carbon credits but also substantial socio-economic benefits, enhancing their appeal in voluntary markets where co-benefits are of high priority.

The Nigerian government has also indicated its intent to operationalise carbon trading in the country. In 2022, the Federal Government announced the launch of a national carbon-market-initiative as part of efforts to achieve net-zero emissions by 2060 This drive aims to attract foreign investors, create frameworks for credit issuance, and align Nigeria with Article 6 mechanisms. However, challenges remain, including capacity, inadequate regulatory lack of technical expertise and limited investor awareness. Nevertheless, Nigeria could leverage partnerships through the African Carbon Markets Initiative (ACMI), which aims to produce 300 million credits annually by 2030 and unlock \$6billion in revenue for the African economies (Aggarwal and Jain, 2022). By positioning solar PV as a leading sector in its carbon market strategy, Nigeria could become a continental hub for RE-driven carbon credit generation.

Anagba and Oyebanjo, (2024) asserted that the ecosystem for carbon credit development in Nigeria's solar PV sector encompasses some diverse stakeholders. Project developers (RE companies or independent power producers) initiate projects, prepare documentation and oversee

implementation. These developers may include local organisations and international actors investing in Nigeria's mini-grid sector. Third-party verifiers are equally essential. Accredited by standards like Gold Standard or VCS, they ensure that emission reductions are genuine, properly monitored, and additional. Their role is to validate baseline calculations, confirm monitoring results, and issue certification once reductions are confirmed and verified. Without credible verification, projects cannot access the international markets.

Government institutions, especially the Department of Climate Change of the Federal Ministry of Environment, play a regulatory role. They are responsible for setting national regulations, aligning the Paris Agreement, and preventing issues such as double-counting of credits. Also, financial institutions such as development banks, commercial lenders, and carbon funds provide the necessary capital for project development or buyers in carbon markets. AfDB, (2021) claim to have supported solar PV projects in Nigeria through blended finance mechanisms linked to carbon revenues (AfDB, 2021). Local communities are also important stakeholders in this initiative. Since many solar PV projects in Nigeria are produced for rural electrification, community engagement ensures both sustainability and social acceptance. Studies show that projects with strong community participation achieve enhanced success rates and deliver broader co-benefits (World Bank, 2023). NGOs and civil society organizations further contribute by raising awareness, holding project developers accountable, and providing capacity building. Finally, international organizations and buyers, ranging from multi-national corporations seeking offsets to governments fulfilling climate pledges, form the demand side of the carbon market. Nigeria's ability to connect with these global stakeholders will decide the financial viability of its solar PV carbon credit projects.

➤ *Current Challenges in Carbon Credit Verification in Nigeria*

Carbon credit verification in Nigeria faces numerous setbacks. One of it is the absence of standardized frameworks for data collection, monitoring, and reporting. In Nigeria, energy data is often fragmented across multiple institutions, such as the Nigerian Electricity Regulatory Commission (NERC), Transmission Company of Nigeria (TCN), and distribution companies (DISCOs). ECN (2022)'s reports show that grid-level data is inconsistent, with discrepancies of up to 15% between generation figures reported by TCN, and those provided by DISCOs. More especially for solar PV projects, challenges emerge in capturing accurate generation data from stand-alone systems and dispersed mini-grids which make up a growing share of Nigeria's RE landscape. IRENA (2023) estimated that more than 1,500 mini-grids are currently operational (or under development) in Nigeria, but less than half have standardized metering systems linked to central monitoring platforms. This gap threatens effective verification, as emission reductions cannot be accurately quantified without actual generation and usage data. The lack of digital Monitoring, Reporting, and Verification (MRV) platforms further worsen the issue. In contrast, countries like

South Africa and India have adopted ICT-enabled registries that integrate project-level data with national reporting systems, thereby streamlining verification attempts (World Bank, 2022). Nigeria's current dependence on manual reporting exposes projects to risks of double-counting, errors, and even fraudulent claims. Without harmonized procedures and centralised registries, the credibility of Nigeria's carbon credits will remain questioned in the global markets, deterring buyers and investors.

Second, third-party or external verification is essential to ensure the credibility of carbon credit projects, but it remains a time-consuming and costly process in Nigeria. Accredited international verifiers, such as DNV, TÜV SÜD, and SGS charge significant fees for verification and validation, with costs often exceeding \$30,000 for small-scale projects (UNFCCC, 2020). Many local solar developers, particularly mini-grid operators whose average project size is below 1MW, the cost of verification can exceed potential carbon revenues. In addition, verification processes can take between six months to a year, depending on the complexity of the project and the procedure applied (Cames and Harthan, 2023). Nigerian developers have reported that long verification timelines discourage participation, especially when compared to alternative sources of financing such as concessional loans or green bonds (Olaniyi et. al., 2023). Geographical challenges of verification in Nigeria also increase costs. Many solar projects are located in remote areas, which requires verifiers to conduct on-site inspections that involve extensive travel and logistics. Over 40% of Nigeria's rural roads are in poor condition, site visits can become costly and time-intensive. While digital monitoring and remote sensing could reduce these barriers, adoption of such technologies remains limited, leaving developers dependent on expensive in-person verification. Notwithstanding, reducing costs and timelines through digital verification tools could be critical for scaling solar PV's role in generating tradable carbon credits.

A third challenge is the shortage of local expertise in carbon credit development and verification. Carbon markets require specialised skills in emissions accounting, baseline analysis, project documentation, and MRV systems. In Nigeria, only few professionals have been trained to international verification standards, resulting in heavy reliance on foreign consultants. AfDB (2021) found that over 70% of carbon market services in Nigeria were outsourced to international organisations, limiting local ownership and increasing costs. Universities and training institutions in Nigeria are yet to fully integrate carbon finance (or MRV) into their curricula, leaving a skills gap in the RE workforce (Anagba and Oyebanjo, 2024). While capacity-building initiatives such as the UNDP's Low Emission Capacity Building, LECB programme have been introduced, although with limited reach, and fewer than 200 professionals trained across the country since 2016 (UNDP, 2020). This lack of expertise extends to government agencies such as Department of Climate Change (DCC) as well. According to a Climate Policy Initiative report, institutional capacity gaps have slowed Nigeria's readiness to operationalise Paris Agreement. Without technical expertise in-house, regulatory

loopholes of carbon credit projects remain, contributing to market unpredictability. Building local capacity is important not only to reduce dependence on international verifiers but also to promote confidence in Nigeria's carbon credit ecosystem. Regional collaborations through the African Carbon Markets Initiative, ACMI offer potential for shared training and development programme, but scaling such initiatives will require policy support and sustained investment.

Forth, trust and transparency are critical for the credibility of carbon markets. In Nigeria, concerns about data integrity undermine investor confidence. Past experiences with weak governance in the energy sector, such as the misreporting of subsidy claims and discrepancies in metering data, have created skepticism about the reliability of reported emissions reductions. Carbon credit projects depend on robust MRV systems to ensure credibility, but Nigeria's energy infrastructure lacks the integration capacity (NERC, 2023). This lack of transparency in electricity data directly impacts the ability to evaluate baseline emissions for projects relating to carbon credit. In voluntary carbon markets, the issue of "non-additional projects" have raised broader questions globally. Investigations by the Guardian (2023) revealed that more than 90% of certain rainforest carbon offsets lacked the required real impact, causing buyers to become more cautious. For Nigeria's solar PV sector, ensuring transparency in reporting is even much more important, as buyers demand assurance that credits represent genuine additional reductions. Blockchain technology, digital registries, and open-access databases could improve trust, but adoption in Nigeria also remains limited. Without these innovations, Nigeria risks reputational damage, and exclusion from high-value international markets. Transparency challenges must be urgently addressed to ensure long-term credibility.

Finally, regulatory uncertainty presents another setback to effective carbon credit verification in Nigeria. The government has announced ambitious initiatives like the Nigeria Carbon Market Initiative in 2022, but regulatory frameworks remain under-developed. A clear, consistent policy environment is important for investors to participate confidently in carbon markets. Institutional overlap also breeds complexities in governance. The DCC, NERC, and Rural Electrification Agency (REA) all have roles in RE and climate governance, but their mandates usually overlap without effective coordination. This segmentation leads to delays in project approvals and poor oversight. In addition, Nigeria lacks a national carbon registry. This makes it difficult to track credits and prevent double-counting. Countries like South Africa and Kenya have already launched registries to fortify market governance (ACMI, 2022). Nigeria's delay in establishing similar systems risks marginalising it in emerging regional carbon markets. Weak enforcement and corruption of existing regulations further threaten institutional credibility. Transparency International (2021) ranks Nigeria 150th of 180 countries in its Corruption Perception Index (CPI), a factor that discourages foreign buyers seeking trustworthy and reliable carbon credits. Strengthening institutions through clear guidelines, reforms,

and digital governance tools is however vital for combating regulatory barriers in carbon credit verification.

➤ *The Role of ICT in Carbon Credit Verification*

Information and communication technologies (ICTs) are reshaping the manner carbon credits are verified and monitored, transparency, offering efficiency, and reduced costs. For Nigeria's solar PV projects, ICT provides solutions to prevailing verification problems such as high costs of field inspections, inconsistent data collection, and lack of trust in reporting system. According to the International Telecommunication Union (ITU), ICT-enabled systems can help cut global GHG emissions by nearly 20% through improved energy efficiency and digital monitoring. By leveraging ICT, regulators and project developers in Nigeria can VCS and Gold Standard.

Remote sensing technologies, comprising drones and satellite imagery, provide accurate geospatial data on solar PV installations, which assists verify project activity without costly site visits. The European Space Agency (ESA) has shown that remote sensing can achieve above 95 percent verification accuracy levels for RE projects. In Nigeria, where solar mini-grids are spread across remote rural areas, this technology strengthens transparency and reduces logistical challenges. The IoTs builds on this by enabling real-time data capture through sensors and smart meters. Smart meters installed in Nigerian solar mini-grids have achieved reporting error margins below two percent (2%) against the 10 to 12 percent (10% to 12%) under manual monitoring systems (Alli et al., 2022). Data loggers further ensure continuous, and automated records of energy production and usage. These digitally-captured datasets are less prone to manipulation, providing a strong basis for trustworthy carbon credit claims.

Blockchain technology addresses one of the core setbacks in carbon markets (vis-à-vis: trust in data). By storing records on decentralised immutable ledgers, blockchain minimises the risks of double-counting and data manipulation. Treiblmaier and Clohessy, (2022) studied blockchain applications in carbon markets found that transaction costs were minimised by up to 40%, while

improving auditability and traceability. According to Treiblmaier and Clohessy's study, institutional restrictions often slow verification in Nigeria, However, blockchain can create a transparent system accessible to project regulators, developers, and international buyers. Initiatives such as the African Carbon Markets Initiative (ACMI) have already demonstrated how blockchain-based initiatives can boost confidence in African carbon credits.

AI and advanced data analytics can strengthen emission reduction estimations by processing complex datasets from IoT systems and remote sensing. AI algorithms can forecast energy generation patterns and avoided emissions with higher accuracy than regular statistical models. In Kenya, AI-based systems improved emissions forecast accuracy by 18%, offering a more reliable baselines for credit issuance (Ndiritu, 2022). In the Nigerian context, such tools can reduce dependence on manual verification processes, allowing faster issuance of verified credits, while improving the financial viability of solar PV projects.

III. BASIC TYPOLOGIES AND STRATEGIC PROCEDURE

➤ *Proposed Architecture of an ICT-Based Verification System*

This study proposed a framework for the ICT-driven verification system for solar PV projects in Nigeria. It is designed as a multi-structured platform that combines data acquisition, blockchain-based storage, automated validation, and user-friendly reporting interfaces. At the foundational layer, IoT devices such as smart meters, inverters with built-in telemetry, and environmental sensors are installed across solar PV installation sites. These devices continuously record key performance indicators such as consumption, energy generation, and grid feed-in. In a country like Nigeria, where over 80 million people still lack electric power access (IEA, 2022), real-time monitoring is essential not only for project management, but also for ensuring the credibility of carbon credit claims. Figure 2 shows the architecture of proposed certification and verification system as with Muhammad and Md. Jawwad (2020)

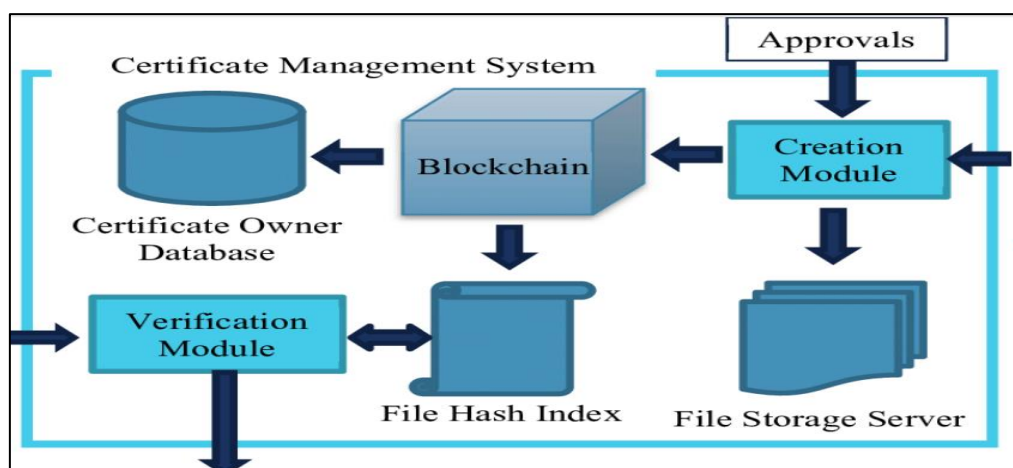


Fig 2 Architecture of Proposed Certificate Creation and Verification System (Muhammad and Md. Jawwad, 2020)

Above this hardware layer sits a data management platform that is cloud-based. This platform collects streams of information from IoT devices and remote sensing inputs such as drone surveys and satellite imagery. Automated anomaly detection can flag irregularities, reducing the burden on human verifiers. According to UNDP (2022), countries that steered such digital platforms for RE carbon credits reduced verification costs by nearly 25 percent while cutting processing timelines by more than half.

The blockchain layer of the framework provides transparent transaction records and immutable storage. Carbon credits issued within this framework are permanently tracked from project inception to trading, thereby addressing the challenge of double-counting that has affected global carbon markets. This layer is integrated with Nigeria's National Carbon Registry (NCR) and international platforms such as the African Carbon Markets Initiative (ACMI), ensuring interoperability. A comparative study in Rwanda and India indicated that blockchain-based registries increased stakeholder confidence and improved investor participation by 35% (Chaudhary and Sethi, 2021).

The top layer of the architecture encompasses user-facing dashboards and audit trails. These allow regulators, verifiers, project developers, and buyers to access information relevant to their roles. By adopting such a holistic framework, Nigeria can align solar PV projects with international carbon standards ensuring that credits generated are accepted in global markets. This architecture thus transforms verification from a costly, opaque process into a transparent and digitally enabled system.

➤ *Data Acquisition: Real-Time Performance Monitoring*

Accurate data acquisition is the foundation of any credible carbon verification framework. In the Nigerian context, where project sites are often remote and data reporting systems remain fragmented, the role of ICT in ensuring consistent, real-time performance monitoring cannot be overstated. Smart meters, IoT-enabled inverters, and data loggers offer project developers and verifiers a reliable way of measuring electricity production and consumption. According to Alli et al. (2022), Nigerian mini-grids equipped with IoT meters achieved error margins of less than 2%, compared to 10–12% with manual monitoring logs. This improvement directly translates into more accurate estimates of avoided carbon emissions. Remote sensing technologies, particularly satellite imagery and drones, complement IoT-based monitoring by providing external validation of solar PV performance. The European Space Agency (ESA, 2021) found that satellite-based monitoring of RE projects can verify plant activity with over 95% accuracy. This is especially relevant in rural Nigeria, where verification teams often face logistical challenges due to poor roads, insecurity, or high travel costs. Drones deployed for aerial inspections can confirm installation sizes, detect faulty panels, and verify operational status, offering additional layers of data reliability.

Another important aspect of data acquisition lies in environmental sensors that record solar irradiation and

weather conditions. These contextual datasets enable cross-validation of energy production claims. By triangulating generation data with weather and irradiation data, Nigeria can strengthen the integrity of its carbon credit claims. The economic impact of real-time monitoring is also significant. A World Bank (2020) study revealed that African mini-grid operators who adopted real-time monitoring saw a 20% reduction in operational costs and improved revenue flows through more accurate billing. Applied to carbon credit verification, such savings could lower barriers for small and medium-scale solar developers in Nigeria. In sum, robust, ICT-enabled data acquisition transforms verification from a periodic, costly exercise into a continuous, reliable process that enhances Nigeria's credibility in global carbon markets.

➤ *Automated Data Validation and Emission Reduction Calculations*

After due data acquisition, automated validation and calculation systems become essential for ensuring that emissions reductions are accurately quantified. Manual validation processes, often used in Nigeria, are prone to delays, human error, and, in some cases, manipulation. Automated systems, by contrast, employ algorithms to cross-check datasets against established baselines. This involves comparing actual electricity output with regional solar irradiation levels and grid emission factors. Emission reduction calculations depend heavily on Nigeria's grid emission factor, which the International Energy Agency (2022) estimated at 0.59 tCO₂/MWh in 2021. Automated tools can integrate this value with performance data from smart meters to generate precise estimates of avoided emissions.

Artificial intelligence (AI) further enhanced validation by identifying patterns and anomalies that traditional statistical methods might miss. Machine learning models trained on large datasets can predict expected solar PV output under varying environmental conditions, flagging discrepancies between actual and predicted values. In South Africa, AI-enabled verification platforms improved fraud detection rates by 25% (Grobler, 2021). Applying similar tools in Nigeria would build trust among investors and regulators, both of whom demand assurance of data integrity. Overall, automated validation and emission reduction calculations not only enhance technical accuracy but also reduce transaction costs. By minimizing human intervention in routine processes, these systems free up verifiers to focus on complex auditing tasks. The result is a more efficient, transparent, and scalable verification system that aligns Nigeria's solar PV projects with international carbon market expectations.

➤ *Integration with National and Regional Carbon Registries*

For ICT-based verification systems to be effective, they must integrate seamlessly with national and regional carbon registries. Nigeria launched its National Carbon Registry in 2023 to streamline carbon trading and ensure compliance with Article 6 of the Paris Agreement. However, without digital interoperability, the registry risks becoming siloed and inaccessible to international markets.

An ICT-driven framework addresses this by automatically transferring verified emissions reduction data from project monitoring systems to the national registry. Blockchain technology can be particularly effective here, ensuring that uploaded data is immutable and traceable. By linking the registry to regional platforms such as the African Carbon Markets Initiative (ACMI), Nigeria can access a broader pool of buyers and investors. ACMI (2022) estimates that Africa could mobilize up to 300 million carbon credits annually by 2030, with Nigeria positioned to capture a significant share if it aligns its systems with global standards. Integration also allows for harmonization with international registries such as Verra's VCS and the Gold Standard. This ensures that credits issued in Nigeria are recognized in voluntary and compliance markets worldwide. In India, integration of its carbon registry with international standards increased carbon credit sales by 22% between 2019 and 2021 (Chaudhary and Sethi, 2021). Nigeria could replicate this success by embedding interoperability into its ICT architecture.

Institutional benefits are also significant. A centralized, digital registry reduces duplication of efforts among regulators, project developers, and verifiers. It also enhances transparency by providing stakeholders with a single platform for tracking project performance and credit issuance. Furthermore, integration strengthens Nigeria's negotiating position in regional and international climate finance discussions by demonstrating robust governance structures. Ultimately, integrating ICT-based verification with national and regional registries ensures that Nigeria's carbon credits are both technically credible and marketable. This step is critical for scaling up solar PV deployment, attracting international investment, and positioning Nigeria as a leader in Africa's emerging carbon economy.

➤ *Reporting Dashboards and Audit Trails for Transparency*

Transparency is a cornerstone of carbon markets, and ICT-driven reporting dashboards and audit trails play a crucial role in ensuring it. Dashboards serve as interfaces where stakeholders, project developers, regulators, investors, and verifiers, can access real-time information on project performance, emissions reductions, and credit issuance. In India, RE projects using digital dashboards improved verifier efficiency by 30% while reducing disputes over credit calculations (Chaudhary and Sethi, 2021).

In Nigeria, such dashboards would enhance accountability by making data more accessible and understandable. For example, a developer could view daily electricity generation and corresponding emissions reductions, while an investor could monitor verified credits in their portfolio. Regulators, on the other hand, could track sector-wide progress towards national climate goals. Dashboards can also be customized with alerts that flag irregularities, ensuring that problems are identified and addressed promptly. Audit trails are equally important for building trust. Every data entry, modification, and transaction can be recorded on blockchain, creating an immutable history of project activities. This addresses concerns about data tampering, a recurring issue in carbon markets. According to

Treiblmaier and Clohessy (2022), blockchain-enabled audit trails increased trust in carbon markets by 40% among surveyed stakeholders. For Nigeria, such transparency mechanisms would attract more buyers who demand high levels of assurance before purchasing credits.

Audit trails also simplify the work of third-party verifiers. Instead of manually reviewing multiple datasets, verifiers can rely on automated, timestamped logs that document every step of the project's performance. This reduces verification time and costs, which are major barriers for small-scale solar PV developers. In Rwanda, projects that adopted blockchain-based audit systems reported a 22% decrease in verification expenses (UNDP, 2022). By embedding reporting dashboards and audit trails into its ICT-driven framework, Nigeria can create a transparent, efficient, and investor-friendly verification system. These tools will not only improve the credibility of its carbon credits but also support broader goals of good governance and institutional strengthening in the RE sector.

➤ *Case Studies and Global Best Practices*

The use of ICT in carbon credit verification has gained global momentum, particularly in regions where RE projects dominate carbon markets. One notable example is India, where digital monitoring and blockchain-based registries have been deployed to track emission reductions from solar PV and wind projects. India's Ministry of New and Renewable Energy (MNRE) introduced a centralized monitoring platform that integrates smart meters and real-time data acquisition from solar plants. This system not only streamlines verification but also improves investor confidence by providing transparent, verifiable records. Studies show that India's adoption of blockchain registries has helped reduce double counting issues and enhanced carbon credit acceptance in international voluntary markets (Chaudhary and Sethi, 2021). Another case is Rwanda, which partnered with the United Nations Development Programme (UNDP) to pilot a blockchain-based carbon registry. This platform enables real-time submission of project data and automated issuance of carbon credits once verification criteria are met. The pilot demonstrated that blockchain systems could cut verification costs by up to 22% while reducing project approval timelines (UNDP, 2022). For a low-income country with limited administrative capacity, ICT innovation provided a cost-effective way of entering the global carbon market.

In Europe, the European Space Agency (ESA) has advanced the use of remote sensing and satellite data to verify RE performance. By monitoring solar irradiation, panel coverage, and operational efficiency from space, ESA-supported programs reduce reliance on costly, on-the-ground audits (ESA, 2021). This innovation is especially relevant for large-scale projects, where field verification may be logistically challenging. These global examples reveal the transformative potential of ICT in enhancing transparency, reducing costs, and improving efficiency in carbon markets.

For Nigeria, which is currently building its national carbon registry, such models provide valuable insights into how digital tools can be leveraged to strengthen verification

frameworks and attract international investment. Table 3 shows the global best practices in ICT-based carbon verification.

Table 1 Global Best Practices in ICT-Based Carbon Verification

Country	ICT tool used	Outcome	Lessons for Nigeria
India	Blockchain registry	Reduced double counting	Regulatory alignment
Rwanda	Digital registry (UNDP)	Verification cost reduced by 22%	Build local capacity
EU	Remote sensing	Lower audit costs	Use satellite data

➤ *Lessons Learned and Relevance to Nigeria*

A key lesson from international experiences is that the effectiveness of ICT-driven verification depends not only on technology adoption but also on strong institutional frameworks and policy support. In the case of India, the success of blockchain-enabled carbon tracking was facilitated by government mandates requiring RE developers to report data through digital platforms (MNRE, 2021). This highlights the importance of aligning ICT adoption with clear regulatory requirements. Nigeria's Federal Ministry of Environment can adopt a similar approach by embedding ICT-based verification within its climate policies and carbon registry guidelines.

Another important lesson concerns stakeholder capacity. Rwanda's pilot demonstrated that while blockchain reduced costs and timelines, initial challenges arose from low technical expertise among regulators and developers (UNDP, 2022). To address this, the government and its partners invested in training programs for project developers, verifiers, and registry administrators. Nigeria, with its diverse and expanding RE sector, must prioritize capacity-building programs to ensure that all stakeholders can effectively use ICT tools for verification.

Transparency and trust are also recurring themes. The European case emphasizes how remote sensing data can independently validate project claims, thereby reducing opportunities for fraud. For Nigeria, where concerns about governance and corruption have sometimes hindered climate finance inflows (World Bank, 2020), ICT-driven verification offers an opportunity to build credibility with international buyers. Embedding blockchain audit trails and open-access dashboards into the verification framework would address long-standing concerns about data manipulation.

Finally, scalability emerges as a critical factor. ICT solutions that work for pilot projects must be adaptable to larger national contexts. India's experience shows that centralized digital platforms can handle data from thousands of RE projects simultaneously. For Nigeria, where solar PV deployment is expected to expand rapidly under the Energy Transition Plan, investing in scalable ICT infrastructure will be crucial for sustaining long-term carbon credit generation.

In summary, the global best practices underscore the need for Nigeria to adopt a holistic approach that combines technology, policy, institutional capacity, and transparency mechanisms. By internalizing these lessons, Nigeria can position itself as a credible participant in international carbon

markets while simultaneously driving its domestic clean energy transition.

➤ *Pilot ICT-Based Verification Projects in Nigeria or West Africa*

In West Africa, ICT-driven carbon verification is still at a nascent stage, but pilot initiatives provide useful insights for scaling. In Nigeria, some mini-grid and solar home system developers have begun experimenting with digital monitoring platforms. Companies such as Lumos have deployed smart metering systems that track electricity generation and consumption in real time. While primarily designed for operational efficiency and billing, these systems offer valuable data streams that could be integrated into carbon verification frameworks (Alli et al., 2022).

At the regional level, the African Carbon Markets Initiative (ACMI) has launched efforts to explore digital registries and blockchain applications for carbon markets. Nigeria, as one of ACMI's priority countries, has participated in stakeholder dialogues aimed at building ICT-driven frameworks (ACMI, 2022). Though still at an exploratory phase, these initiatives highlight the continent's readiness to embrace digital solutions for carbon verification.

Ghana provides a more advanced example within the region. Through partnerships with the World Bank, Ghana has piloted digital monitoring systems for its RE projects. The World Bank (2021) reported that these platforms improved transparency and reduced verification costs by 15%, setting a precedent for neighboring countries, including Nigeria, to replicate.

Despite these encouraging pilots, challenges remain. In Nigeria, limited internet connectivity in rural areas poses a barrier to real-time data transmission. Additionally, weak institutional capacity and a lack of harmonized standards across agencies have slowed progress. However, ongoing government initiatives, such as the operationalization of the National Carbon Registry in 2023, indicate growing political will to integrate ICT into verification systems (Federal Ministry of Environment, 2023).

The way forward for Nigeria lies in scaling these pilots into nationally recognized platforms, supported by regulatory frameworks and international partnerships. By building on early experiments with smart metering and leveraging ACMI's continental momentum, Nigeria can pioneer ICT-driven carbon verification in West Africa.

This will not only improve the country's carbon market competitiveness but also attract climate finance to support its

RE transition. Table 4 summarises the role of various ICT tools in carbon credit verification.

Table 2 ICT Tools and their Role in Verification

ICT Tool	Application in MRV	Benefits
IoT (smart meters)	Real-time energy monitoring	Accuracy, reliability
Remote sensing	Solar irradiation verification	Independent validation
Blockchain	Registry & transaction tracking	Transparency, trust
AI & Analytics	Baseline forecasting	Efficiency, scalability

IV. IMPLEMENTATION ROADMAP FOR NIGERIA

The deployment of ICT-driven verification systems in Nigeria must follow a phased and strategic approach that aligns with both national climate goals and international carbon market standards. The first step is establishing a robust regulatory foundation. This requires the Federal Ministry of Environment, in collaboration with agencies such as the Energy Commission of Nigeria and the Rural Electrification Agency, to adopt formal guidelines that mandate the integration of ICT tools in carbon credit monitoring. For example, India's Ministry of New and Renewable Energy (MNRE) issued such directives before rolling out its national digital monitoring platform, ensuring uniform compliance across projects.

The second step involves the digitization of data flows from solar PV installations. Nigeria's growing solar market, with over 1.25 million solar home systems installed by 2023 (World Bank, 2023), presents a substantial opportunity for embedding IoT-enabled smart meters, sensors, and cloud-

based data loggers. These devices can feed into a centralized verification platform, allowing regulators and verifiers to monitor real-time generation and grid contributions.

A third step is piloting the ICT verification framework in selected regions. For an instance, mini-grids in Kaduna, Kano, and Lagos could serve as testbeds, enabling the government and project developers to refine digital tools and address technical or logistical bottlenecks before national roll-out. Rwanda's blockchain-based carbon registry provides an example of how pilot projects can build the confidence necessary for scaling (UNDP, 2022).

Finally, integration with international carbon registries must be prioritized to secure Nigeria's position in global markets. By linking ICT systems to platforms like the African Carbon Markets Initiative and Verra's Verified Carbon Standard, Nigeria can guarantee that its emission reductions meet recognized international benchmarks. This step ensures global credibility while enabling project developers to access higher-value carbon finance streams.

Table 3 Implementation Roadmap for ICT-Driven Verification in Nigeria

Step	Action	Stakeholders	Timeline
1	Develop ICT-inclusive MRV guidelines	Fed. Min. of Environment, NITDA	Short term
2	Deploy pilot smart metering systems	Solar developers, ACMI	Medium term
3	Scale blockchain-based registry	Carbon Registry, Private ICT firms	Long term

➤ Capacity Building and Stakeholder Engagement

Successful implementation requires equipping stakeholders with the knowledge and technical expertise to use ICT verification tools effectively. Nigeria's RE sector involves a diverse set of actors, including government regulators, project developers, independent verifiers, financiers, and community organizations. Each group must be trained to understand how ICT platforms operate, their role in the verification process, and how to ensure data integrity.

Capacity building can be achieved through structured training programs delivered in partnership with universities, technical institutions, and international organizations. For example, the African Development Bank has previously supported climate-related training initiatives for African regulators, which improved carbon market participation by over 30% in participating countries. Similar programs in Nigeria could focus on blockchain technology, IoT-based monitoring, and AI-driven emissions modeling.

Stakeholder engagement is equally important. Communities hosting solar PV projects must be sensitized about how ICT-based monitoring will function and how it contributes to both climate finance and local energy security. This builds trust and encourages cooperation in data collection. For private developers, engagement must center on demonstrating how ICT-driven systems reduce verification costs and enhance access to international finance.

Moreover, Nigeria can establish multi-stakeholder working groups that include representatives from government, private sector, civil society, and academia. Such forums, modeled after the Indian Renewable Energy Development Agency's stakeholder platforms, provide a structured avenue for feedback, policy refinement, and collective decision-making (IREDA, 2020). Effective stakeholder engagement thus ensures inclusivity, transparency, and long-term sustainability of ICT-driven verification systems.

➤ *Infrastructure and Policy Requirements*

The backbone of ICT-driven verification is digital infrastructure. Nigeria faces challenges of weak internet penetration in rural areas, unreliable electricity supply, and limited data management systems. To overcome these barriers, the government must prioritize the expansion of broadband networks and invest in reliable data storage facilities. Satellite-based internet services and mobile data platforms can bridge connectivity gaps, particularly for remote solar PV installations in rural communities (GSMA, 2022). Policy frameworks must evolve to integrate digital monitoring into carbon markets. Current Nigerian energy policies, such as the Renewable Energy Master Plan (REMP) and the National Climate Change Policy, provide a general framework but lack specific provisions for ICT-driven carbon verification. New regulatory instruments should mandate the use of smart metering for all large-scale RE projects and encourage smaller developers to adopt cost-effective digital tools through subsidies or tax incentives.

Data governance also requires attention. Establishing national standards for data collection, storage, and sharing is crucial for interoperability and consistency across projects. Countries like Kenya have adopted national data governance frameworks for RE that Nigeria can emulate (KNBS, 2020). Finally, clear enforcement mechanisms are needed to ensure compliance. Independent regulatory bodies could be tasked with auditing data flows and imposing penalties for fraudulent reporting, thereby safeguarding the credibility of Nigeria's carbon market.

➤ *Public-Private Partnerships and Funding Opportunities*

Financing the deployment of ICT-driven verification systems is a significant challenge, especially given Nigeria's constrained fiscal space. Public-private partnerships (PPPs) present a viable pathway for mobilizing the necessary investments. The government can provide enabling policies, subsidies, and infrastructure support, while private actors, including RE developers, ICT firms, and financial institutions, invest in hardware and software systems.

Several funding opportunities exist at both national and international levels. Nigeria can leverage the Green Climate Fund (GCF), which has allocated over USD 10 billion globally for climate projects, with a strong focus on digital innovation. Similarly, the World Bank's Scaling Solar Program and the African Development Bank's Desert to Power Initiative offer financing mechanisms that could support ICT integration into verification systems. Domestically, sovereign green bonds issued by the Nigerian government provide another avenue. Nigeria's green bond program, launched in 2017, has already raised billions of naira for RE projects (SEC Nigeria, 2020). A portion of future issuances could be earmarked for ICT verification infrastructure.

Partnerships with technology firms also offer innovative funding models. For example, blockchain developers have supported carbon markets in Latin America by providing digital platforms in exchange for transaction fees, reducing upfront costs for governments (De León and

Guild, 2021). Nigerian ICT companies could similarly co-invest in verification platforms, with revenue generated from project developers who use the systems. By combining international climate finance, domestic green bonds, and PPP models, Nigeria can mobilize sufficient resources to operationalize ICT-driven verification systems. This funding mix will be critical in scaling beyond pilot projects and ensuring the sustainability of verification frameworks in the long term.

V. CHALLENGES OF ICT ADOPTION IN THE NIGERIAN CONTEXT

➤ *ICT Infrastructure Limitations (Connectivity, Power Supply)*

The successful deployment of ICT-driven carbon credit verification systems in Nigeria faces significant barriers stemming from infrastructural weaknesses. Reliable internet connectivity is foundational for real-time monitoring and reporting, yet Nigeria continues to grapple with inconsistent broadband access. According to the Nigerian Communications Commission (NCC), while internet penetration has improved to over 50 percent of the population, service quality remains uneven, particularly in rural and semi-urban areas where solar photovoltaic (PV) projects are most commonly located. Poor network stability undermines the efficiency of digital platforms that depend on uninterrupted data transmission from smart meters, sensors, and remote sensing devices.

Equally critical is the challenge of electricity reliability. ICT-enabled systems, including blockchain platforms and Internet of Things (IoT) devices, require a steady power supply to ensure continuous operation. Nigeria's national grid, however, remains characterized by instability, with frequent outages and limited generation capacity. A report by the International Energy Agency notes that approximately 85 million Nigerians, nearly 40 percent of the population, still lack access to electricity. This limitation not only hinders ICT adoption but also undermines the credibility of carbon credit verification systems, which require consistency to avoid gaps in data collection.

The cost of alternative power sources, such as diesel generators or backup solar systems, further exacerbates the financial burden on project developers. Smaller-scale solar PV initiatives in rural communities are often constrained by funding and cannot afford redundant power solutions to keep ICT systems online. Moreover, the lack of national broadband infrastructure, including fiber-optic networks and satellite coverage, constrains the scalability of ICT-driven verification mechanisms (World Bank, 2021).

Addressing these infrastructural constraints will require coordinated efforts between government, private investors, and international partners. Policies that incentivize investment in rural broadband expansion, as well as programs that enhance access to reliable electricity, are critical enablers. Without these foundational improvements, ICT adoption in Nigeria's carbon credit verification process will remain fragmented and limited in scope.

➤ *Data Privacy, Cybersecurity, and Trust Issues*

In addition to infrastructural challenges, concerns around data security and trust present substantial hurdles for ICT adoption in Nigeria's carbon credit verification landscape. Verification systems rely on sensitive data, including project performance metrics, energy production records, and emissions reduction calculations. The risk of cyberattacks, hacking, or unauthorized manipulation of data threatens the credibility of carbon markets, particularly when financial incentives such as carbon credits are at stake (Akinwale, 2021).

Blockchain technology has been promoted as a solution to enhance transparency and immutability in carbon trading (Schletz et al., 2020). However, blockchain itself is not immune to vulnerabilities, such as smart contract bugs or exploitation by malicious actors. In Nigeria, weak enforcement of cybersecurity regulations compounds these risks. While the National Information Technology Development Agency (NITDA) has introduced data protection guidelines, their implementation remains inconsistent across sectors (NITDA, 2022). This creates uncertainty for international carbon market participants who may be hesitant to engage with Nigerian projects lacking robust data safeguards.

Trust issues also extend beyond technical vulnerabilities. Many local communities and stakeholders have limited understanding of ICT systems, leading to skepticism about whether data is being accurately captured and reported. Historical experiences of corruption and data manipulation in Nigeria's governance systems have further fueled doubts about the reliability of digital verification mechanisms (Transparency International, 2022). Building trust will require not only technical safeguards but also transparent governance structures, third-party audits, and continuous stakeholder engagement.

Cybersecurity awareness among local project developers and regulators is another critical gap. A 2023 study by the African Union Commission highlights that only a small percentage of Nigerian ICT professionals have specialized training in cybersecurity and data protection (African Union Commission, 2023). This skills deficit leaves verification systems vulnerable and reduces the confidence of international buyers of carbon credits. To mitigate these risks, Nigeria must prioritize capacity building, establish stronger cybersecurity laws, and develop sector-specific standards for carbon credit verification platforms.

➤ *Need for Regulatory Alignment and Standards Development*

Perhaps the most significant challenge to ICT adoption in carbon credit verification is the absence of a coherent

regulatory framework that integrates ICT applications with carbon market mechanisms. Nigeria has shown interest in participating in global climate initiatives, as demonstrated by its commitment to the Paris Agreement and its updated Nationally Determined Contributions (NDCs). However, there remains a lack of standardized guidelines for how ICT tools, such as IoT sensors, blockchain platforms, or AI-driven data analytics, should be integrated into carbon credit verification protocols.

The Clean Development Mechanism (CDM) and other international standards, such as the Verified Carbon Standard (VCS) and the Gold Standard, provide general frameworks for verification. Yet, these are not tailored to Nigeria's context, where infrastructural and institutional weaknesses require customized solutions. The lack of domesticated policies creates uncertainty for project developers who wish to invest in ICT systems but face unclear regulatory pathways (Okereke and Esiobu, 2022).

Moreover, fragmented institutional responsibilities exacerbate the problem. Multiple agencies—including the Department of Climate Change under the Federal Ministry of Environment, NITDA, and the Energy Commission of Nigeria, have overlapping mandates related to ICT, energy, and climate. This creates bureaucratic bottlenecks and slows down the development of comprehensive regulations that would streamline ICT adoption in carbon markets (Adebayo, 2022). Without clear institutional coordination, project developers face inconsistent requirements and higher transaction costs.

The development of standards is also crucial for ensuring interoperability across ICT platforms. If different solar PV projects adopt incompatible data collection systems or blockchain architectures, it becomes difficult to aggregate and verify emissions reductions at a national or regional level. International investors and carbon market actors require harmonized data protocols to ensure comparability and reliability across projects.

To overcome these barriers, Nigeria needs a multi-stakeholder task force to align regulatory and technical standards for ICT-driven verification systems. Lessons can be drawn from countries such as India and Kenya, where regulatory reforms have established clearer pathways for digital monitoring and reporting in climate-related sectors (Aggarwal and Jain, 2021). Aligning domestic regulations with international standards while addressing local realities will be key to unlocking Nigeria's potential in ICT-enabled carbon credit markets. Table 5 shows some key challenges in carbon credit verification in Nigeria.

Table 4 Key Challenges in Carbon Credit Verification in Nigeria

Challenge	Impact on verification	Reference
Lack of standardized data systems	Data inconsistency	(Okereke and Esiobu, 2022)
High verification cost	Limited participation	(World Bank, 2021)
Low technical expertise	Errors in reporting	(Adebayo, 2022)
Transparency concerns	Weak investor trust	(Aggarwal and Jain, 2021)

VI. POLICY AND REGULATORY RECOMMENDATIONS

➤ *Development of ICT-Inclusive Carbon Verification Guidelines*

A key recommendation for advancing carbon credit verification in Nigeria is the establishment of ICT-inclusive guidelines that recognize the role of digital technologies in monitoring, reporting, and verification (MRV) processes. Current frameworks for carbon markets, such as the Clean Development Mechanism (CDM) or Verified Carbon Standard (VCS), provide general procedures for MRV but do not sufficiently address how ICT tools like blockchain, Internet of Things (IoT) devices, or artificial intelligence (AI) analytics should be integrated into national systems (UNFCCC, 2021). In Nigeria, this gap has resulted in project developers adopting fragmented approaches, with limited alignment to global best practices.

The creation of specific ICT-inclusive guidelines by the Federal Ministry of Environment, in collaboration with the National Information Technology Development Agency (NITDA), would offer clarity on the use of smart meters, remote sensing technologies, and automated verification platforms. Such guidelines could outline requirements for data collection frequency, acceptable data formats, cybersecurity measures, and transparency protocols. Incorporating digital technologies into regulatory frameworks would not only improve the accuracy and credibility of Nigeria's carbon credit projects but also enhance international confidence in credits originating from the country (Akinwale, 2021).

Additionally, aligning these guidelines with Nigeria's Digital Economy Policy and Strategy (2020–2030) would ensure coherence between climate governance and the national digital transformation agenda (NITDA, 2020). By mainstreaming ICT tools into verification standards, Nigeria could leapfrog traditional verification challenges such as high costs, data integrity issues, and limited local expertise. Over time, these ICT-inclusive guidelines would position Nigeria as a regional leader in digital climate governance, attracting greater participation from private investors and international carbon market actors.

➤ *Incentives for Technology Adoption Among Project Developers*

Another critical policy direction involves creating targeted incentives to encourage the adoption of ICT tools by project developers engaged in RE and carbon reduction initiatives. The deployment of smart technologies such as IoT sensors, blockchain-based registries, and AI-powered verification platforms entails high upfront costs that many small and medium-sized developers in Nigeria may not be able to afford (Okereke and Esiobu, 2022). Without supportive policy interventions, there is a risk that ICT-driven verification systems will be restricted to large-scale developers, leaving smaller initiatives excluded from carbon markets.

The Nigerian government could establish fiscal incentives, such as tax credits, import duty waivers, and low-interest green financing facilities, to reduce the financial burden on developers who invest in ICT-based monitoring and verification systems (World Bank, 2021). Additionally, the creation of innovation grants or matching funds through climate finance partnerships with multilateral institutions like the Green Climate Fund (GCF) could further catalyze adoption. These incentives should be designed to reward not just the installation of ICT tools but also their effective utilization in improving data accuracy and transparency.

Equally important is the establishment of capacity-building programs that provide technical support for smaller developers. Training programs could be implemented in partnership with universities, technology hubs, and international agencies to enhance digital literacy and ensure developers can operate and maintain ICT systems. By reducing cost barriers and providing practical support, Nigeria can democratize access to ICT-enabled verification tools, ensuring inclusivity and scalability of carbon market participation across diverse project sizes.

➤ *Strengthening Institutions for Carbon Market Governance*

Strong institutional capacity is fundamental to ensuring that ICT adoption in carbon credit verification yields sustainable benefits. At present, Nigeria's institutional landscape is characterized by overlapping mandates between agencies such as the Department of Climate Change, NITDA, and the Energy Commission of Nigeria. This institutional fragmentation leads to inefficiencies, regulatory inconsistencies, and delays in verification processes (Adebayo, 2022).

To address these challenges, there is a need for a centralized coordinating body dedicated to carbon market governance, with a clear mandate to integrate ICT solutions into national MRV systems. This body could function as a one-stop platform, harmonizing policies, setting standards, and liaising with international accreditation bodies such as the Gold Standard and VCS. Furthermore, institutions must be strengthened with technical expertise, adequate funding, and digital infrastructure to effectively manage verification systems (Aggarwal and Jain, 2021).

Institutional strengthening also entails improving transparency and accountability mechanisms. Establishing digital audit trails, independent third-party oversight, and blockchain-enabled registries would reduce opportunities for corruption and enhance trust in Nigeria's carbon credit system. Moreover, partnerships with regional organizations, such as the African Development Bank (AfDB), could provide both financial and technical support for institutional reforms. With stronger governance frameworks, Nigeria would be better positioned to meet its commitments under the Paris Agreement and leverage carbon markets as a tool for sustainable development.

➤ *Alignment with National Climate and Digital Economy Strategies*

Finally, ICT-driven carbon verification must be aligned with Nigeria's broader climate action strategies and digital economy goals. The country's updated Nationally Determined Contributions (NDCs) commit to reducing greenhouse gas emissions by 20 percent unconditionally and up to 47 percent with international support by 2030. Achieving these ambitious targets requires effective monitoring systems that can track progress in real time. Embedding ICT verification mechanisms within national climate policy frameworks would improve the accuracy of emissions data and strengthen Nigeria's credibility in reporting to international bodies such as the UNFCCC.

Alignment is also essential with the National Digital Economy Policy and Strategy, which envisions Nigeria as a digital leader in Africa by 2030 (NITDA, 2020). By integrating ICT-enabled carbon verification into this digital transformation agenda, Nigeria can simultaneously pursue environmental sustainability and economic modernization. This alignment would encourage cross-sectoral collaboration, leveraging the expertise of ICT companies, startups, and research institutions to advance climate goals.

Furthermore, policy coherence can attract investment by signaling to both domestic and international stakeholders that Nigeria is committed to harmonizing its digital and climate agendas. Investors are more likely to fund projects in countries where regulatory frameworks demonstrate stability, forward-thinking, and alignment with global sustainability standards (World Bank, 2021). In this way, policy integration would not only facilitate climate action but also enhance Nigeria's competitiveness in the emerging global digital economy.

VII. CONCLUSION

This research has examined the role of ICT in overcoming persistent challenges in carbon credit verification for solar photovoltaic (PV) projects in Nigeria. The analysis revealed that while solar PV holds enormous potential to reduce greenhouse gas emissions and expand access to clean energy, the credibility of carbon credits generated depends on robust monitoring, reporting, and verification (MRV) processes. In Nigeria, verification has been hampered by issues such as weak institutional capacity, high costs of third-party audits, lack of standardized data collection methods, and limited trust in reporting systems (Okereke and Esiobu, 2022). These shortcomings have restricted Nigeria's ability to fully participate in both voluntary and compliance carbon markets.

The literature and case studies demonstrate that ICT-driven innovations offer practical solutions to these challenges. Blockchain applications improve transparency and prevent double counting of credits, while IoT-enabled smart meters provide accurate real-time data on energy generation and consumption (Chaudhary and Sethi, 2021; UNDP, 2022). Lessons from India, Rwanda, and Europe confirm that digital platforms can reduce verification costs by

15–25 percent, shorten approval timelines, and enhance investor confidence in carbon markets (World Bank, 2021).

The Nigerian context highlights both opportunities and constraints. On the one hand, the establishment of the National Carbon Registry in 2023 and the country's commitment to achieving its updated Nationally Determined Contributions (NDCs) by 2030 provide a strong policy backdrop. On the other hand, structural barriers such as poor internet connectivity, inconsistent regulations, and low technical expertise continue to hinder progress. Therefore, successful adoption of ICT-based verification systems will require an integrated approach that combines digital innovation, institutional reforms, and international partnerships.

The adoption of ICT-enabled verification systems could be transformative for scaling carbon finance in Nigeria's solar PV sector. Accurate and low-cost verification mechanisms would unlock greater access to international carbon markets, particularly voluntary markets where buyers increasingly demand high levels of transparency and traceability. Blockchain-enabled audit trails could make Nigerian carbon credits more competitive, increasing their acceptance among corporate buyers committed to achieving net-zero targets (Aggarwal and Jain, 2021).

Financially, the potential impact is significant. The African Carbon Markets Initiative (ACMI) projects that Africa could mobilize up to 1.5 billion carbon credits annually by 2050, generating over \$100 billion in revenue. If Nigeria captures even 10% of this market, the revenues could substantially support its RE transition. ICT will be central to achieving this, as traditional verification models are too expensive and cumbersome to handle the anticipated scale of projects.

Furthermore, ICT-based MRV systems can enhance energy planning and grid integration by generating high-quality datasets on solar PV performance. These datasets can support national electrification goals, inform tariff design, and improve policy-making (Alli et al., 2022). Beyond finance, ICT adoption would also build trust among local and international stakeholders, reducing investor risk and encouraging greater inflows of climate finance. Importantly, these systems would allow Nigeria to demonstrate leadership in Africa by aligning its carbon verification frameworks with global digital innovations.

At the community level, improved carbon finance could expand access to decentralized solar solutions such as mini-grids and solar home systems. The revenues from carbon credits could subsidize deployment in rural areas, addressing Nigeria's persistent electricity access deficit. This creates a virtuous cycle where ICT enhances verification, verification strengthens finance, and finance drives broader access to solar energy.

➤ *Credit Author Statement*

Prosper Oghenemaro Ugbehe; Conceptualisation, Methodology, Data curation, writing the original draft,

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➤ *Data Availability Statement*

The data that support the findings of this study are available in a public, open access repository.

➤ *Ethics and Consent to Participate Declarations*

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