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Review Article

Internet of things-enabled distributed solar energy contribution and trading framework for Nigeria's national grid

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ABSTRACT

Nigeria's persistent electricity reliability challenges have accelerated household adoption of distributed solar photovoltaic (PV) systems. However, most residential PV installations operate in isolation, with surplus generation frequently unused while the national grid remains supply-constrained. This paper presents an Internet of Things-enabled framework for integrating household and small-scale solar PV exports into Nigeria's national electricity grid using a credit-based, net-billing-aligned settlement model. The proposed architecture combines bidirectional smart metering, edge gateways, secure communication, and a cloud-based settlement engine to enable safe, measurable, and auditable prosumer participation. The study outlines the system architecture, transaction and settlement logic, and an evaluation plan based on synthetic data modeling and small-scale testbed validation in lieu of full-grid simulation. Policy and operational implications for emerging prosumer regulation and distribution network operations in Nigeria are also discussed.

Keywords: Distributed solar, energy trading, internet of things, net billing, Nigeria, prosumers, smart meters

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INTRODUCTION

Nigeria continues to face a significant electricity access and reliability challenge. Despite being Africa's largest economy and most populous country, more than 85 million Nigerians remain without access to grid electricity, while consumers connected to the national grid experience frequent and prolonged outages.[1] This persistent supply deficit has eroded public confidence in grid electricity and constrained economic productivity. As a coping strategy, households and micro, small, and medium enterprises (MSMEs) have increasingly adopted distributed generation solutions – particularly solar photovoltaic (PV) systems – often paired with inverters and battery storage for self-consumption. Recent estimates suggest that over 40% of electrified households now deploy some form of solar power, much of it installed informally and primarily used as backup during grid failures rather than as grid-interactive generation.[1]

While distributed solar enhances resilience at the household level, its potential contribution to the wider power system remains largely untapped. Most residential PV installations operate in an "islanded" mode, supplying only local loads and remaining disconnected from grid balancing or formal electricity markets. At the same time, Nigeria's national grid continues to suffer from generation shortfalls, heavy reliance on centralized power plants, and weak transmission and distribution infrastructure. This disconnect creates a structural inefficiency in which surplus solar generation is frequently wasted locally, even as system-wide electricity deficits persist. Addressing Nigeria's electricity supply–demand gap, therefore, requires not only additional generation capacity but also smarter mechanisms for integrating distributed energy resources (DERs) into grid operations.

Recent regulatory developments indicate growing intent to enable distributed renewable integration and prosumer participation, notably through draft net billing provisions and updated metering requirements.[2] However, regulatory intent alone does not constitute an operational solution. Effective implementation requires: (i) Tamper-resistant measurement

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of imported and exported energy, (ii) secure and auditable settlement mechanisms, (iii) utility-side visibility and grid-safety controls, and (iv) user-facing tools that make participation transparent and economically meaningful.

In response to these challenges, this paper proposes an IoT-enabled distributed solar energy contribution and trading framework for Nigeria's national grid. The proposed framework enables residential and small commercial solar users to export verified surplus electricity to the grid and receive credits or payments aligned with net-billing principles. The system is built on an Internet of Things (IoT) infrastructure – including bidirectional smart meters, sensors, edge gateways, and a cloud-based trading platform – to support real-time monitoring, verification, and control. Under this model, households become prosumers – both producers and consumers of electricity – capable of tracking energy flows, accumulating and redeeming credits, and contributing to grid reliability in a transparent and regulated manner.

Contributions of this Work Include

1. Nigeria-context IoT architecture: A system architecture for prosumer export measurement, secure telemetry, and settlement using IoT-based smart metering, edge gateways, and a cloud trading engine
2. Credit-based settlement model: A net-billing-compatible credit settlement and utility reconciliation mechanism, providing transparent accounting of exported energy and earned credits
3. Evaluation approach: An evaluation plan using synthetic data modeling and a prototype testbed (in lieu of full-grid simulation) to validate the framework's performance and feasibility.

LITERATURE REVIEW

Smart Grid, Advanced Metering, and IoT for Energy Management

Smart grid technologies have progressively evolved to incorporate advanced metering infrastructure (AMI), bidirectional measurement, and secure communication systems as foundational components for integrating DERs, decentralized generation, and data-driven grid operation. IoT devices – such as smart meters, sensors, and edge gateways – play a central role in this evolution by enabling fine-grained, near real-time data acquisition on energy consumption, voltage conditions, and power quality.[3-5] Utilities leverage these data streams for demand forecasting, fault detection, outage management, and asset optimization.[6] In addition, IoT-based platforms support advanced demand-side management strategies, including dynamic pricing schemes and automated load control.

Beyond operational optimization, IoT has emerged as a key enabler of new electricity market structures. In energy trading applications, IoT-enabled measurement transparency allows accurate verification of energy exports and imports, forming the basis for mechanisms, such as peer-to-peer (P2P) energy exchange, virtual power plants, and aggregated prosumer participation. Several studies demonstrate the application of blockchain or distributed ledger technologies to record transactions originating from IoT meters, thereby enhancing trust, auditability, and transparency in settlement processes.[4] At the same time, the literature consistently identifies cybersecurity and data integrity as critical challenges in IoT-enabled power systems. Risks, such as false data injection, device tampering, and privacy breaches necessitate robust authentication, encryption, anomaly detection, and secure device lifecycle management.[7,8] Importantly, credit-based compensation schemes – such as net billing – depend on reliable, time-stamped metering data and seamless reconciliation with utility billing systems. This operational linkage between IoT-based measurement and formal utility settlement remains insufficiently addressed in much of the existing literature, particularly in developing electricity markets.

Distributed Solar Generation in Nigeria

Nigeria has experienced rapid growth in small-scale solar PV deployment, driven primarily by unreliable grid supply, high outage frequency, and declining PV technology costs. The International Energy Agency reports that a substantial share of electricity consumption in Nigeria now occurs through off-grid and self-generation sources, with solar PV representing the fastest-growing segment within this category.[9] Complementary assessments by development partners, such as GIZ estimate that over one million standalone solar systems are currently in operation nationwide, supplying electricity to households, as well as MSMEs.[10] Despite their growing prevalence, the vast majority of these installations are designed for self-consumption and operate as isolated systems, with minimal or no interaction with the national grid.

The regulatory framework governing distributed generation has evolved incrementally in response to these trends. The Nigerian Electricity Regulatory Commission's Mini-Grid Regulation (2017) established a legal basis for both isolated and interconnected solar mini-grids, providing clarity for private-sector participation at the community level. More recently, the Draft Net Billing Regulations (2025) signal regulatory intent to enable residential customers to export surplus solar electricity to the grid in exchange for monetary credits.[2] Nevertheless, significant implementation challenges persist. These include limited deployment of certified bidirectional smart meters, reluctance by distribution companies (DisCos) due to concerns over revenue adequacy and network protection, the absence of standardized communication and data exchange protocols, and constrained regulatory enforcement capacity. Consequently, a gap remains between policy intent and operational reality, with no scalable mechanism currently in place to translate household-level surplus solar generation into verifiable, grid-safe, and compensable contributions.

Prosumer Models and Energy Trading Frameworks

Prosumers – electricity consumers who also generate energy – have become central actors in modern electricity systems. In developed electricity markets, policy instruments, such as feed-in tariffs and net metering have historically incentivized residential rooftop solar exports. Germany's feed-in tariff regime, for example, played a pivotal role in accelerating small-scale PV deployment by guaranteeing fixed compensation for exported electricity, thereby reducing investment risk for households and small producers.[11] More recently, digital platforms have enabled decentralized prosumer participation beyond administratively fixed tariff schemes. In Australia, the power ledger platform demonstrated blockchain-enabled P2P solar energy trading, allowing prosumers to trade surplus generation directly with local consumers while maintaining transparent and auditable settlement records.[12] These systems depend on AMI, near real-time data validation, and automated settlement algorithms to ensure accurate accounting of exported and imported energy. Compensation mechanisms vary across implementations, ranging from fixed volumetric export rates to time-of-use credits and dynamic market-based pricing models.[4]

In emerging and developing economies, however, the direct transfer of such prosumer trading frameworks faces significant challenges. Empirical and conceptual studies identify constraints, including weak grid infrastructure, limited penetration of certified smart meters, regulatory uncertainty, and uneven levels of digital literacy among end users.[13] Despite these barriers, pilot initiatives in countries, such as Kenya, India, and Brazil indicate that IoT-enabled prosumer participation can be feasible when supported by appropriate regulatory safeguards, simplified user interfaces, and active utility oversight.[12] Importantly, localized solar trading frameworks align closely with the objectives of the United Nations Sustainable Development Goal 7, which emphasizes affordable, reliable, and clean energy access through decentralized and innovative solutions.[14] Collectively, these findings suggest relevance for the Nigerian context, provided that prosumer models are adapted to local institutional, regulatory, and infrastructural conditions.

IoT System Architectures for Grid Integration

A substantial body of literature proposes IoT-based architectures for integrating DERs into modern power systems. Common architectural patterns adopt layered models comprising device, edge, and cloud tiers. At the device layer, smart meters and sensors measure bidirectional energy flows at consumer premises. These devices communicate through gateways using lightweight protocols, such as message queuing telemetry transport (MQTT), long range wide area network (LoRaWAN), or Narrowband IoT, enabling reliable telemetry under constrained network and bandwidth conditions.[3,8,9] At the cloud layer, centralized platforms store time-series data, perform analytics, execute control and settlement logic, and expose application programming interfaces (APIs) to user applications and utility dashboards.[15] Several studies further emphasize the role of distributed ledger technologies, including blockchain, in enhancing transparency and auditability in energy trading by providing tamper-resistant transaction records and automated settlement through smart contracts.[4] However, blockchain integration introduces additional design considerations related to scalability, latency, computational overhead, and governance, particularly within utility-regulated environments. As a result, the literature increasingly advocates hybrid architectures in which blockchain complements – rather than replaces – centralized utility billing and control systems.[4]

Security and trust remain critical concerns in IoT-enabled grid integration. Threats, such as cyberattacks, false data injection, and device tampering can undermine both grid stability and market confidence. Accordingly, robust authentication, encryption, anomaly detection, and device certification mechanisms are widely regarded as pre-requisites for large-scale deployment.[7,8] In the Nigerian context, empirical and policy-oriented studies underscore the urgency of investing in AMI and the digitalization of DisCo operations. Babatunde *et al.*[13] identify inadequate metering and limited system visibility as major contributors to commercial losses and operational inefficiencies in Nigeria's electricity sector, while Ugwu *et al.*[5] argue that large-scale AMI deployment and interoperable data platforms are foundational requirements for enabling IoT-based grid services, including distributed energy trading.

Identified Research Gaps

The reviewed literature reveals several gaps that motivate this study. First, although IoT-enabled smart grids and AMIs are widely studied, most work emphasizes monitoring, optimization, and demand-side management, with limited focus on market-integrated settlement mechanisms that allow household-level prosumers to export energy and receive compensation in grid-connected systems. Consequently, the operational linkage between IoT-based measurement and formal electricity market participation remains weakly developed.

Second, despite Nigeria's rapid growth in distributed solar adoption and the emergence of supportive regulatory instruments – such as the Mini-Grid Regulation and draft Net Billing provisions – there is no end-to-end framework that integrates household IoT metering, grid-safety enforcement, and utility billing reconciliation in a scalable manner. Regulatory intent has therefore not yet translated into deployable technical and market architectures for residential prosumers.

Third, most existing prosumer trading and P2P energy frameworks are designed for stable power systems with high smart meter penetration and mature regulatory institutions, limiting their applicability to Nigeria's fragile distribution network and financially constrained DisCos. While Nigerian-focused studies emphasize the need for AMI deployment and sector digitalization, they stop short of proposing implementable architectures that align technical feasibility, regulatory compliance, and economic incentives for both prosumers and utilities. Addressing these gaps requires a context-specific solution that bridges technical design with policy and market considerations – precisely the focus of this research.

PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Problem Statement

Despite the increasing adoption of decentralized solar PV systems by Nigerian households – particularly in semi-urban and rural areas – these distributed energy assets largely operate in isolation from the national electricity grid. Surplus electricity generated during periods of low household demand is typically curtailed or unused, even as the national grid continues to experience chronic undersupply, operational instability, and recurrent system disturbances. This persistent mismatch between distributed generation capacity and grid demand contributes to economic losses, reduced productivity, and declining public confidence in the electricity sector. At present, no established system exists that allows households to seamlessly export surplus solar energy to the grid, transparently track transactions, and receive fair and verifiable compensation for their contributions. Without an integrated technological and market framework, Nigeria's expanding base of distributed solar assets remains underutilized, and potential prosumers are excluded from participation in the formal electricity market.

Research Objectives

The overarching objective of this research is to design and evaluate a practical framework that enables residential solar prosumers to participate in Nigeria's national electricity system in a secure, measurable, and economically viable manner. To achieve this, the study pursues the following specific objectives:

1. System architecture: Propose a comprehensive system architecture for integrating household-level solar PV systems into Nigeria's national grid using IoT-enabled smart meters, edge gateways, and cloud-based coordination platforms.
2. Measurement and settlement mechanism: Develop a secure and transparent energy measurement and settlement mechanism that supports bidirectional energy flows, verifiable export accounting, and credit or payment settlement aligned with net-billing principles, with optional support for distributed ledger technologies.
3. User interface design: Design a user-facing mobile and web application that enables prosumers to monitor real-time energy generation and consumption, track accumulated credits, redeem or transfer energy credits, and receive operational notifications.
4. Implications assessment: Assess the technical, policy, and economic implications of enabling residential prosumer participation in Nigeria's electricity market, with particular emphasis on grid stability, utility revenue adequacy, regulatory readiness, and consumer incentives.

METHODOLOGY AND SYSTEM ARCHITECTURE

This study adopts a system-oriented design methodology to develop an IoT-enabled framework that supports secure energy measurement, controlled grid injection, and transparent settlement of surplus residential solar generation. The methodology emphasizes practical deployability within Nigeria's electricity distribution environment and is aligned with emerging net-billing regulatory provisions. Rather than pursuing full-scale power system simulation, the approach focuses on architectural design, component specification, and operational workflow definition suitable for phased pilot deployment.

System Components

The proposed framework comprises five primary components that collectively enable end-to-end prosumer participation:

- Smart solar meters: Bidirectional smart meters are installed at prosumer premises to measure electricity generation, household consumption, and energy exported to the grid. These meters provide time-stamped import and export readings and incorporate tamper-detection mechanisms to ensure data integrity. Meter outputs serve as the authoritative source of truth for settlement, auditability, and reconciliation.
- IoT gateway: An IoT gateway located at the prosumer site aggregates data from the smart meter and, where applicable, the solar inverter. The gateway encrypts and transmits telemetry data to the cloud platform over available communication networks, such as GSM (4G/LTE) or low-power wide-area technologies (e.g., LoRaWAN). In addition, the gateway supports edge-level functions, including temporary data buffering during connectivity loss and enforcement of basic grid-safety constraints.
- Cloud platform: The cloud-based platform ingests metering data, performs validation and plausibility checks, and executes settlement logic. It maintains a transaction ledger, computes export credits based on pre-defined

tariffs, and exposes APIs to both user-facing applications and utility systems. This platform forms the core of the energy trading, accounting, and reconciliation process.
- Mobile/Web application: A mobile and web-based application provides the primary user interface for prosumers. Across this interface, users can monitor real-time and historical energy flows, view accumulated credits, initiate credit redemption or transfer, and receive system notifications related to grid conditions or policy constraints.
- DisCo dashboard: A utility-facing dashboard enables DisCos to monitor aggregated energy injections from connected prosumers, enforce feeder-level export limits, and reconcile credits within existing billing or prepaid metering systems. This component ensures that prosumer participation remains compatible with grid operations, regulatory requirements, and utility revenue models.

Energy Trading and Settlement Flow

The operational flow of energy trading and settlement within the proposed framework proceeds as follows:

1. Local consumption: Solar energy generated at the prosumer's premises is first consumed locally
2. Grid export: Surplus electricity is exported to the distribution network through a grid-tied inverter operating under standard protection mechanisms, including anti-islanding and voltage/frequency constraints
3. Data transmission: The smart meter records exported energy in kilowatt-hours (kWh) with timestamps and transmits the data via the IoT gateway to the cloud platform in near real time
4. Cloud processing: Upon receipt, the cloud platform performs data validation and plausibility checks, applies settlement rules, and converts verified exported energy into credits (or monetary value) in accordance with applicable net-billing tariffs
5. Credit allocation: Accrued credits are recorded in the prosumer's account and can be viewed, redeemed, or transferred through the mobile/web application, subject to regulatory requirements and utility-defined policies. This process establishes an auditable linkage between physical energy export and digital settlement, ensuring transparency, traceability, and compatibility with utility billing systems.

Communication and Data Management Model

Communication between system components employs lightweight, secure protocols suitable for resource-constrained and intermittently connected environments. Telemetry data from smart meters and IoT gateways are transmitted using protocols, such as MQTT or hypertext transfer protocols over available access networks, including GSM (4G/LTE) and low-power wide-area technologies, such as LoRaWAN, depending on deployment context, coverage, and cost considerations. All energy transaction records are time-stamped and stored within the cloud platform to support validation, settlement, and reconciliation processes. Where enhanced auditability and transparency are required, selected transaction records may be mirrored to a permissioned blockchain or distributed ledger layer to provide non-repudiation and tamper resistance. Importantly, this ledger layer is designed to complement – rather than replace – the utility's centralized billing and settlement authority, ensuring compatibility with regulated electricity market structures.

Credit Ledger and Net-Billing Model

The proposed settlement mechanism adopts a credit-based net-billing structure in which exported and imported energy are accounted for separately. Verified exported energy is converted into credits based on pre-defined tariff rates, while imported energy continues to be billed under existing utility tariff structures.

The core credit calculation is expressed as:

$$Credit\ Value = E_{export} * T_{export}$$

where E_{export} denotes energy exported to the grid in kWh and T_{export} represents the applicable export tariff rate. Accumulated credits are recorded in a prosumer-specific ledger and may be applied to offset future electricity consumption, redeemed in accordance with regulatory provisions, or transferred within a regulated marketplace if permitted. This accounting model preserves transparency and auditability while maintaining DisCo oversight and compatibility with existing billing systems.

System Architecture Diagram and Explanation

Figure 1 illustrates the overall system architecture of the proposed IoT-enabled distributed solar energy trading framework.

The proposed architecture comprises two interconnected flows: A physical energy flow and a digital data/transaction flow. Solar energy generated at the prosumer premises is first consumed locally, with surplus electricity exported to the distribution network through a grid-tied inverter. Bidirectional smart meters record both imported and exported energy in time-stamped intervals. Metering data are transmitted via an IoT gateway to the cloud platform, where data validation, settlement processing, and credit computation are performed in accordance with net-billing principles. Processed information is made available to the DisCo backend for reconciliation and operational oversight, as well as to the user mobile/web application for real-time monitoring, credit tracking, and redemption. Control signals, including export limits and safety constraints, may be issued from the utility or cloud platform to the gateway, enabling grid-safe operation. Overall,

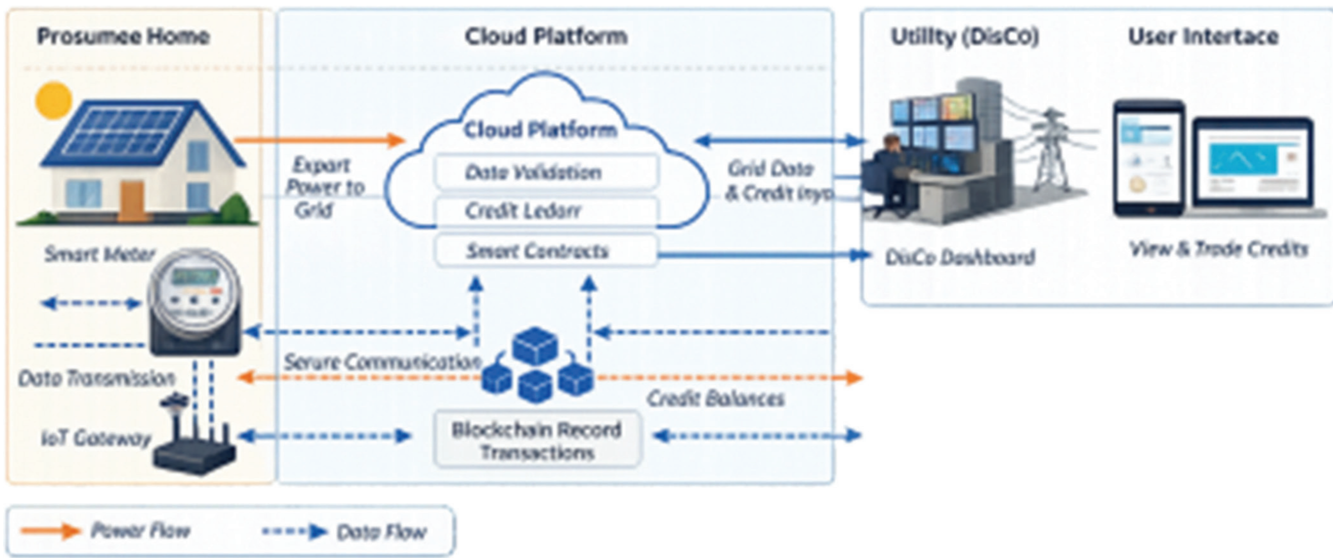

Figure 1: System architecture diagram. A schematic showing the household solar photovoltaic system connected via a bidirectional smart meter and internet of things gateway to a cloud platform, which interfaces with the distribution company backend and the prosumer's user application

the architecture is designed to ensure that household solar contributions are integrated into grid operations in a secure, transparent, and controlled manner.

MODELING AND EVALUATION PLAN

As this study presents a conceptual system and architectural proposal, evaluation is framed around model-based validation and prototype-oriented testbed assessment, rather than full transmission or distribution network simulation. This approach is appropriate given the focus on measurement accuracy, data integrity, and settlement logic at the prosumer-distribution interface, rather than bulk power system dynamics.

Synthetic Data Modeling

Synthetic (but realistic) time-series data are generated to emulate key operational conditions, including:

- Solar PV generation profiles reflecting diurnal and seasonal variability
- Household electricity demand profiles with characteristic morning and evening peaks
- Communication disturbances, such as packet delays, intermittent connectivity, and temporary outages.

Using these datasets, the framework is evaluated against the following criteria:

- Energy accounting accuracy: Correct accounting of imported and exported energy across diverse operating scenarios.
- Settlement integrity: Accuracy and consistency of credit computation and reconciliation logic under various conditions.
- Temporal granularity sensitivity: Sensitivity of settlement outcomes to metering and reporting granularity (e.g., comparing 1-min vs. 15-min data intervals).

This modeling approach enables controlled evaluation of system behavior, robustness, and accounting correctness before field deployment. By varying generation and load patterns, as well as network conditions, we can verify that the system correctly calculates credits, balances energy flows, and maintains data integrity even under non-ideal communication scenarios.

Testbed Prototype Plan

To complement synthetic data modeling, a small-scale prototype testbed is proposed to demonstrate practical feasibility and validate key system functions. The prototype implementation will use the following components:

- Metering layer: Low-cost sensing hardware combined with a certified meter emulator, or a commercially available bidirectional smart meter suitable for pilot deployment
- Edge layer: An edge gateway device (e.g., Raspberry Pi-class hardware) responsible for data aggregation, encryption, buffering during outages, and communication management
- Platform layer: A lightweight cloud stack comprising an MQTT broker, a time-series database, and a simple settlement service implementing the credit ledger logic
- Application layer: A dashboard or mobile/web application mock-up providing visibility into energy flows, credit balances, and system status for both prosumers and the utility.

This prototype is intended to validate end-to-end data flow, settlement correctness, and system resilience under realistic operating conditions, rather than to serve as a production deployment. Key functions to be tested include real-time meter data capture and transmission, credit calculation on the cloud platform, and user/utility interface displays.

Validation Metrics

System performance and correctness are evaluated using the following metrics:

- Metering accuracy: Deviation between reference meter readings and reported import/export values at the platform level
- Communication latency: Time elapsed between an energy measurement at the meter and the corresponding data persistence plus credit update at the cloud platform
- Settlement consistency: Consistency between metered exported energy and credited kWh (monetary credits), including completeness of audit logs and detection of any discrepancies
- Resilience: Ability to maintain data continuity through offline buffering and subsequent reconciliation after connectivity interruptions (i.e., does the system catch up and accurately log exports that occurred during an outage).

Data collected from the testbed (e.g., log files, database entries, application displays) will be analyzed to ensure that the system meets the design requirements. Any anomalies (such as missing data points, incorrect credit values, or delayed processing) will inform iterative refinements to the architecture and algorithms.

DISCUSSION AND POLICY IMPLICATIONS

Technical Feasibility and Grid Constraints

Large-scale prosumer participation requires careful management of feeder-level constraints, protection coordination, and compliance with anti-islanding requirements. Uncontrolled exports can aggravate voltage fluctuations and protection miscoordination, particularly in weak distribution networks. A phased rollout – prioritizing feeders with adequate capacity and voltage regulation – can reduce these risks. Edge-level control mechanisms (at the gateway or meter) are essential to enforce export limits and ensure safe operation during grid instability. The proposed framework's ability to issue remote disconnect signals or curtail exports in emergency conditions provides a critical safety backstop. Over time, insights from pilot implementations can guide distribution network upgrades (e.g., voltage regulators, static VAR compensators) to accommodate higher penetration of prosumers.

Metering Trust, Fraud, and Cybersecurity

Compensation for exported energy increases incentives for meter tampering and data manipulation. Accordingly, metering and gateway devices must be certified, tamper-evident, and cryptographically authenticated. Platform-level anomaly detection and audit trails are necessary to identify irregularities and support accountability. Where appropriate, permissioned distributed ledger technologies may further enhance transparency and non-repudiation of transactions. Ensuring end-to-end data integrity and trust is paramount to the success of any prosumer integration program. This may involve independent verification of device firmware, regular audits of the data logs, and possibly engagement of third-party escrow agents for the credit ledger in initial phases.

Utility Economics and Incentives

Residential prosumer integration raises concerns about revenue adequacy for DisCos. Clear regulatory guidance is required on how export credits interact with existing retail tariffs. Policymakers may employ mechanisms, such as non-bypassable network charges, fixed service fees, or differentiated export tariffs to preserve utility cost recovery while maintaining incentives for prosumer participation. Aligning the economic interests of all stakeholders (prosumers, utilities, and regulators) is critical to the sustainable adoption of the framework. For example, a buy-all, sell-all tariff might be set slightly below retail rates to reward prosumers while covering network costs. The net impact on DisCo revenue should be modeled under various uptake scenarios to inform tariff design.

Regulatory Readiness

Moving from draft regulation to large-scale deployment requires additional institutional readiness. Key needs include standardized interconnection procedures, certification regimes for meters and gateways, defined dispute resolution mechanisms for prosumer billing, and consumer data protection safeguards. Addressing these requirements is essential for the safe and scalable deployment of IoT-enabled prosumer participation in Nigeria's electricity sector. Regulatory and policy support must evolve in tandem with technological deployments to ensure that pilot projects can transition into long-term operational programs. Capacity-building for regulators and utilities – covering topics, such as cybersecurity, data analytics, and consumer engagement – will further enhance readiness. On the legislative side, refining the electricity act to explicitly accommodate prosumer rights and obligations will provide a strong legal foundation for the framework.

CONCLUSION

This paper presented an IoT-enabled framework for integrating household solar PV systems into Nigeria's national electricity grid using a credit-based, net-billing-aligned approach. The proposed architecture combines bidirectional smart metering, edge gateways, secure communication, and a cloud-based settlement platform to enable safe, auditable, and measurable export of surplus solar energy by residential prosumers. The framework addresses several key barriers to effective prosumer participation, including limited grid visibility at the distribution level, lack of trusted and verifiable energy accounting, and the absence of automated settlement and reconciliation mechanisms. By explicitly aligning technical design choices with emerging regulatory provisions and renewable energy objectives in Nigeria, the proposed solution demonstrates how distributed household solar assets can be transformed from isolated backup systems into active contributors to grid reliability and energy supply.

Although the framework is conceptual at this stage, it is grounded in current policy developments, prevailing deployment trends, and practical constraints within Nigeria's electricity distribution environment. Future work will focus on pilot implementation using certified metering infrastructure, feeder-level impact analysis to assess voltage and protection implications, and refinement of tariff and credit structures to ensure long-term economic sustainability for both residential prosumers and DisCos.

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