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Assessing Sudan's Capabilities for IIoT-Based Power Systems

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ABSTRACT

Sudan's power sector stands at a critical point. The country faces serious challenges such as aging infrastructure, frequent power outages, and very high transmission and distribution losses compared to other countries in the region. At the same time, Sudan has a foundation for improvement, including significant hydro and thermal power capacity and a telecommunications sector that, although still limited, is gradually expanding.
This paper explores whether the Industrial Internet of Things (IIoT) can provide a realistic pathway forward. It argues that a carefully planned, step-by-step implementation of IIoT technologies—such as real-time grid monitoring, predictive maintenance, and smart metering—could significantly improve the performance of the power system. The proposed roadmap aligns technical advancement with Sudan's financial and institutional constraints. Studies indicate that a systematic IIoT rollout could reduce system losses by 8–12% over a 3–5-year horizon and enhance grid reliability and resilience, particularly by supporting smart microgrids that deliver power to remote areas..

1. INTRODUCTION

For over a century, the backbone of global electricity has been the centralized alternating current (AC) classic grid. In this conventional model, power flows in one direction: from large-scale generators through transmission and distribution lines, ultimately to passive consumers. This system has been shown in practice to be highly wasteful and to suffer from numerous limitations. Inefficiencies arise at every stage, from outdated consumer appliances and inefficient energy routing to a lack of real-time monitoring and, crucially, an inability to store excess energy [1]. These inherent flaws are compounded by modern pressures such as increasing demand, aging physical assets, security threats, and the complex integration of variable renewable sources.

Today, power systems worldwide are undergoing a rapid digital transformation, driven by the need to enhance reliability, operational flexibility, and efficiency. This evolution integrates advanced sensing, communication, and control technologies across all grid layers, marking a fundamental shift from traditional electromechanical infrastructure toward intelligent, data-driven architectures [2]. A key driver of this shift is the Industrial Internet of Things (IIoT). By integrating field sensors, robust communication networks, and cloud-based analytics, IIoT enables a level of real-time visibility and automated control that was previously impossible on the classic system [3].

For many years, Sudan's energy sector has suffered from profound challenges similar to those faced by many developing nations. Despite having a substantial installed capacity of around 4.5 GW—heavily dependent on hydropower from the 1,250 MW Merowe Dam [4]—the reality on the ground is one of **chronic insufficiency.** Only around 66% of people in the country have access to electricity, and there are significant disparities between rural and urban areas. Transmission and distribution losses, which are thought to be between 25% and 30% [5], and the lack of extensive real-time monitoring have made both supply reliability and financial sustainability harder [6]. The recent period of war, which has severely disrupted infrastructure up to the present day, has further crippled operational control and communications, making the grid even more vulnerable [7].

This study looks at how IIoT ideas and architectures can be applied in Sudan, focusing on important technological uses, predicted benefits, and a step-by-step plan for putting them into action. The central thesis is that for Sudan, a slow and steady, digitally-enabled modernization is not just preferable, but essential for its economic recovery and future energy security.

2. IIoT ARCHITECTURES AND KEY TECHNOLOGIES FOR POWER SYSTEMS

The potential of IIoT to enhance power systems is vast, in every subsystem from generation to consumption. In generation, IIoT facilitates the monitoring of energy output, equipment health, and emissions, while also enabling more accurate forecasting and the management of diverse sources like pumped storage, wind, and photovoltaic plants [1]. For transmission, applications include the monitoring and protection of lines and substations. In distribution, IIoT paves the way for widespread automation and improved asset management. Finally, on the consumer end, it supports smart homes, automated meter reading, electric vehicle charging management, and detailed energy consumption analytics [3].

A typical IIoT architecture for a power system is conceptualized in four layers. The perception layer consists of the physical hardware—sensors, smart meters, phasor measurement units (PMUs), and actuators—that gathers raw operational data from the field. The network layer is responsible for communication, employing a mix of wired (e.g., Ethernet, fiber) and wireless (e.g., Wi-Fi, 4G/5G, LPWAN) technologies, often using lightweight protocols like MQTT or DNP3 [8]. The edge-cloud layer performs critical data processing and filtering at or near the data source (e.g., at a substation), reducing latency and bandwidth needs before sending refined data to centralized platforms [9]. The application layer integrates this data into user-interface systems like SCADA, Energy Management Systems (EMS), and Distribution Management Systems (DMS) for visualization, analysis, and control [2].

The architectures used in IIoT are vital standards that ensure security and interoperability. IEC 61850 standardizes communication within substations [10], while cybersecurity frameworks like IEC 62351 provide the necessary protocols to protect this critical infrastructure from cyber threats [11]. IIoT also enables the integration of information flow, power flow, and distribution management within the power system.

3. APPLICATIONS OF IIOT IN POWER SYSTEMS (GLOBAL EXAMPLES)

3.1. Grid Monitoring and Asset Management

Real-time condition monitoring has yielded impressive results in pilot projects. For instance, implementations focusing on power transformers have demonstrated fault reductions of approximately 27% and achieved a 93% accuracy rate in forecasting transformer-related faults within a six-month period. Also, response time to potential failure events improved by 41%, allowing grid operators to take corrective actions earlier in the failure cycle. [12]

3.2. Smart Metering and Demand Management

Large-scale rollouts in countries like India, Sudan and Kenya provide compelling evidence for non-technical loss reduction. These programs have reported reductions of 10–15% in non-technical losses [13], with some specific feeder initiatives achieving theft reductions of up to 50% after deploying smart prepaid meters [14].

3.3 Renewable and Microgrid Integration

Integrating IIoT and edge controllers into PV–battery systems yields measurable efficiency gains and cost benefits, with one edge-based battery energy management implementation achieving about a 6% reduction in energy use relative to a conventional rule-based scheme, while broader microgrid EMS reviews consistently show that such architectures improve reliability, optimize dispatch of distributed resources, and reduce operational expenditures in smart-grid and microgrid contexts. [15, 16].

3.4 Distribution Automation

Field experience and cost–benefit analyses of IEC 61850-based digital substations report substantial efficiency and reliability gains. Utilities adopting standardized digital protection and control architectures have documented 5–30% reductions in selected capital costs and 5–60% savings in operational and maintenance expenditures, together with improved fault detection and faster restoration enabled by self-monitoring IEDs and automated schemes—contributing to shorter outage durations and higher service availability. [17, 18].

4. MAPPING IIoT APPLICATIONS TO SUDAN'S POWER-SECTOR CHALLENGES

While the global case studies are instructive, implementing IIoT in Sudan requires a clear assessment of its specific operational, economic, and infrastructural context. The country's energy system is plagued by low generation reliability, massive network losses, limited access, and minimal renewable penetration—all areas where IIoT technologies can offer targeted solutions. This section connects specific IIoT applications to Sudan's most pressing problems, identifying where digital monitoring, predictive analytics, and distributed intelligence could deliver the greatest impact.

4.1 Capacity and Reliability

Sudan’s installed generation capacity is estimated to be 4.5 GW, primarily from hydropower and thermal plants, but effective available capacity frequently falls below 3 GW because of recurring maintenance constraints and unplanned outages [4, 5]. Implementing predictive-maintenance frameworks supported by IIoT-Based condition-monitoring sensors on key assets such as transformers and turbines can realistically improve equipment availability by approximately 10–15%, as evidenced by pilot-scale IIoT and machine-learning studies in comparable power-system environments [12, 39].

4.2 Transmission and Distribution Efficiency

Sudan’s electricity network suffers from **technical** losses of roughly 20–25%, reflecting outdated infrastructure and limited grid monitoring. In addition, conflict-related attacks and blackouts—such as those reported in early 2025—have further constrained supply and economic activity [6]. The strategic deployment of feeder sensors, automatic fault-location systems, and smart meters could significantly reduce technical and commercial losses. Drawing on outcomes from comparable smart-grid pilots in East Africa, such as Kenya Power’s 2023 program, a reduction of 8–12% over a 3–5-year horizon is realistic—equivalent to roughly 400–500 GWh of recovered energy annually for a system of Sudan’s scale [24].

4.3 Access and Equity

With national electricity access estimated at around 66%, large portions of Sudan’s population—especially those in rural and peripheral regions—remain without reliable supply [5]. IIoT-Based microgrids present a decentralized pathway to expand electricity access. Empirical evidence from global edge-enabled microgrid projects shows that such systems can maintain operational uptimes of 98–99**%** while reduce operation and maintenance (O&M) costs by roughly 20–30%, particularly through predictive analytics and automated energy management. These results demonstrate that IIoT-integrated microgrids are both technically robust and financially viable for rural electrification contexts such as Sudan [15, 34].

4.4. Renewable Integration

Currently, non-hydropower renewable sources—primarily solar and wind—account for only about 4% of Sudan’s total installed generation capacity, underscoring the country’s heavy dependence on hydropower and thermal plants [25]. Industrial Internet of Things (IIoT) technologies can substantially enhance renewable integration by enabling high-accuracy forecasting, real-time control, and coordinated management of distributed energy resources (DERs). Studies show that advanced IIoT-Based architectures improve grid flexibility and forecasting accuracy, supporting higher renewable penetration in developing power systems [2], [26]. With appropriate policy and infrastructure investment, Sudan could realistically raise the renewable-energy share to 15–20% by 2035, consistent with regional projections from the Africa Energy Outlook 2024 [29].

4.5 Resilience

The grid's vulnerability has been exposed by recent conflict-related disruptions [6]. Resilience enhancement in modern power systems increasingly depends on distributed intelligence and automation. Implementations of self-healing microgrids based on the IEC 61850 communication standard have demonstrated rapid fault isolation and restoration, significantly improving reliability indices and minimizing downtime [7]. National-scale results from the U.S. Department of Energy’s Smart Grid Investment Grant program similarly report measurable reductions in outage duration and customer interruption minutes through distribution automation and feeder-level fault location, isolation, and service restoration (FLISR) schemes [20]. Complementary studies on sensor-network-based microgrid monitoring show that integrating uncertainty-aware risk assessment can further accelerate recovery and reduce restoration time under disruptive conditions [27].

Figure 1 summarizes how the proposed IIoT roadmap is expected to shift Sudan’s power-sector performance across five strategic dimensions. Capacity and reliability, T&D efficiency, and access and equity all show moderate baseline levels but substantial projected gains once IIoT-Based monitoring, AMI, and feeder automation are deployed, reflecting the priority given to loss reduction and outage mitigation in the early phases. Renewable integration starts from a very low base but exhibits the largest relative improvement, driven by IIoT-enabled forecasting, DG/microgrid control, and edge-based energy management. Resilience also improves markedly as digital substations, FLISR schemes, and cybersecurity monitoring are phased in. The novelty of this framework lies in explicitly linking each performance dimension to a targeted IIoT toolset—rather than treating "digitalization" as a generic upgrade—so that investment priorities (e.g., AMI and feeder sensors before advanced analytics and digital twins) are directly justified by expected quantitative improvements in specific KPIs.

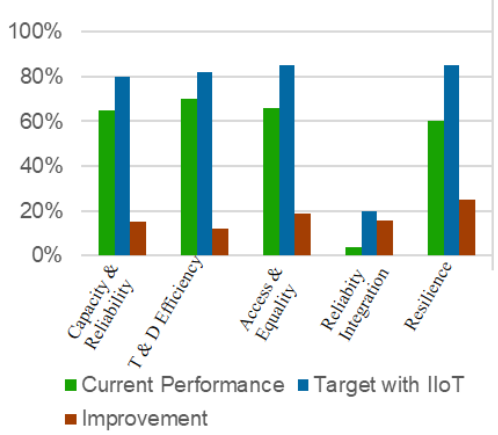

Figure 1: Mapping IIoT Solutions to Sudan's Power Sector Challenges

5. STRATEGIC ROADMAP FOR IIoT IMPLEMENTATION IN SUDAN'S POWER SECTOR

For Sudan, a "big bang" IIoT implementation is neither practical nor advisable given the country's institutional and financial constraints. A phased, capacity-aligned rollout—grounded in achievable milestones and guided by measurable policy and performance indicators—is essential. This roadmap envisions a step-by-step digital transformation of the power sector, integrating IIoT technologies incrementally with grid modernization efforts. Such a strategy connects technical upgrades with policy, financial, and governance reforms, ensuring that progress is both scalable and sustainable. Similar frameworks have been recommended in African Development Bank and World Bank analyses on digital infrastructure and smart-grid investment planning, emphasizing context-sensitive approaches for fragile and conflict-affected systems [21, 22, 38].

5.1 Vision and Phasing Overview

The plan envisions a digitally enabled, data-driven power system by 2035. This system will be more reliable, efficient, and sustainable. There are four overlapping phases of implementation, each of which focuses on increasing technical, institutional, and financial readiness.

This incremental approach allows for lessons from early, smaller-scale deployments to inform subsequent expansion, thereby minimizing both financial and technical risk. Table 1 summarizes these phases.

Table 1. Summary of IIoT Deployment Phases and Expected Outcomes in Sudan

Phase	**Time-line**	**Scope**	**Expected Outcome**
1-Foundational Deployment	2025 – 2027	Pilot IIoT in 3–5 substations and 2 hydropower plants; build data center & communication backbone	5% reduction in downtime
2- Expansion & Standardization	2028 – 2030	Deploy 50 000 smart meters; automate 20% of feeders; integrate SCADA–cloud EMS	8–10 % loss reduction (≈ 350 GWh/yr); enhanced data visibility
3- Renewable & Microgrid Integration	2030 – 2033	Add 150 MW solar/wind; deploy IIoT microgrid control; predictive maintenance in 15 plants	15–20% renewable share; uptime ≈ 98 %
4- Digital-Twin & National Platform	2033 – 2035	Develop digital twins; launch AI analytics & cybersecurity operations center	60% asset digitization; 20% O&M cost reduction [29]

5.2 Institutional and Policy Actions

To ensure sustainability and coordination across different agencies, the roadmap necessitates institutional reform. The plan suggests that the Ministry of Energy and Petroleum establish a dedicated Digital Energy Unit (DEU) to oversee IIoT integration, cybersecurity, and standardization. Key policy actions should include:

i. The formal adoption of interoperability standards consistent with IEC 61850 and IEC 62351 [10, 11].
ii. The development of a national cybersecurity framework specifically for energy utilities to ensure sector-specific resilience, threat detection, and incident-response capabilities [33, 36].
iii. The initiation of public-private partnership (PPP) frameworks to attract investment in smart-grid technologies [40].
iv. The implementation of a comprehensive capacity-building initiative, aiming to train approximately 500 engineers in digital operations, IIoT maintenance, and data analytics [21, 32].

5.3 Technical Infrastructure Priorities

The success of this plan depends on strengthening Sudan's digital backbone:

Communication Layer — Prioritize the expansion of fiber-optic and 4G/5G coverage to key substations and prospective renewable sites [18, 23].

Edge–Cloud Integration — Deploy local edge servers at strategic locations to enable real-time control and data filtering to minimize dependence on centralized cloud processing and improves system responsiveness [9, 16].

Data Governance — Establish protocols for data validation, storage, and secure backup from the outset.

Interoperability — Mandate the use of open, standard protocols (e.g., MQTT, DNP3) to ensure future system integration and avoid vendor lock-in [8].

5.4 Financial and Economic Considerations

The total estimated investment required for this IIoT roadmap is US$150–200 million. This should be distributed across the four phases and funded through a blended finance structure to mitigate the burden on the national budget [21, 22, 40].

5.5 Key Performance Indicators (KPIs)

Monitoring progress through quantifiable KPIs is critical for accountability and ensuring the project stays on track [22, 38]. Table-2 shows these KPIs.

By 2035, the full implementation of this roadmap could yield a 20% reduction in losses, achieve 15–20% renewable energy penetration, and provide near-real-time visibility of the entire grid. For Sudan, integrating IIoT is not merely a technological upgrade but a strategic leap toward building a sustainable and resilient energy system capable of supporting long-term economic recovery.

Table 2. KPIs values

Dimension	Baseline (2024)	Target (2035)
Generation availability (%)	≈ 70	≥ 85
Transmission & distribution losses (%)	27	≤ 18
Renewable energy share (%)	4	20
Average outage duration (hours/day)	6	< 1
Cybersecurity compliance (IEC 62351)	Low	Full Compliance

6. CHALLENGES, BARRIERS, AND POLICY CONSIDERATIONS

While the strategic roadmap outlines a clear path, the large-scale implementation of IIoT in Sudan faces profound structural, institutional, and technical barriers. Addressing these challenges systematically through targeted policy, regulatory reform, and capacity-building is a prerequisite for long-term success [21, 22, 31].

6.1 Limitations in Technology and Infrastructure

IIoT solutions depend on reliable power and communication networks, which are still severely lacking in Sudan. 4G coverage reaches less than 30% of the population, and the fiber-optic backbone is largely confined to major cities [23]. Many substations still operate with analog control systems instead of SCADA or Remote Terminal Units (RTUs). Furthermore, frequent power outages and a scarcity of spare parts make sensor calibration and equipment maintenance a significant hurdle.

A critical first step is to strengthen the gap between the telecommunications and power sectors. This requires coordinated investment between the National Telecommunications Corporation and the Ministry of Energy and Petroleum to expand the fiber backbone, upgrade 4G/5G towers near critical grid assets, and establish redundant communication channels for key substations [7, 18, 23].

6.2 Financial Limitations

The financial capacity of Sudanese utilities is severely constrained. Current annual budgets allocate less than US$ 10 million for grid modernization—a fraction of the estimated US$ 25–30 million required annually for a minimal IIoT rollout [22, 31]. High inflation and currency volatility further affect private investment. Table 3 shows a summary for major financial limitation.

Table 3. Summary of major financial bottlenecks

Constraint	Current Estimate (2024)	Required / Target	Gap
Annual modernization budget	< US$ 10 M	US$ 25–30 M	≈ US$ 15–20 M
Smart-meter coverage	< 5% of consumers	≥ 50% by 2030	≈ 45%
Cybersecurity budget (share of O&M)	< 1%	5–8 % (global benchmark)	≈ 4–7%
Donor/PPP inflow	Low	Medium	Limited credit guarantee

Bridging this gap necessitates innovative, blended financing instruments. These could include sovereign guarantees for PPPs, concessional credit lines from development banks, and targeted grants for digital infrastructure from institutions like the African Development Bank (AFDB) and the Green Climate Fund [21, 29, 40].

6.3 Institutional and Regulatory Gaps

Sudan currently lacks a coherent digital-energy policy or a robust data-governance framework. Operational fragmentation between the Ministry of Energy, the Sudanese Electricity Distribution Company, and regional utilities leads to duplicated efforts and inconsistent cybersecurity standards. Compounding this, only about 20% of technical staff have received training in automation, and dedicated cybersecurity roles are virtually non-existent [32, 41].

To overcome this, the government should prioritize the establishment of a National IIoT and Smart-Grid Regulatory Framework. This framework should cover:

i. Clear data ownership, sharing, and privacy protocols.
ii. Mandatory standards for IIoT device certification and network compliance with IEC 62351 [11, 33].
iii. Incentives for private operators to invest in and host data platforms [40].
iv. Periodic digital-maturity audits conducted by an independent institute.

6.4 Human-Capacity and Knowledge Gaps

The shortage of skilled human resources is perhaps the most critical bottleneck. Only about one in five engineers in grid operations has received formal training in digital skills. Furthermore, universities and technical colleges in Sudan offer limited, if any, specialized courses in IIoT, automation, or power data analytics [32, 41].

A national digital skills initiative is urgently needed. This should be launched in collaboration with institutions like the University of Khartoum and Sudan University of Science and Technology, with support from international partners.

Partnerships with donor agencies and regional centers of excellence can facilitate curriculum development, provide scholarships, and create hands-on internship opportunities within utilities [21, 34, 41]. Table 4 gives the proposed indicative training targets

Table 4. Proposed indicative training targets.

Category	Baseline (2024)	Target (2030)	Target (2035)
Engineers trained in IIoT & automation	≈ 100	300	500
Cybersecurity professionals	< 20	150	300
Technicians for sensor & field devices	≈ 150	400	600
Data analysts / AI specialists	≈ 30	120	200

6.5 Cybersecurity as cross-cutting constraint

Cybersecurity is not a peripheral add-on to IIoT deployment, but a cross-cutting constraint that shapes what is technically and institutionally feasible. Every proposed use case—smart metering, feeder automation, DG/microgrid control, and digital-substation integration—expands the grid's attack surface and increases dependence on the integrity and availability of data flows. As a result, secure-by-design architectures, consistent application of standards such as IEC 62351 and the NIST Cybersecurity Framework, and the establishment of a sectoral Cybersecurity Operations Center (CSOC) must advance in parallel with field-level roll-outs rather than in a later "cleanup" phase. Framing cybersecurity in this way clarifies that many IIoT investments in Sudan will only deliver their intended reliability and efficiency gains if they are embedded in robust governance, monitoring, and incident-response capabilities from the outset. [19]

According to the above discussion, the following priority policy and implementation actions, shown in Table 5, are recommended. for Sudan's IIoT roadmap.

Table 5. Priority Policy and Implementation Actions for Sudan's IIoT Roadmap

Priority Action	Lead Institution	Time Frame	Expected Outcome
Create National IIoT & Smart-Grid Framework	MoEP / Regulatory Authority	2025 – 2026	Unified governance & standards
Establish Digital Energy Unit (DEU)	MoEP	2026	Centralized coordination
Implement National Cybersecurity Framework	CSOC + NISS	2026 – 2027	Secure data management
Launch national training initiative (500 engineers)	Universities + MoHE	2025 – 2030	Human-capacity improvement
Expand PPP-based financing for smart metering	MoF + Private	2028 – 2032	Sustainable investment inflow

Sudan's transition toward a digitalized energy future presents considerable challenges. According to the Africa Digital Readiness Index, Sudan scores significantly below regional peers such as Kenya and Egypt, underscoring the magnitude of institutional, infrastructural, and human-capital reforms needed to achieve meaningful digital transformation [28]. However, the potential payoff is substantial. Full IIoT deployment could save approximately 1.2 TWh/year by 2035, lower CO_2 emissions by about 0.7 Mt/year, and crucially, raise the share of renewables in the energy mix to nearly 20% [26, 29]. Furthermore, enhanced regional cooperation through the Eastern Africa Power Pool could leverage IIoT data for better load balancing, potentially reducing operational costs by up to 25% [22, 30].

CONCLUSION AND FUTURE PROSPECTS

This paper outlined how Industrial Internet of Things (IIoT) capabilities can be pragmatically applied to Sudan's power sector by mapping priority use cases to operational challenges and proposing a phased implementation roadmap. Near-term gains can be achieved by deploying low-regret sensing, communications, and data platforms to improve situational awareness, reduce outage restoration time, and enable condition-based and predictive maintenance for critical assets. Medium-to-long term progress depends on strengthening governance, cybersecurity, interoperability (e.g., IEC-61850-aligned digital substations), and workforce capacity so that analytics and automation can be scaled across generation, transmission, and distribution. The recommended staged approach balances affordability and risk while building the technical and institutional foundations needed for resilient, data-driven grid operations in Sudan.

Looking ahead, future research should focus on developing context-specific solutions. This includes designing edge-AI algorithms that can function effectively on low-bandwidth networks, exploring models for domestic sensor assembly to reduce costs and create jobs, and advancing resilience modeling to account for the unique cyber-physical risks faced by post-conflict nations like Sudan [20, 27, 35]. The path is steep, but the strategic integration of IIoT offers a tangible route to overcome Sudan's energy crisis and power a more stable and prosperous future.

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