مجلة جامعة بني وليد للعلوم الإنسانية والتطبيقية
Bani Waleed University Journal of Humanities and Applied Sciences
تصدر عن– جامعة بني وليد – ليبيا
Website:https://jhas-bwu.com/index.php/bwjhas/index

ISSN 3005-3900 | الصفحات (10- 20) | المجلد الحادي عشر – العدد الخامس – 2026

A Phased Framework for Smart Grid Integration in Libya: Enhancing Grid Reliability and Mitigating Recurrent Outages

Ali Salim Abunuar *
Information Engineering Department, Faculty of Technical Engineering, Mesallata, Libya
asabunouwar@ftem.edu.ly

إطار عمل مرحلي لدمج الشبكات الذكية في ليبيا
تعزيز موثوقية الشبكة والحد من الانقطاعات المتكررة

علي سليم أبونوار *
قسم هندسة تقنية المعلومات، كلية التقنية الهندسية ،مسلاته، ليبيا

Received: 11-05-2026	Accepted: 14-06-2026	Published: 01-07-2026

الملخص:
يواجه قطاع الكهرباء في ليبيا تحديات جمة ذات جوانب مادية وتشغيلية ونظامية؛ إذ تعاني العناصر المادية لنظام الطاقة الوطني من التقادم وعدم الصيانة الكافية نتيجةً للإدارة المركزية لقطاع الطاقة. إضافةً إلى ذلك، يُشكل هشاشة النظام، وعدم الاستقرار السياسي، والظروف الأمنية المتردية مخاطر مستمرة على الشبكة، مما يجعلها نظامًا هشًا للغاية. ونتيجةً لهذه التحديات، ينقطع التيار الكهربائي بشكل متكرر ومفاجئ عن المستهلكين، وتعجز الشبكة عمومًا عن توفير كميات كافية من الكهرباء لتلبية الطلب المتزايد. ويتطلب حل هذه المشكلات المستمرة إيجاد حلول عاجلة لها. ويُعد إطار الشبكة الذكية أحد الحلول التقنية المبتكرة المقترحة لمساعدة الدول النامية على معالجة هذه المشكلات. ويمثل إطار الشبكة الذكية فرصة لتحديث نظام توزيع الكهرباء الوطني بأكمله، وبالتالي تحسين موثوقية واستدامة إمدادات الكهرباء على المدى الطويل. ومع ذلك، يُمثل الانتقال إلى الشبكة الذكية في ليبيا تحديًا نظرًا لأن جميع الأبحاث تقريبًا حول نشر الشبكات الذكية أُجريت في ظل هياكل مؤسسية مستقرة، مما يُصعّب على السلطات الانتقالية في دول هشة كليبيا تنفيذها بنجاح. تُشكل القيود المرتبطة بليبيا تحديًا كبيرًا، لا سيما فيما يتعلق بتوافر الموارد وعدم استقرار النظام، مما يضع السلطات الانتقالية أمام ضرورة إيجاد حلول لتجاوز هذه العقبات من أجل تطبيق إطار عمل الشبكة الذكية بنجاح. تقترح هذه الورقة إطار مرحلي لتطوير الشبكة الذكية ، يرتكز هذا الإطار على بنية تواصلية هرمية ثلاثية الطبقات: تبدأ بشبكة المنطقة المنزلية (HAN) كنقطة دخول أولى للتحوّل الرقمي عبر نشر عدادات ذكية تجريبية في المدن الكبرى كطرابلس وبنغازي ومصراتة، مروراً بشبكة المنطقة المجاورة (NAN) التي تتولى تجميع البيانات وتعزيز الرقابة التشغيلية على شبكة التوزيع، ووصولاً إلى شبكة المنطقة الواسعة (WAN) بوصفها العمود الفقري الاستراتيجي الذي يربط المحطات الفرعية ومراكز التحكم ومصادر الطاقة المتجددة. ويُصنّف الإطار المقترح التحوّل إلى الشبكة الذكية في ثلاث مراحل زمنية: قصيرة المدى (1-3 سنوات)، ومتوسطة المدى (3-7 سنوات)، وطويلة المدى (أكثر من 7 سنوات)، مع التأكيد المتوازي على ثلاثة ركائز متشابكة: البنية التحتية التقنية، ورأس المال البشري، والجاهزية المؤسسية. ويُقدّم هذا الإطار نموذجاً قابلاً للتكرار والتطبيق في الدول الهشة وما بعد النزاع التي تشاطر ليبيا قيودها البنيوية، مُسهماً في ترسيخ مسار واقعي نحو تحديث منظومة الكهرباء وتعزيز مرونتها واستدامتها.

الكلمات الدالة: شبكة الكهرباء في ليبيا ، الشبكة الذكية ، شبكة المنطقة المنزلية ، شبكة المنطقة المجاورة ، شبكة المنطقة الواسعة ، تحديات وفرص الشبكة الذكية في ليبيا.

Abstract

The Libyan electricity sector faces multifaceted challenges spanning physical, operational, and systemic dimensions. The national grid is plagued by aging infrastructure and inadequate maintenance resulting from centralized energy management. These issues, coupled with political instability and security risks, have created a highly fragile system characterized by recurrent power outages and an inability to satisfy growing electricity demand. To mitigate these persistent problems, the integration of Smart Grid technology is proposed as an innovative solution to modernize the national distribution network and enhance long-term supply reliability. Despite the potential, the transition to a smart grid in Libya is hindered by the fact that most existing research assumes stable institutional environments, which is not the case for fragile states. To overcome these resource and stability constraints, this paper introduces a phased framework based on a three-layer hierarchical communication architecture. The first layer, the Home Area Network (HAN), initiates digitalization through pilot smart meters in cities like Tripoli, Benghazi, and Misrata. The second layer, the Neighborhood Area Network (NAN), focuses on data aggregation and distribution-level monitoring. The final layer, the Wide Area Network (WAN), acts as the strategic backbone linking substations, control hubs, and renewable energy installations. This transition is structured across three timeframes: short-term (1-3 years), medium-term (3-7 years), and long-term (7+ years), focusing on three parallel pillars: technical infrastructure, human capital, and institutional readiness. This model serves as a scalable reference for post-conflict nations with similar structural constraints, providing a realistic roadmap toward grid modernization and resilience.

Keywords: Smart Grid, Libyan Electricity Network, Home Area Network (HAN), Neighborhood Area Network (NAN), Wide Area Network (WAN), Power Sector Modernization.

Introduction

The production, transmission, and delivery of electrical energy constitute a foundational pillar of contemporary global economies. The inherent adequacy of a power system is fundamentally determined by its capacity to precisely match dynamic, time-varying electricity demand while rigorously maintaining critical operational parameters, specifically voltage magnitude and system frequency, within prescribed acceptable tolerances. Achieving this complex equilibrium necessitates robust generation assets equipped with sufficient operational reserve margins, high-capacity transmission corridors designed to facilitate the bulk transfer of electrical power over extensive geographical distances without exceeding thermal or dynamic stability constraints, and resilient distribution infrastructures capable of ensuring secure and efficient energy delivery to end-users. These three interconnected functional layers work synergistically as part of one grid architecture. The generation stratum consists of power stations with associated step-up transformer facilities that convert various primary energy sources into electrical power. This energy is then bulk transferred across the network at high voltage through interconnected substations in the transmission stratum. At this final stage, the distribution stratum consists of many substations, feeder lines, and local transformers, providing the interface for the direct supply of energy to the consumer at the desired utilization voltage levels [1]. Figure 1 shows the inherent hierarchical structure of a typical electrical power grid. Such systems' design is pretty common in most developed industrial countries, with characteristic stable operating behavior and well-established, centralized control paradigms. On the other hand, electrical grids in most developing countries, particularly those affected by long-lasting conflicts and deep institutional instability, fail to possess these basic features. Moreover, the fundamental architectural paradigm of the electrical power grid has not undergone any substantial modification over several decades, making it intrinsically incompatible with smoothly integrating most new, modern energy technologies [2].

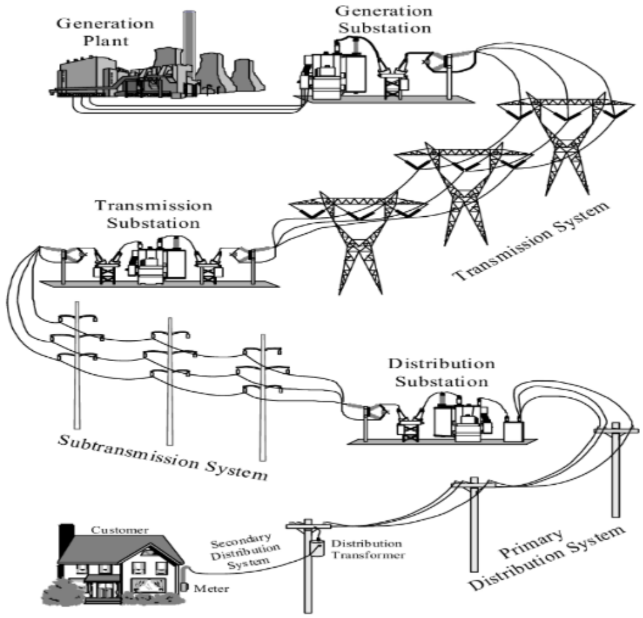

Figure 1: Traditional grids and electrical power systems consisting of many subsystems [1].

I. An Overview of the Energy Sector in Libya

Since its establishment in 1984, the state-owned General Electricity Company of Libya (GECOL) has been fully responsible for the power infrastructure's strategic planning, management, and operation [3]. Currently, the total installed capacity of the Libyan electrical system is about 6768 MW. The transmission configuration is subdivided into six major interconnected operational areas: West, Tripoli, Central, Benghazi, East, and South, to overcome technical and logistical problems due to the country's large size. The Libyan power system's backbone is the 400 kV, 220 kV, and 132 kV transmission system. The primary networks are connected through the 66 kV sub-transmission network, while the distribution network provides the end user with 30 kV and 11 kV. Physically, the system is mainly overhead line (OHL) type with an overall length of 14747 km, and underground cabling (UGC) is a negligible part with only 138 km. On the other hand, the 30 kV distribution network has a total length of 11142 km [4]. Figure 2: Single-line diagram of the Libyan national power grid. The network topology is based on the standard GECOL model, extensively utilized in recent stability assessments

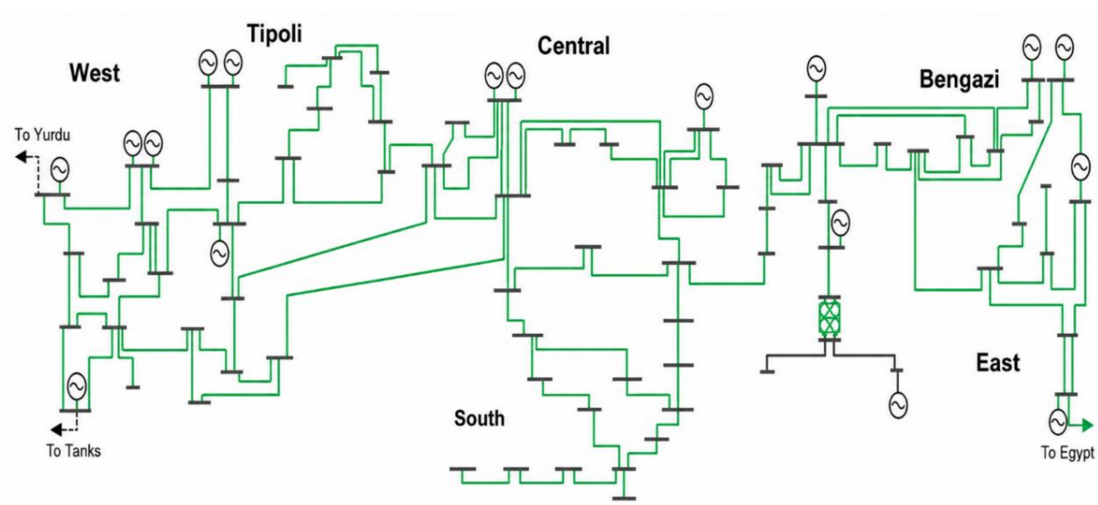

Figure 2: Transmission power system of Libya.

As the system topology in Figure 2 suggests, the Libyan grid must cover considerable distances over vast geographic areas to accommodate a widely dispersed population. This large geographical footprint adds many dimensions to network modernization. It implies a gradual, systematic shift from conventional centralization to smart grid architectures. Thus, fully realizing an integrated and resilient modern utility will require a strategic and staged implementation approach fitted to the socio-technical and operational peculiarities of the Libyan energy landscape.

II. The Smart Grid Paradigm

A smart grid represents an advanced power network characterized by the integration of modern communication and information technologies (ICT). This integration enables intelligent monitoring, optimal control, and efficient management of energy generation, transmission, and distribution. By accommodating renewable energy sources (RES), energy storage systems (ESS), and electric vehicles (EVs), the smart grid significantly enhances the reliability, security, and efficiency of the power supply for all consumers. The core distinguishing feature of a smart grid is its capability to facilitate bidirectional flows of both electricity and real-time information, ensuring dynamic interaction between utility providers and end-users [5] .

TABLE 1 ILLUSTRATES THE CHARACTERISTICS OF CONVENTIONAL POWER GRIDS COMPARED TO SMART GRIDS [6] .

	Typical Power Grid	Smart Power Grid
Generation	Centralized, away from load centers, limited renewable	Distributed, less size, considerable renewable
Power Flow	Radial, unidirectional	Networked, multi-directional
Main Focus	Continuity of Service	Continuity & Quality
Control Centers	Based on manual communications systems during faults	Computer based data collectors, processors and decision making
Response to Faults	Focus on protecting assets and prevent future damage	Predicts and prevents faults
Blackouts	Cascading effect	Islanding capability
Relays	Electro-mechanical based	
Attacks	Exposed to natural and terrorist attacks	

The realization of a comprehensive smart grid, as illustrated in Figure 3, depends on the deployment of advanced infrastructure built upon a resilient operational foundation. This requires the synergistic transformation of both the electrical and telecommunications sectors into an integrated ecosystem characterized by secure, bidirectional information exchange and embedded computational intelligence [7],[8].

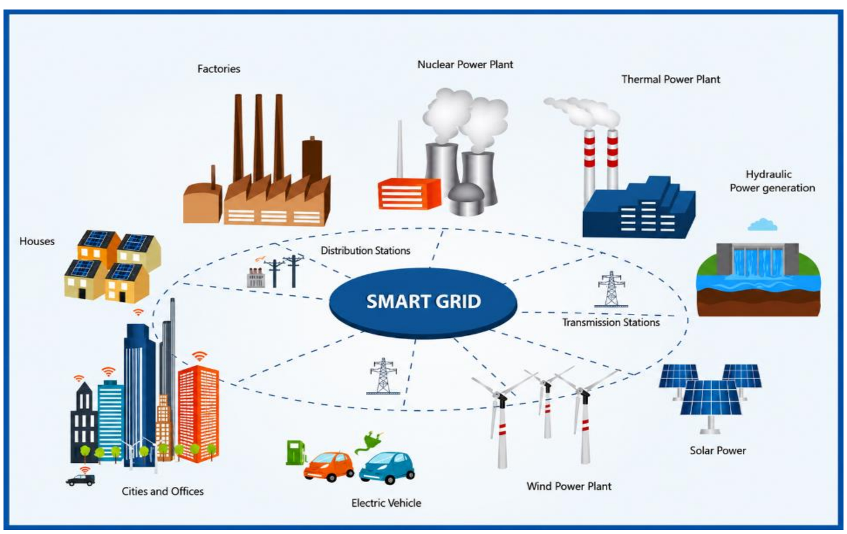

Figure 3: The Smart Power Grid ecosystem, integrating diverse energy sources, transmission, and consumption points [9].

This integrated system is supported by a hierarchical communication architecture comprising three distinct layers Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN). The Home Area Network (HAN) provides connectivity within residential or commercial premises. The Neighborhood Area Network (NAN) aggregates data from multiple HANs. The Wide Area Network (WAN) serves as the high-capacity backbone, connecting substations, control centers, and bulk generation facilities [7],[9]. In Libya, these communication networks are currently underdeveloped and require substantial investment. Therefore, the modernization process must begin with the systematic development of these foundational layers before large-scale smart grid technologies can be feasibly deployed [10].

III. Human Resource Requirements and Technical Capacity

The successful implementation of smart grid technologies in Libya faces substantial human capital challenges, including shortages of qualified professionals with expertise in power systems, communication networks, data analytics, automation, and cybersecurity. Addressing these workforce gaps through targeted education, training, and capacity-building initiatives is essential for ensuring the effective deployment and sustainable operation of smart grid infrastructure [11].

III.1 Current Workforce Gap Analysis:

Libya's electricity sector currently operates with a workforce trained predominantly in conventional power system management. The transition to smart grid infrastructure requires expertise in[12].

- **ICT and Network Engineering:** Available evidence suggests that the Libyan power sector faces shortages in personnel trained in digital communication systems, smart grid networking, and cybersecurity, which may hinder the deployment of HAN, NAN, and WAN infrastructures.
- **Data Analytics and Software Engineering:** Smart grid operation depends on real-time data processing, predictive analytics, and algorithm development—competencies largely absent in the current workforce structure.
- **Advanced Metering and Sensor Technologies:** Installation, calibration, and maintenance of AMI systems require specialized training that extends beyond traditional electromechanical meter expertise.
- **System Integration Specialists:** Personnel capable of integrating legacy infrastructure with modern digital systems are essential but currently unavailable in sufficient numbers.

IV. Capacity Building Strategy

III.2 Institutional Capacity Requirements

Beyond individual competencies, strengthening the institutional capabilities of the organizational workforce is paramount. In the context of the General Electricity Company, this represents a critical imperative. The organization must prioritize enhancing employee proficiency, particularly in computational literacy and digital tool utilization. This need is especially pronounced among technical personnel and frontline maintenance teams, where a substantial proportion of technicians continue to demonstrate limited computer proficiency. Consequently, the following institutional capacity dimensions require strategic reinforcement [13] :

• **Project Management Capabilities**: Large-scale infrastructure initiatives necessitate robust project management frameworks, which remain underdeveloped within transitional governance contexts. These frameworks must encompass comprehensive planning, resource allocation, risk mitigation, and stakeholder coordination mechanisms.

• **Regulatory Expertise**: The formulation of technical standards, cybersecurity protocols, and consumer protection frameworks demands systematic regulatory capacity development. This includes establishing institutional knowledge in compliance monitoring, quality assurance, and adaptive regulatory mechanisms responsive to technological evolution.

• **Maintenance and Support Infrastructure**: Establishing resilient supply chains, implementing comprehensive spare parts inventory management systems, and deploying rapid-response maintenance teams constitute foundational requirements for operational sustainability.

V. Telecommunication Infrastructure Readiness Assessment

The successful implementation of smart grid technologies relies heavily on the availability of a robust, secure, and resilient communication infrastructure capable of supporting real-time data exchange, monitoring, and control functions. In developing countries such as Libya, the readiness of the telecommunications sector represents a critical factor influencing the feasibility, scalability, and long-term sustainability of smart grid deployment initiatives. Consequently, a comprehensive assessment of existing communication capabilities is essential for identifying infrastructure gaps and establishing appropriate deployment strategies [14].

V.1 Current Telecommunications Environment

The telecommunications sector in Libya and the world has experienced numerous operational and infrastructural challenges over recent years. These challenges have affected the availability, reliability, and performance of communication services required to support advanced smart grid applications. While ongoing modernization efforts have improved connectivity in several regions, significant disparities remain between urban and remote areas, creating obstacles for nationwide smart grid integration [14]. Fixed communication networks constitute an important foundation for smart grid operation due to their ability to provide secure and high-capacity data transmission. However, the expansion of fiber-optic infrastructure remains uneven, and legacy communication systems continue to impose limitations on bandwidth, reliability, and interoperability. Such constraints may reduce the effectiveness of applications requiring continuous monitoring, automation, and low-latency communication. Mobile communication technologies have become increasingly important as a practical solution for supporting smart grid services, particularly in regions where fixed-line infrastructure is limited. Although cellular networks offer flexible and cost-effective connectivity, their performance may be affected by network congestion, service interruptions, and varying quality-of-service levels. These factors can impact the reliability of mission-critical smart grid communications and operational control functions [15]. Satellite communication systems provide an additional communication alternative for geographically isolated locations and remote substations. Nevertheless, their relatively high operational costs and latency characteristics limit their suitability for applications requiring rapid response and real-time control. As a result, satellite technologies are generally more appropriate as supplementary or backup communication solutions rather than primary communication channels [16].

VI. A Structured Framework for Smart Grid Development in Libya

Introducing intelligent grid capabilities within the Libyan electricity sector requires a structured transition strategy built on gradual implementation, layered architecture, and explicit risk containment. The evolution of the communication ecosystem—spanning home, neighborhood, and wide-area domains—needs to advance step by step in harmony with prevailing technical capacities, financial limitations, and institutional readiness. Emphasis should therefore be placed on creating an initial digital foundation that can reliably host successive functional upgrades instead of pursuing an immediate, system-wide rollout [17].Adopting such a trajectory strengthens the robustness of the communication environment, promotes compatibility among heterogeneous technologies, and preserves the flexibility required for long-term expansion. Establishing these attributes forms a fundamental condition for unlocking higher-level automation, monitoring, and control services associated with smart grid operation [18].

VI.1 Stage 1: Home Area Network (HAN) Development

The home domain represents the entry point of intelligence within the smart grid environment, forming the operational boundary between consumers and the utility. At the outset, its mission should concentrate on fundamental observability and systematic data collection, while sophisticated automation functions are introduced only after the supporting ecosystem matures [19].Priority actions at this stage involve initiating limited pilot programs for advanced metering in major metropolitan areas such as Tripoli, Benghazi, and Misrata, where communication services and technical support structures are comparatively stronger. The deployed devices are expected to align with Advanced Metering Infrastructure requirements and incorporate capabilities for local data retention to enhance reliability during connectivity interruptions. From an economic and operational perspective, cost-effective communication options—particularly power line carrier solutions and radio mesh configurations—offer practical starting points. Conversely, large-scale dependence on intricate Internet-of-Things frameworks should be postponed, given the financial burden and the specialized maintenance expertise they demand. An equally decisive element of this phase concerns strengthening user engagement. Structured awareness initiatives can improve understanding of consumption behavior, encourage efficient utilization, and build trust in digital metering practices. Through these measures, the system can obtain an initial evidence base on demand characteristics, curb commercial losses, and prepare the technical and organizational groundwork required for subsequent demand-side management strategies [19].The principal components of this introductory stage are illustrated in Figure 4.

Home Area Network (HAN) -Bottom Layer

Function: Pilot deployment in urban canters, basic monitoring and consumer engagement.

Key Actions:

- Deploy pilot smart meters in cities such as Tripoli, Benghazi, and Misrata.
- Use AMI-compliant smart meters.
- Utilize cost-efficient network technologies such as PLC and RF mesh.
- Delay advanced IoT solutions.
- Raise consumer awareness on energy efficiency.

Expected Outcomes:

- Visibility into energy consumption patterns.
- Reduced non-technical losses.
- Readiness for future demand-side management initiatives.

Figure 4: Stage 1 Home Area Network (HAN) -Bottom Layer. Resources: [19],[20], [21].

VI.2 Stage 2: Neighborhood Area Network (NAN) Development

The neighborhood domain performs the role of a regional coordination layer within the smart grid communication hierarchy. It aggregates information streams originating from numerous home installations and supports supervisory functions that enhance visibility across distribution assets [20].Key steps in this stage involve linking advanced meters to data concentrators positioned at electrically strategic locations, including feeder termini and secondary substations. System architecture should incorporate redundancy mechanisms, such as auxiliary energy supplies and diversified communication routes, in order to preserve data continuity when disturbances or blackouts occur. Selection of the communication medium is best guided by local constraints; a blended model that may include radio mesh arrangements, commercial cellular services, or dedicated LTE infrastructures provides flexibility while addressing coverage and security considerations. Preference should be given to solutions that limit the need for heavy field construction and that can maintain performance under volatile operating conditions. With these capabilities in place, utilities gain access to practical tools for early fault identification, faster determination of interruption boundaries, and detailed assessment of loading behavior at the feeder scale. The immediate benefit is a marked improvement in operational awareness throughout the distribution grid, which in turn strengthens restoration practices and establishes the technical platform upon which more advanced automation schemes can be progressively introduced [20].

Function: Aggregates data from multiple HANs, localized monitoring, efficient shortcomings

- Link smart meters to data concentrators at key feeders and substations.
- Implement backup power and communication paths.
- Utilize mixed network architectures like RF mesh, 3G/4G/LTE.
- Prioritize technologies that minimize civil works.
- Detect, identify, and grid faults and outages planning.
- Facilitate short-term load analysis and planning.

Figure 5: Stage 2 Neighborhood Area Network (NAN) Aggregates data from multiple HANs. Resources : [19],[20], [21].

VI.3 Stage 3: Wide Area Network (WAN) Development

The wide-area network represents the strategic communication spine of an intelligent power system, linking substations, control hubs, generation facilities, and large-scale renewable installations. Its establishment is essential for achieving comprehensive system coordination and enabling real-time operational oversight [21].Implementation priorities include leveraging existing fiber-optic assets along high-voltage transmission routes while augmenting connectivity in remote regions through microwave links and cellular technologies. Upgrades to national and regional control centers are required, incorporating advanced Supervisory Control and Data Acquisition (SCADA) systems alongside Distribution Management Systems (DMS) to enhance monitoring and control capabilities. The integration of real-time analytics platforms is vital for informed operational decision-making. Equally critical is the formulation of a robust cybersecurity strategy encompassing data governance, encryption protocols, and access management, with security considerations embedded at the design stage. Successfully deploying the WAN establishes a secure framework for system-level coordination, reinforces overall grid stability, and enables the scalable integration of renewable energy sources [21].

Wide Area Network (WAN) Backbone connecting substations, control centres, and renewable resources

Function: Leverage fiber-optic networks along transmission lines.

Key Actions:

- Complement fiber with microwave and cellular tech .
- Advance control centers with SCADA and E-cloud DMS.
- Implement real-time data analytics platforms.
- Establish centralized cybersecurity monitoring.
- Develop governance and cybersecurity frameworks.
- planning.

Expected Outcomes:

- The WAN layer enables secure and reliable system-level coordination.
- Enhances grid stability, and facilitates large-scale integration of renewable energy resources.
- A foundation for future distribution automation.

Figure 6: Stage 3 Wide Area Network (WAN)Backbone connecting substations, control centers, and renewable. Resources: : [19],[20], [21].

VII. Discussion: Implementation Timeline and Key Considerations

The transformation of Libya's conventional grid requires a clearly defined implementation timeline. Table 2 outlines a proposed multi-phase approach, designed to align technological integration with evolving operational maturity and infrastructure readiness.

TABLE 2 IS A PROPOSED TIMELINE FOR THE DEVELOPMENT OF THE SMART GRID IN LIBYA'S ELECTRICITY SECTOR.

Phase	Focus	Duration
Phase I	HAN pilots and basic WAN upgrades	Short-term (1-3 years)
Phase II	NAN expansion and initial distribution automation	Medium-term (3-7 years)
Phase III	Full WAN integration and advanced smart grid services	Long-term (7+ years)

The transition to a smart grid is not merely a technical upgrade but a comprehensive infrastructure transformation [7].Its success is contingent upon several non-technical factors. Institutional and political stability are paramount; a stable security environment and coherent governance are prerequisites for attracting investment, ensuring effective project management, and coordinating among implementing bodies. Without these, even the most well-designed technical plans are unlikely to succeed. From an economic standpoint, smart grid implementation demands significant upfront capital investment and long-term financial planning [22].While Libya possesses energy resources, the effective mobilization and allocation of capital for large-scale infrastructure projects are directly enabled by political and security stability. Furthermore, socio-technical readiness is a critical determinant. Research suggests that successful adoption depends less on overcoming inherent societal resistance and more on proactive stakeholder engagement, institutional capacity building, and consumer education [23].Public trust in advanced metering, data privacy, and control technologies must be cultivated through strategic planning and transparent communication. Therefore, these social and governance aspects should be treated as integral components of the implementation strategy, not as secondary obstacles.

VIII. Conclusion and Strategic Recommendations

The analysis presented in this paper confirms that transforming Libya's electricity sector through smart grid integration is neither a mere technical option nor an overnight overhaul. Rather, it is an urgent necessity fraught with considerable challenges. At the heart of this transformation lies the need to reconceptualize the process as a gradual, adaptive, and context-sensitive transition rather than a disruptive, one-time replacement that could further destabilize an already fragile system. The findings clearly indicate that any successful pathway toward smart grid adoption in the Libyan context must rest upon three interdependent pillars: technical infrastructure, human capital, and institutional readiness. On the technical front, establishing an integrated communications hierarchy spanning the home area, neighborhood area, and wide area networks is essential to ensure data flow and operational reliability. Simultaneously, the critical gap in workforce competencies capable of handling these technologies cannot be overlooked, making comprehensive training programs a top priority. At the institutional level, political stability, clear regulatory frameworks, and sound governance capacities do not merely serve as enabling factors—they constitute fundamental preconditions for the success of any technical endeavor, regardless of how meticulously it is designed. The phased framework proposed in this paper offers sufficient flexibility to adapt the pace of implementation to the actual level of institutional maturity, rendering it a replicable model not only for Libya but also for other fragile and post-conflict states facing similar constraints. The emphasis on staged execution, proactive risk mitigation, and context-appropriate technology selection provides a practical alternative to conventional smart grid literature, which typically assumes stable institutions and abundant resources. From a realistic perspective, Libya's chronic electricity problems—frequent outages, aging infrastructure, and the inability to meet growing demand—will not be resolved quickly or easily. Nevertheless, the stepwise approach outlined here charts a feasible path forward: by systematically building communication infrastructure, developing human capacity in parallel, and implementing technologies incrementally, Libya can progressively enhance grid reliability and resilience. Ultimately, however, success will depend not only on the quality of technical execution but also on sustained political commitment, transparent governance, and long-term investment in both infrastructure and people. In conclusion, the journey from Libya's current grid fragility to a resilient smart grid will be long and arduous, but it is by no means unattainable. If the aforementioned conditions can be met, this transformation offers Libya a rare opportunity to leapfrog decades of conventional grid development and establish a modern, efficient, and sustainable electricity system capable of supporting national development for generations to come. This paper has provided a clear roadmap; executing it will require collective will and sustained effort from policymakers, utility managers, technical professionals, and the Libyan people alike.

References

1. Abdalla, M. A. A. (2025). Satellite Communication Technologies for Smart Grid Applications: A Comprehensive Review of GEO VSAT and LEO Constellations. *International Journal of Science and Research Archive*, *17*(2), 178–190. https://doi.org/10.30574/ijsra.2025.17.2.2976
2. Abdul Salam, R., Iqbal Ratyal, N., Ahmed, U., Aziz, I., Sajid, M., & Mahmood, A. (2024). An Overview of Recent Wireless Technologies for IoT-Enabled Smart Grids. *Journal of Electrical and Computer Engineering*, *2024*(1), 2568751. https://doi.org/10.1155/jece/2568751
3. Abrahamsen, F. E., Ai, Y., & Cheffena, M. (2021). Communication Technologies for Smart Grid: A Comprehensive Survey. *Sensors*, *21*(23). https://doi.org/10.3390/s21238087
4. Almaktar, M., Elbreki, A. M., & Shaaban, M. (2021). Revitalizing operational reliability of the electrical energy system in Libya: Feasibility analysis of solar generation in local communities. *Journal of Cleaner Production*, *279*, 123647. https://doi.org/10.1016/j.jclepro.2020.123647
5. Balamurugan, M., Narayanan, K., Raghu, N., Arjun Kumar, G. B., & Trupti, V. N. (2025). Role of artificial intelligence in smart grid – a mini review. *Frontiers in Artificial Intelligence*, *8*. https://doi.org/10.3389/frai.2025.1551661
6. Beigi-Mohammadi, N., Khazaei, H., Mišić, J., & Mišić, V. B. (2012). On Intrusion Detection in a Neighbourhood Area Network in the Smart Grid. *JITA - Journal of Information Technology and Applications (Banja Luka) - APEIRON*, *3*(1). https://doi.org/10.7251/JIT1201007M
7. Chhaya, L., Sharma, P., Kumar, A., & Bhagwatikar, G. (2018). IoT-Based Implementation of Field Area Network Using Smart Grid Communication Infrastructure. *Smart Cities*, *1*(1), 176–189. https://doi.org/10.3390/smartcities1010011
8. *General Electricity Company of Libya*. (n.d.). Retrieved 14 June 2026, from https://www.gecol.ly/Home/AboutEN
9. Gönen, T., Ten, C.-W., & Mehrizi-Sani, A. (2024). *Electric Power Distribution Engineering* (4th edn). CRC Press. https://doi.org/10.1201/9781003129721
10. Husain, M., & Abdulla, A. (2021). *Possibility of using Prepaid Meters as a Proposed Solution to Electricity Load Management Problem in Libya Case Study Tobruk City*.
11. IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads. (2011). *IEEE Std 2030-2011*, 1–126. https://doi.org/10.1109/IEEESTD.2011.6018239
12. *InEExS_Technology-Experience-Package_Final.pdf*. (n.d.). Retrieved 15 June 2026, from https://ieecp.org/wp-content/uploads/2025/09/InEExS_Technology-Experience-Package_Final.pdf
13. International Energy Agency. (2023). *Electricity Grids and Secure Energy Transitions: Enhancing the Foundations of Resilient, Sustainable and Affordable Power Systems*. OECD. https://doi.org/10.1787/455dd4fb-en
14. Ohanu, C. P., Rufai, S. A., & Oluchi, U. C. (2024). A comprehensive review of recent developments in smart grid through renewable energy resources integration. *Heliyon*, *10*(3). https://doi.org/10.1016/j.heliyon.2024.e25705
15. Okeke, A., & Onyemere, I. (2025). Sustainable supply chain practices as catalyst for energy poverty alleviation in developing countries: A necessary condition analysis. *Discover Sustainability*, *6*(1), 357. https://doi.org/10.1007/s43621-025-01003-4
16. Okokpujie, I. P. (2026). Smart Grids with IOT for Integrating Renewable Energy: Its Social, Organizational, and Economic Regulatory Challenges: A Systematic Review. *ABUAD Journal of Engineering Research and Development (AJERD)*, *9*(1), 288–310. https://doi.org/10.53982/ajerd.2026.0901.25-j
17. Pirta-Dreimane, R., Romanovs, A., Bikovska, J., Pekša, J., Vartiainen, T., Valliou, M., Kamsamrong, J., & Eltahawy, B. (2024). Enhancing Smart Grid Resilience: An Educational Approach to Smart Grid Cybersecurity Skill Gap Mitigation. *Energies*, *17*(8), 1876. https://doi.org/10.3390/en17081876

18. *Purchase Communication network requirements for major smart grid applications in HAN, NAN and WAN | ScienceDirect*. (n.d.). Retrieved 29 January 2026, from https://www.sciencedirect.com/getaccess/pii/S1389128614001431/purchase
19. Sanjalawe, Y., Al-E'Mari, S., Fraihat, S., Naser Makhadmeh, S., & Alzubi, E. (2025a). AI-Powered Smart Grids in the 6G Era: A Comprehensive Survey on Security and Intelligent Energy Systems. *IEEE Open Journal of the Communications Society*, *6*, 7677–7719. https://doi.org/10.1109/OJCOMS.2025.3609144
20. Sanjalawe, Y., Al-E'Mari, S., Fraihat, S., Naser Makhadmeh, S., & Alzubi, E. (2025b). AI-Powered Smart Grids in the 6G Era: A Comprehensive Survey on Security and Intelligent Energy Systems. *IEEE Open Journal of the Communications Society*, *6*, 7677–7719. https://doi.org/10.1109/OJCOMS.2025.3609144
21. Silmee, S. M., & Hosen, S. (2021). *Internet of Things Integrated Smart Grid: The Future of Energy*. *08*(10).
22. Zafar, U., Bayhan, S., & Sanfilippo, A. (2020). Home Energy Management System Concepts, Configurations, and Technologies for the Smart Grid. *IEEE Access*, *8*, 119271–119286. https://doi.org/10.1109/ACCESS.2020.3005244
23. معاينة *Towards Next-Generation Mobile Networks: A Comparative Analysis of 5G and 6G Development in Libya and its Neighbors*. (n.d.). Retrieved 15 June 2026, from https://jhas-bwu.com/index.php/bwjhas/article/view/978/805