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Recent Advances in the Efficiency and Reliability of Renewable Energy Systems in Libya: A Critical Review of Solar, Wind, Energy Storage, and Smart-Grid Technologies

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التطورات الحديثة في كفاءة وموثوقية أنظمة الطاقة المتجددة في ليبيا: مراجعة نقدية للطاقة الشمسية وطاقة الرياح وتخزين الطاقة وتقنيات الشبكات الذكية

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Abstract

Background: Libya combines high solar-resource availability and geographically differentiated wind potential with an electricity system affected by ageing infrastructure, operational constraints, and limited diversification. Local research has expanded across photovoltaic (PV) performance, small wind systems, energy storage, intelligent control, and power quality, yet the evidence remains fragmented.
Objective: This review critically evaluates renewable-energy technologies relevant to Libya, compares studies published with stronger local and international evidence, and develops a deployment-oriented research framework.
Methods: A structured critical-review design was used. Sixteen core Local journals articles published during 2020–2026 were bibliographically checked against the journal archive and assessed alongside purposively selected peer-reviewed and institutional sources from 2015–2026, with older foundational studies retained where necessary. Evidence was synthesized thematically across PV, wind, storage and electric mobility, artificial intelligence (AI), smart grids, power quality, and emerging technologies. Study quality was appraised using nine domains covering objectives, methods, data adequacy, reproducibility, validation, statistics, limitations, and relevance. This manuscript does not claim PRISMA-compliant systematic-review status because auditable subscription-database exports and record-level de-duplication logs were unavailable.
Results: PV is the most mature near-term option, but high temperature, soiling, cleaning-water demand, and limited long-term field monitoring constrain transferable performance estimates. Libyan wind research demonstrates promising sites but relies heavily on short campaigns, satellite products, manufacturer curves, or simulations. Storage and electric-mobility studies remain mostly secondary or simulation-based. AI and physics-informed

models are promising for forecasting, diagnostics, and control, but local evidence rarely provides open datasets, external validation, uncertainty analysis, or operational deployment. Grid protection, converter stability, cybersecurity, lifecycle assessment, and bankable economic analysis are underdeveloped.
Conclusion: Libya should prioritize measured resource and asset-performance datasets, climate-adapted PV operations, multi-year wind campaigns, storage-enabled microgrids, and staged grid-code and protection studies. The review contributes a phased framework linking generation, storage, digital intelligence, power quality, regulation, finance, and workforce development.

Keywords: renewable energy; photovoltaic systems; wind energy; battery storage; smart grids; artificial intelligence; power-system reliability; Libya.

الملخص
تتمتع ليبيا بموارد شمسية مرتفعة وإمكانات واعدة لطاقة الرياح تختلف باختلاف المناطق الجغرافية، في حين يواجه نظام الطاقة الكهربائية تحديات تتمثل في تقادم البنية التحتية، والقيود التشغيلية، وضعف تنوع مصادر الطاقة. وقد شهدت الدراسات المحلية توسعًا ملحوظًا في مجالات أداء الأنظمة الكهروضوئية، وأنظمة الرياح الصغيرة، وتخزين الطاقة، وأنظمة التحكم الذكية، وجودة القدرة الكهربائية، إلا أن الأدلة العلمية ما تزال متفرقة وغير متكاملة.
الهدف
تهدف هذه المراجعة إلى إجراء تقييم نقدي لتقنيات الطاقة المتجددة ذات الصلة بليبيا، ومقارنة نتائج الدراسات المحلية والدولية الأكثر قوة من حيث الأدلة العلمية، واقتراح إطار بحثي عملي يدعم نشر هذه التقنيات وتطبيقها على المستوى الوطني.
المنهجية
اعتمدت الدراسة منهج المراجعة النقدية المنظمة. وتمت مراجعة ستة عشر مقالًا أساسيًا منشورًا في مجلة محلية خلال الفترة (2020–2026)، مع التحقق الببليوغرافي من بياناتها بالرجوع إلى أرشيف المجلة، بالإضافة إلى تحليل مجموعة مختارة عمديًا من الدراسات المحكمة والتقارير المؤسسية المنشورة خلال الفترة (2015–2026)، مع الاحتفاظ ببعض الدراسات المرجعية الأقدم عند الحاجة. وتم تجميع الأدلة وتصنيفها موضوعيًا ضمن محاور تشمل: الأنظمة الكهروضوئية، وطاقة الرياح، وتخزين الطاقة والتنقل الكهربائي، والذكاء الاصطناعي، والشبكات الذكية، وجودة القدرة الكهربائية، والتقنيات الناشئة. كما جرى تقييم جودة الدراسات باستخدام تسعة معايير تضمنت: وضوح الأهداف، والمنهجية، وكفاية البيانات، وقابلية إعادة الإنتاج، وأساليب التحقق، والتحليل الإحصائي، والقيود، ومدى الصلة بموضوع الدراسة. ولا تدّعي هذه المراجعة الامتثال الكامل لإرشادات PRISMA الخاصة بالمراجعات المنهجية، نظرًا لعدم توفر سجلات موثقة لعمليات البحث في قواعد البيانات التجارية أو سجلات إزالة التكرار على مستوى الدراسات.
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الكلمات المفتاحية: لمبدد الحراري ذو القنوات الدقيقة، المائع النانوي، انتقال الحرارة بالحمل، المقاومة الحرارية، هبوط الضغط، تبريد الإلكترونيات، مائع أكسيد الألومنيوم–الماء النانوي.

1. Introduction

Renewable electricity is no longer a peripheral component of power-system planning. The International Energy Agency (IEA, 2025) projects that renewable power capacity will expand rapidly through 2030 and that solar PV will provide most of the added capacity. This global change is driven by lower technology costs, energy-security concerns, climate commitments, and the modularity of solar and storage technologies. It also exposes a second-order challenge: generation capacity alone does not guarantee reliable electricity. Power systems must accommodate variability, new converter dynamics, network congestion, protection changes, data requirements, and increasingly complex operational decisions (Aljarrah et al., 2024; Zhang et al., 2021).

These issues are especially important in Libya. The national electricity sector has historically depended on fossil-fuelled generation and a vertically organized network, while maintenance limitations, fuel availability, damaged infrastructure, and institutional fragmentation have contributed to reliability problems (World Bank, 2017a, 2017b). Renewable deployment therefore has two linked purposes: diversifying primary energy and improving the resilience of electricity services. The second purpose means that projects should be judged not only by annual energy yield, but also by their contribution to adequacy, voltage and frequency performance, reserve needs, maintainability, and recovery from disturbances.

Libya has substantial renewable-resource potential, but resource potential is not equivalent to deployable energy. High irradiation favours PV, while coastal and selected inland corridors may support wind generation. Yet actual yield depends on module temperature, dust deposition, tilt and azimuth, component quality, inverter loading, maintenance, curtailment, and network availability. Maka et al. (2021) identified broad opportunities for PV in Libya while also emphasizing institutional and infrastructure barriers. More recent work has improved the evidence base by comparing measured and satellite solar and wind data and by extending techno-economic and lifecycle analysis across multiple locations (Lagili et al., 2023; Nassar et al., 2024). These studies demonstrate progress, but they also show how limited measurement access constrains national-scale inference.

The thermal and soiling environment is a central design condition. PV output decreases as cell temperature increases, while dust attenuates incident radiation and can generate non-uniform shading. Water cooling can reduce temperature and improve instantaneous electrical output, as demonstrated in hot-climate experiments (Alami, 2014; Bahaidarah et al., 2013). However, cooling gains cannot be interpreted independently of pumping energy, water consumption, treatment, corrosion, reliability, and maintenance. Similarly, cleaning frequency must be optimized rather than maximized because water is scarce and cleaning operations have financial and mechanical costs. Reviews of arid-region PV consistently support site-specific strategies based on measured soiling rates rather than universal schedules (Mani & Pillai, 2010; Said et al., 2018; Shenouda et al., 2022).

The local literature reflects these priorities. Studies have examined PV tilt and azimuth using PVsyst, optimal tilt under Tripoli microclimatic conditions, water cooling of a small module in Benghazi, TiO_2 photoanodes, PV-cell technologies, and solar absorption refrigeration (Assalai & Mohamed, 2025; Awsha et al., 2021; Hamad et al., 2025; Jumaa & Adbar, 2020; Muftah & Alzaaluk, 2025; Shahboun & Adeilla, 2021). Together, they demonstrate active research across resource optimization, materials, and thermal management. Their policy value, however, depends on whether the findings were validated over adequate periods, whether uncertainty and auxiliary energy were considered, and whether the study scale matches the deployment decision.

Wind energy represents a complementary resource because wind and solar profiles can differ temporally. A hybrid portfolio may reduce—but does not eliminate—balancing requirements. Libya-specific wind studies have applied Weibull models, satellite datasets, RETScreen, lifecycle assessment, and power-system simulations. Recent work using one year of measurements to evaluate several satellite products is methodologically stronger than assessments that rely on a single unvalidated data source (Lagili et al., 2023). Nassar et al. (2024) also advanced the field by linking long-term climate data and System Advisor Model simulations with lifecycle boundaries that include manufacturing and transport to Libya. Nevertheless, short local turbine tests and CFD studies remain insufficient for utility-scale bankability, which normally requires traceable measurement campaigns, hub-height extrapolation, uncertainty budgets, wake analysis, and grid studies.

Energy storage changes the value of variable renewable generation. Lithium-ion batteries can shift energy, provide reserves, support voltage and frequency, enable islanded microgrids, and reduce the need for inefficient thermal-unit cycling. The same assets are sensitive to temperature, depth of discharge, charge rate, calendar ageing, and control policy (Edge et al., 2021). Machine-learning studies have demonstrated that early-cycle data can predict battery lifetime under defined laboratory conditions, but performance may degrade under chemistry, duty-cycle, or temperature shifts (Severson et al., 2019). For Libya, high ambient temperature, supply-chain limitations, maintenance capability, fire safety, and spare-parts availability must be included in storage design from the outset.

Digital intelligence is another emerging layer. Artificial neural networks, machine learning, physics-informed neural networks (PINNs), Internet of Things (IoT) sensing, and digital twins can improve forecasting, anomaly detection, state estimation, and predictive maintenance. PINNs embed physical constraints in learning objectives and can reduce physically implausible predictions, but they do not automatically solve poor data quality, model misspecification, or weak validation (Huang & Wang, 2023; Raissi et al., 2019). A local *Albahit* paper reports a PINN applied to telemetry from a solar grid in southern Spain (Almonier, 2025). Its inclusion is relevant to Libyan research capacity, but it should not be misclassified as field evidence from the Libyan grid.

Power quality and grid integration connect these technology domains. Higher shares of converter-interfaced generation change fault currents, system inertia, reactive-power behaviour, and protection coordination. Grid-following converters can become vulnerable in weak systems, while grid-forming controls may support voltage and frequency but introduce new stability and current-limiting questions (Aljarrah et al., 2024; Song et al., 2022; Zhang et al., 2021). Capacitor-switching transients, harmonics, voltage control, and protection should therefore be studied as part of renewable planning, not as separate afterthoughts.

The central gap is not a lack of individual studies; it is the absence of an integrated evidence chain from resource measurement to bankable design, verified operation, grid integration, lifecycle performance, and policy implementation. The local literature is often organized around single devices or simulations, whereas deployment decisions require consistent performance indicators, transparent uncertainty, real operating data, and connections between technical and institutional constraints. This review addresses that gap by critically comparing the verified *Albahit* corpus with international and higher-resolution Libya-specific evidence.

The review asks: (1) which technological developments are most relevant to Libya; (2) how heat, dust, orientation, and cooling affect PV performance; (3) what the present wind evidence can support; (4) what roles storage, electric mobility, hydrogen, and fuel cells may play; (5) how AI and smart-grid methods are being used and validated; (6) which technical, economic, environmental, institutional, and regulatory barriers dominate; and (7) which research priorities can convert promising studies into deployable systems. The novelty lies in separating locally authored research from Libya-based operational evidence, jointly evaluating generation, storage, intelligence, and grid reliability, and translating evidence gaps into a phased implementation framework.

2. Review methodology

2.1 Review design

The study is a **structured critical review**. This design was selected because the core local corpus was predetermined, while the broader evidence was assembled to enable technical comparison and gap analysis rather than to estimate a pooled effect. The technologies, outcomes, scales, and methods are too heterogeneous for meta-analysis: reviewed studies range from materials and component models to field tests, national resource assessments, lifecycle models, and narrative reviews. A statistical pooled estimate would therefore be misleading.

The review is not labelled a systematic review and does not report a PRISMA flow diagram with numerical counts. A defensible PRISMA 2020 report requires record-level exports from named databases, documented duplicate removal, and auditable exclusion decisions. Those materials were not available for the present draft. Figure 1 instead reports the transparent logic of the structured process. The database-specific strategy in Table 1 can be executed and the manuscript upgraded to a systematic review after the authors obtain Scopus and Web of Science exports.

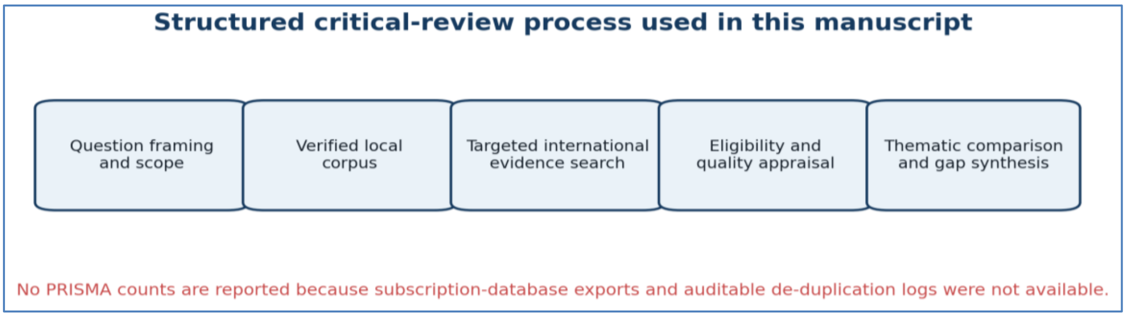

Figure 1. *Structured critical-review process.*

2.2 Information sources and search period

The evidence search was conducted on 20 July 2026. The primary publication window was 2015–2026, with priority given to 2020 onward. Older studies were retained when they established widely used methods or provided foundational hot-climate evidence. archive, publisher pages for peer-reviewed articles, IEEE Xplore, ScienceDirect, SpringerLink, and authoritative institutional reports. Google Scholar was treated as a discovery aid only and was not cited as an evidence source.

2.3 Search strategy

Table 1 provides a reproducible strategy for a later record-level systematic search. Search syntax should be adapted to each database field structure. The final systematic version should export full records and cited references in RIS or BibTeX format, merge them in a reference manager, and preserve a de-duplication log.

Table 1. Database-specific search strategy.

Source	Fields	Search string (abridged but executable)	Filters
Scopus	TITLE-ABS-KEY	(renewable energy OR photovoltaic OR solar energy OR wind energy OR energy storage OR smart grid) AND (Libya OR North Africa OR arid) AND (efficien* OR reliab* OR performance OR integration)	2015–2026; article/review/conference; English/Arabic
Web of Science Core Collection	TS	Same concepts using TS= and NEAR/x where appropriate	2015–2026; engineering/energy/environment
IEEE Xplore	Metadata	(smart grid OR power-system reliability OR inverter OR physics-informed neural network OR battery management) AND (Libya OR arid OR renewable)	Journals and major conferences; 2015–2026
Science Direct	Title/abstract/keywords	(photovoltaic OR wind OR storage OR hydrogen) AND (hot climate OR dust OR Libya OR North Africa)	Research/review; 2015–2026
Springer Link	Title	(PV cooling OR soiling OR wind assessment OR hybrid renewable OR PINN) AND (arid OR Libya OR MENA)	Article/review; 2015–2026
Albahit archive	Full archive search	photovoltaic; solar; wind; battery; electric vehicle; neural network; smart grid; fuel cell; overvoltage; superconduct*	2020–2026; verify article

			page and PDF

2.4 Eligibility criteria

Table 2. Inclusion and exclusion criteria

Domain	Inclusion	Exclusion
Topic	Solar, wind, storage, EVs, hybrid vehicles, smart grids, AI, power quality, hydrogen, fuel cells, or relevant policy	Unrelated engineering or general energy commentary
Geography	Libya; comparable arid/MENA climates; internationally transferable technology evidence	No plausible technical or policy relevance to Libya
Evidence	Peer-reviewed article, rigorous review, major conference paper, standard, or authoritative institutional report	News, marketing material, unverifiable manuscripts, retracted work
Methods	Sufficient description of data, experiment, model, review process, or analytical framework	Claims without traceable methods or sources
Language	English or Arabic	Other languages without reliable translation
Date	Mainly 2015–2026; older foundational work permitted	Older descriptive work superseded by stronger evidence

2.5 Screening and bibliographic verification

Each core local reference was checked against the official journal article or issue page. Author lists, titles, year, volume, issue, pages, and DOI were corrected where verifiable. The process identified three recurrent problems in the supplied list: omitted co-authors, missing volume/issue information, and inconsistent page or DOI metadata. Table 3 records corrections rather than silently reproducing inaccurate references. International sources were retained when their bibliographic details could be verified through a publisher, DOI record, university repository, or authoritative institution.

2.6 Data extraction and synthesis

For each study, the extraction framework covered author/year, geography, technology, objective, study type, data source, software or test method, climatic conditions, performance metrics, main contribution, limitations, and relevance to Libya. The synthesis used five linked questions: **what was tested; under which conditions; against what benchmark; with what uncertainty; and at what technology-readiness level?** Narrative synthesis was used because technologies and outcomes were heterogeneous.

2.7 Quality appraisal

Nine domains were scored 0 (not reported/inadequate), 1 (partial), or 2 (clear/adequate): objective clarity, method appropriateness, data adequacy, reproducibility, measurement reliability, model validation, statistical/uncertainty treatment, limitation transparency, and relevance to the review question. Total scores of 14–18 were classified high, 9–13 moderate, and 0–8 low. The score is an appraisal for this review, not a judgment of research integrity or journal quality.

Table 3. Bibliographic verification of the core local corpus.

Supplied item	Verified correction	DOI/status	Verification note
Assalai & Mohamed (2025)	4(2), 66–79	10.65419/albahit.v4i2.83	Verified
Hamad et al. (2025)	4(1), 269–276	10.65419/albahit.v4i1.63	Verified
Muftah & Alzaaluk (2025)	4(1), 361–372	10.65419/albahit.v4i1.76	Verified
Almonier (2025)	4(1), 182–194	10.65419/albahit.v4i1.56	Verified; field data described as southern Spain, not Libya
Awsha et al. (2021)	2(2), 9–16	10.65419/albahit.v2i2.27	Verified
Shahboun & Adeilla (2021)	2(1), 13–18	No DOI displayed	Verified author names/pages
Jumaa (2020)	Add co-author Shukri Adbar; 1(1), 63–67	No DOI displayed	Supplied reference omitted co-author
Khaleel & Ali (2025)	Second author: Taha Muftah Abu Ali; 4(1), 9–17	Article page shows 10.65419/albahit.v4i1.38	Issue metadata has shown an inconsistency; article DOI retained
Elsheikhi et al. (2025)	4(1), 28–40	No DOI displayed	Verified
Basher & Hamdan (2022)	3(1), 6–9	No DOI displayed	Verified
Alsharif (2025)	4(1), 1–8	No DOI displayed	Verified
Said & Ahmed (2021)	2(1), 24–29	No DOI displayed	Verified
Khalifa & Alatai (2026)	5(1), 126–140	10.65419/albahit.v5i1.122	Verified
Ammar & Abuzaid (2020)	Add co-author Almbrok A. Emhemed; 1(1), 51–55	No DOI displayed	Supplied reference omitted co-author

Supplied item	Verified correction	DOI/status	Verification note
Sghayer et al. (2020)	1(1), 12–18	No DOI displayed	OJS metadata says 12–18; accessible PDF has shown inconsistent pagination
Barnos (2025)	4(1), 300–308	10.65419/albahit.v4i1.67	Verified article; issue archive contains overlapping page metadata

Table 4. Quality-assessment framework

Domain	0	1	2
Objective	Absent/unclear	Broad	Specific and testable
Method	Inappropriate/undocumented	Partly justified	Appropriate and justified
Data	Insufficient/unknown	Limited	Adequate for inference
Reproducibility	Cannot reproduce	Partial details	Data/code/protocol sufficient
Measurement reliability	Not addressed	Basic instrumentation	Calibration/quality control reported
Validation	None	Internal or limited	Independent/external/field validation
Statistics/uncertainty	None	Basic summaries	Uncertainty and robust inference
Limitations	Not discussed	Generic	Specific and consequential
Relevance	Peripheral	Indirect	Directly answers review question

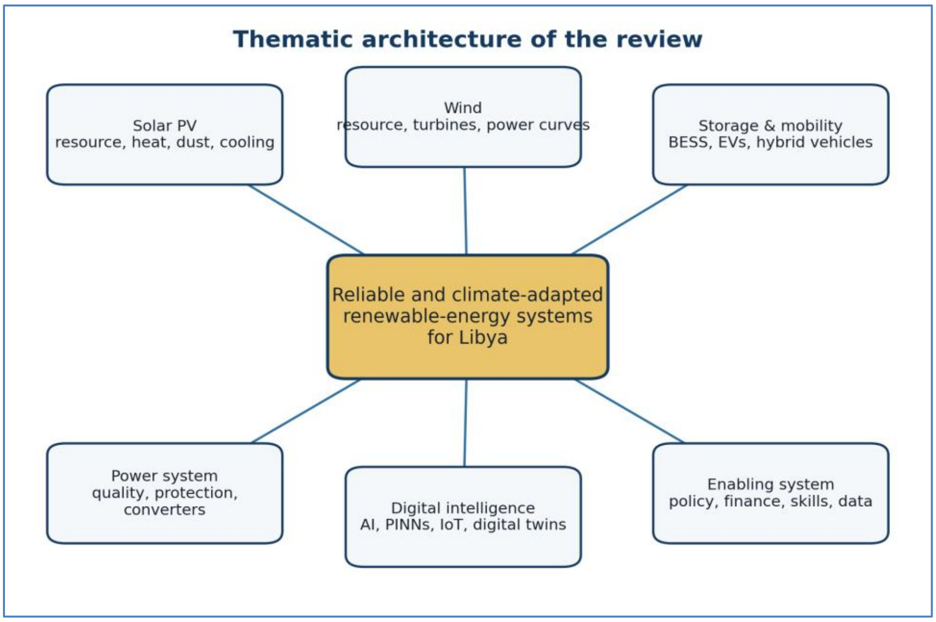

Figure 2. *Thematic architecture of the review.*

3. Global transition and the Libyan decision context

The global transition provides Libya with mature generation hardware but not a ready-made implementation model. Solar PV, onshore wind, and lithium-ion storage are commercially established, yet their performance and system value are location-specific. The relevant unit of analysis is therefore not the isolated module, turbine, or battery. It is the service delivered by an integrated asset under local climatic, network, institutional, and maintenance conditions. This distinction is central in Libya, where high-quality resources coexist with weak data continuity, constrained infrastructure, and uncertain procurement and operating arrangements.

Three decision scales must be separated. At the **component scale**, temperature coefficients, soiling, cooling, aerodynamics, converter control, and degradation determine technical performance. At the **project scale**, availability, auxiliary consumption, replacement schedules, logistics, financing, curtailment, and connection costs determine lifetime value. At the **system scale**, capacity adequacy, ramping, reserves, protection, network constraints, fuel savings, resilience, and institutional capability determine whether a portfolio improves electricity service. Many local studies provide useful component-scale insight but are not designed to answer project- or system-scale questions.

The electricity-sector reform work commissioned by the World Bank (2017a, 2017b) underscores the need for strategic planning, clearer technical rules, investment sequencing, and operational reform. Renewable deployment should be embedded in that wider program. Distributed PV may reduce daytime net load at selected feeders, but unmanaged inverters can create voltage or reverse-flow problems. Utility-scale wind can diversify output profiles, but a plant with poor road access, weak spare-parts support, or an unresolved interconnection study will not deliver its modelled annual energy. Batteries can provide several grid services, but stacking those services requires dispatch rules, metering, warranties, and accountable operators.

A robust Libyan strategy should consequently be **portfolio-based and staged**. Near-term investment should emphasize PV and targeted hybrid microgrids where demand, network constraints, and operational responsibility are well characterized. Wind development should proceed through bankable measurement and staged demonstration at priority sites. Storage should be sized around explicit services rather than added generically to renewable projects. Digital systems should first improve observability, data quality, forecasting, and maintenance;

advanced AI should follow only when baseline data and operational processes can support it. Emerging options such as green hydrogen and superconducting technologies should remain research or pilot topics until their system case, water requirements, infrastructure, and economics are demonstrated.

4. Solar photovoltaic technologies and thermal management

4.1 Technology development and local manufacturing potential

Assalai and Mohamed (2025) review PV operating principles, cell families, performance, and manufacturing potential in Libya. The paper is valuable as a local technology overview and as a prompt for industrial-policy discussion. Its conclusions should, however, be separated into different levels of feasibility. Module assembly, mounting structures, cables, enclosures, cleaning equipment, and balance-of-system services present a different industrial challenge from upstream polysilicon, wafer, cell, or advanced thin-film manufacturing. A credible localization plan requires scale, quality assurance, reliable utilities, access to inputs, certification, warranty capability, and an export or sufficiently large domestic market. The evidence reviewed here supports progressive localization of balance-of-system and service activities more strongly than an immediate full-cell manufacturing chain.

Awsha et al. (2021) examine TiO_2 photoanodes for solar applications. The review highlights materials engineering pathways relevant to dye-sensitized or related devices, including morphology, transport, and surface modification. Such work is scientifically useful but has limited direct bearing on near-term Libyan electricity planning because commercial deployment depends on long-duration stability, encapsulation, manufacturing yield, standardized testing, and cost at module scale. The appropriate bridge is not to dismiss materials research, but to connect it to outdoor degradation protocols and clearly defined technology-readiness milestones.

4.2 Orientation, resource modelling, and climatic transferability

Jumaa and Adbar (2020) used PVsyst to assess tilt and azimuth effects in Al Khums and reported a south-facing configuration near 30° as favourable within the tested design space. Muftah and Alzaaluk (2025) similarly addressed tilt optimization under Tripoli microclimatic conditions. These studies provide useful first-order design guidance, particularly for fixed arrays. A single annual optimum, however, should not be converted into a national rule. Optimal geometry varies with latitude, horizon, diffuse fraction, albedo, array-row spacing, cleaning strategy, load profile, tariff, and whether the objective is annual yield or seasonal capacity value.

Model results are also only as reliable as their inputs. Typical meteorological-year data can support feasibility analysis, but bankable design benefits from local sensor quality control, interannual variability, and validation against measured plane-of-array irradiance and delivered AC energy. Lagili et al. (2023) illustrate a stronger validation logic by comparing multiple satellite products with a year of measurements before using longer time series. Future Libyan PV studies should publish sensor class, calibration, sampling interval, missing-data treatment, shading assessment, and uncertainty. They should also distinguish DC yield, AC yield, performance ratio, availability, curtailment, and self-consumption.

4.3 Heat, water cooling, and net benefit

Hamad et al. (2025) tested water cooling on a 50 W polycrystalline module in Benghazi. The reported average temperature reduction of about 3 °C and improvement in peak power of approximately 8% indicate that cooling can improve instantaneous performance under the tested conditions. The result is directionally consistent with hot-climate experiments by Bahaidarah et al. (2013), Alami (2014), Bevilacqua et al. (2020), and Hadipour et al. (2021). It should nevertheless be interpreted as a pilot result, not a universal annual-energy gain.

The decision variable is net lifetime benefit:

$$E_{net}=E_{PV,cool}-E_{pump}-E_{treatment}-E_{control},$$
with economic and environmental evaluation also including water consumption, equipment cost, maintenance, leakage, scaling, corrosion, and replacement. A cooling system that raises midday output but consumes scarce potable water or fails frequently may be inferior to passive ventilation, higher-efficiency modules with favourable temperature coefficients, altered DC/AC sizing, or selective cleaning. Future experiments should include an uncooled randomized or well-matched control, continuous irradiance and backsheet/cell-temperature measurements, flow and pump power, water quality, uncertainty, and at least seasonal operation.

4.4 Soiling, cleaning, and degradation

Soiling is likely to be one of the most consequential PV operating variables in Libya, yet the core local corpus does not provide a multi-site, multi-year soiling dataset. International evidence shows that deposition and loss are shaped by particle size and composition, humidity, wind, tilt, rainfall, surface properties, and cleaning history (Mani & Pillai, 2010; Said et al., 2018; Sayyah et al., 2014; Shenouda et al., 2022). Average regional loss factors should therefore not replace site measurement.

The preferred research design combines paired clean/soiled reference devices, rainfall and particulate observations, image or transmittance measurements, and a logged cleaning protocol. Cleaning should be triggered by an economic or reliability threshold, not a fixed calendar alone. Waterless or low-water cleaning deserves evaluation, but abrasion, labour, robotics reliability, energy consumption, and warranty implications must be measured. Degradation analysis should separate reversible soiling loss from irreversible module, encapsulant, interconnect, and inverter ageing (Jordan et al., 2016).

4.5 Solar thermal and refrigeration applications

Shahboun and Adeilla (2021) modelled a modified ejector in an NH_3/H_2O solar absorption refrigeration system. This line of work is relevant to cooling-dominated demand, cold chains, and remote applications because it couples solar availability with thermal loads. Its deployment case depends on collector performance, safe handling, part-load behaviour, water availability, parasitic electricity, and maintenance capability. Field demonstrations should compare the proposed cycle with efficient vapour-compression cooling supplied by PV and storage on equal service, cost, and reliability boundaries.

Table 5. Critical appraisal of core solar studies

Study	Method and scale	Main contribution	Key limitation	Review score / quality	Deployment relevance
Assalai & Mohamed (2025)	Narrative technology review	Connects PV principles and manufacturing discussion to Libya	No plant-level industrial feasibility or supply-chain model	9/18, moderate	Industrial-roadmap hypothesis
Hamad et al. (2025)	Water-cooled 50 W module; short field observations	Demonstrates thermal and electrical response in Benghazi	Small scale; annual net energy, water, pump load, and uncertainty not established	12/18, moderate	Pilot evidence requiring seasonal replication

Study	Method and scale	Main contribution	Key limitation	Review score / quality	Deployment relevance
Muftah & Alzaaluk (2025)	Tilt optimization for Tripoli microclimate	Site-oriented fixed-array design guidance	Input validation and interannual transferability are limited	9/18, moderate	Preliminary design input
Awsha et al. (2021)	TiO_2 photoanode review	Summarizes materials-development routes	Not a deployment or outdoor durability study	9/18, moderate	Long-term research capacity
Shahboun & Adeilla (2021)	Solar absorption-refrigeration model	Explores ejector modification for thermal cooling	Field validation and equal-service comparison absent	10/18, moderate	Niche demonstration candidate
Jumaa & Adbar (2020)	PVsyst tilt/azimuth sensitivity in Al Khums	Indicates south-facing, near-30° geometry within model	Coarse angular steps and no operational-energy validation	8/18, low	Screening-level guidance

5. Wind-energy evidence and hybrid systems

5.1 Resource assessment and bankability

Wind development requires a stricter measurement chain than resource screening. Reanalysis and satellite data are useful for locating candidates and characterizing long-term variability, while bankable energy assessment requires traceable on-site measurements, documented mast or lidar configuration, sensor calibration, data recovery, flow modelling, hub-height extrapolation, extreme-wind assessment, wake modelling, losses, and an uncertainty-based exceedance estimate. Weibull distributions can summarize wind-speed frequency, but their fit and parameter method should be validated rather than assumed (Wais, 2017).

Lagili et al. (2023) improve the Libyan evidence base by comparing measured solar and wind observations with five satellite products and then extending analysis over a longer period. Nassar et al. (2024) evaluate twelve Libyan locations using long-term SolarGIS inputs and System Advisor Model simulations, adding lifecycle and carbon-footprint boundaries. These studies are stronger for national screening than isolated short tests because they connect long-term resource, technology choice, and project outputs. They still do not replace site-specific pre-construction campaigns and network studies.

5.2 Local turbine and aerodynamic studies

Elsheikhi et al. (2025) compared a 1 kW turbine's manufacturer information with observations at the Benghazi Solar Radiation Center. The reported maximum of 555.81 W at 9 m/s, compared with 584 W on the referenced curve, usefully demonstrates that local output can differ from nominal performance. The test also reveals the limits of small-turbine evidence: instantaneous wind speed may not represent rotor-equivalent wind speed; turbulence, air density, yaw error, electrical loading, sensor placement, and averaging conventions affect the curve. IEC-consistent power-curve testing over adequate wind bins would strengthen inference.

Basher and Hamdan (2022) used computational fluid dynamics to examine guide-vane tilt for a Savonius rotor. CFD is valuable for screening geometries and explaining flow mechanisms, especially for low-speed or built-environment concepts. Results depend on domain size, mesh independence, turbulence model, boundary conditions, time step, blockage, and experimental validation. Savonius devices may be appropriate for specific low-power applications, but their lower aerodynamic efficiency and structural loading mean that national wind-energy conclusions should not be drawn from a single rotor simulation.

5.3 Solar–wind–storage integration

Khaleel and Abu Ali (2025) synthesize experimental evidence on efficiency and reliability across solar, wind, and storage. The cross-technology framing is appropriate because hybridization can smooth aggregate profiles and share infrastructure. However, meta-study claims require an explicit search strategy, study comparability, effect definitions, heterogeneity treatment, and sensitivity analysis. Without these elements, numerical aggregation can create false precision.

Hybrid design should be based on coincident time series rather than separate annual capacity factors. Hourly or sub-hourly load, PV, wind, outage, and network constraints should feed capacity-expansion and dispatch models. Outputs should include loss of load probability or expected energy not served, renewable curtailment, thermal-unit starts, fuel use, storage cycling, replacement, and cost under uncertainty. Bhimaraju and Mahesh (2024) show the breadth of control and optimization methods available, but Libya-focused models require transparent local inputs and should test robustness to fuel-price, demand, and component-replacement uncertainty.

Table 6. Critical appraisal of core wind and hybrid-system studies

Study	Method and scale	Main contribution	Key limitation	Review score / quality	Appropriate use
Khaleel & Abu Ali (2025)	Cross-technology meta-study	Frames efficiency and reliability jointly	Search, comparability, and heterogeneity reporting are limited	9/18, moderate	Hypothesis and indicator selection
Elsheikhi et al. (2025)	Small 1 kW turbine observations and curve comparison	Shows gap between catalogue and local performance	Limited turbine scale, wind bins, and campaign detail	11/18, moderate	Instrumentation and pilot-test design
Basher & Hamdan (2022)	CFD of Savonius guide-vane tilt	Identifies aerodynamic sensitivity to configuration	Experimental validation and scale-up evidence absent	8/18, low	Exploratory rotor optimization
Lagili et al. (2023)	One-year measured comparison plus satellite time series	Tests several remote products against local observations	One measured year and farm-use case do not establish all sites	14/18, high	Regional screening and data-product selection

Study	Method and scale	Main contribution	Key limitation	Review score / quality	Appropriate use
Nassar et al. (2024)	Twelve-site long-term simulation and lifecycle assessment	Integrates energy yield, carbon, manufacturing, and transport	Model-dependent; site-specific bankability still required	15/18, high	National prioritization and lifecycle framing

6. Energy storage, electric mobility, and hybrid vehicles

6.1 Battery degradation and climate

Alsharif (2025) reviews published experimental results on electric-vehicle battery performance, charging, and degradation. The study correctly places degradation at the centre of mobility and storage economics. Transfer to Libya requires care because laboratory datasets frequently cover particular cell formats, chemistries, temperature windows, and cycling protocols. High ambient temperature accelerates several ageing mechanisms, while aggressive fast charging can increase lithium plating risk under particular conditions (Attia et al., 2020; Edge et al., 2021). Thermal management is therefore a safety, warranty, and capacity-retention function rather than a minor auxiliary load.

Battery analytics have progressed from equivalent-circuit estimation to data-driven lifetime prediction and joint state estimation. Early-cycle features can predict life within the domain represented by the training data (Severson et al., 2019), and machine-learning methods can support state-of-charge and state-of-health estimation (Ng et al., 2020). Yet cross-chemistry and cross-climate generalization is not assured. A Libyan program should test locally relevant temperature, charging access, driving duty cycles, grid outages, and stationary service profiles. Datasets should include cell and pack temperature, current, voltage, balancing, charge throughput, depth of discharge, calendar time, faults, and maintenance.

6.2 Storage as a power-system asset

Stationary batteries should be procured against defined services: renewable smoothing, peak reduction, contingency reserve, black start, voltage support, diesel displacement in microgrids, or deferral of a constrained network upgrade. A single asset can sometimes stack services, but incompatible state-of-charge requirements and warranty limits must be resolved in the dispatch policy. Sizing solely from renewable nameplate capacity is inadequate.

For Libya, early projects should favour bounded operational environments where responsibility and value can be measured: hospital or water-facility microgrids, remote telecom or community systems, university campuses, and constrained distribution feeders. Each pilot should have a baseline, service-level indicators, fire detection and suppression design, isolation procedures, spare parts, trained operators, cybersecurity controls, and a decommissioning route. Lifetime models should be updated with field degradation rather than treated as fixed input assumptions.

6.3 Hybrid-electric vehicle power management and vehicle–grid interaction

Said and Ahmed (2021) used MATLAB/Simulink to investigate a power-split strategy for a series hybrid electric vehicle. Simulation is appropriate for developing supervisory control and comparing energy flows, but results depend on drive-cycle representativeness, component maps, battery model, thermal constraints, and validation. Libyan mobility research should incorporate hot-weather air-conditioning demand, congestion, road conditions, vehicle age, charging availability, and fuel and electricity supply interruptions.

Vehicle-to-grid operation may provide flexibility, but it is not free energy. It changes cycling, user availability, charger requirements, metering, communication, and warranty exposure. Uddin et al. (2017) demonstrate that intelligently managed grid services can under some conditions avoid or offset harmful use, yet the outcome is policy- and duty-cycle-dependent. Near-term priorities are interoperable charging standards, distribution-hosting studies, managed charging, consumer protection, and fleet pilots with predictable dwell times. Broad V2G deployment should follow measured evidence.

Table 7. Storage and electric-mobility evidence

Study	Evidence type	Strength	Limitation	Review score / quality	Libya-specific next test
Alsharif (2025)	Meta-study of published battery experiments	Brings performance, charging, and degradation together	Secondary data heterogeneity and limited local conditions	9/18, moderate	Hot-climate pack and charging dataset
Said & Ahmed (2021)	Series-hybrid control simulation	Demonstrates power-split modelling workflow	No vehicle or hardware-in-loop validation reported	9/18, moderate	Local drive cycles and thermal validation
Edge et al. (2021)	International mechanism-focused review	Strong synthesis of degradation pathways	Not a Libyan operating study	High external evidence	Translate mechanisms into procurement tests
Severson et al. (2019)	Laboratory data-driven life prediction	Shows value of early-cycle features	Domain shift limits direct transfer	High external evidence	External validation on local chemistries/duty cycles
Attia et al. (2020)	Closed-loop fast-charge optimization	Demonstrates efficient protocol search	Controlled cells and objectives differ from fleet operation	High external evidence	Safety-constrained, pack-level hot-climate trial

7. Artificial intelligence, IoT, and smart grids

7.1 What AI can and cannot solve

AI can add value when a decision is repeated, measurable, and connected to action. Relevant applications include solar and wind forecasting, load prediction, fault classification, battery-state estimation, non-technical-loss detection, predictive maintenance, optimal dispatch, and asset inspection. The essential sequence is **measurement → validated model → operational decision → monitored outcome**. A high predictive score without a defined decision or baseline has little system value.

PINNs add governing equations, conservation relationships, or engineering constraints to the learning process (Raissi et al., 2019). In power systems they have been proposed for dynamic simulation, state estimation, and parameter inference (Huang & Wang, 2023). Their attraction in data-scarce settings is understandable, but physics constraints do not compensate for incorrect topology, unobserved disturbances, biased measurements, or a poorly posed objective. PINNs also face optimization, scaling, stiffness, and uncertainty-calibration challenges.

Almonier (2025) reports a PINN for energy-dissipation pathways using telemetry from a 12.4 MWp smart solar grid in southern Spain. The study is relevant to methods that Libyan researchers could adapt, but its dataset is not Libya-based. Reproduction requires clear equations, architecture, training protocol, baselines, split strategy, hyperparameters, code or sufficient detail, and testing under distribution shift. A Libyan validation should begin with simpler physical and statistical baselines and evaluate forecast error, constraint violations, runtime, robustness, and decision benefit.

7.2 From neural-network identification to operational digital twins

Ammar et al. (2020) applied artificial neural-network techniques to identify DC motor-drive systems. This is a relevant precursor to data-driven control and asset modelling. The work would become more operationally valuable through excitation-design reporting, comparison with conventional identification, noise tests, stability constraints, and hardware validation.

Digital twins go beyond a static model by maintaining a structured link between a physical asset, data, models, and decisions (Fuller et al., 2020). For the Libyan power sector, the first useful twins are likely to be narrow: a PV plant with soiling and inverter diagnostics, a battery microgrid with degradation-aware dispatch, or a substation model that ingests switching and disturbance records. Building a national "digital twin" before asset registers, time synchronization, telemetry quality, topology, and data governance are reliable would add complexity without dependable insight.

7.3 Data governance, cybersecurity, and responsible deployment

Smart grids enlarge the cyber-physical attack surface. Remote controls, smart inverters, advanced meters, charging infrastructure, and cloud analytics create dependencies on identity management, communications, software updates, vendor access, and incident response. Cybersecurity should be designed into pilots through network segmentation, least-privilege access, authenticated updates, logging, backups, manual fallback, and vulnerability management. AI governance should also address model versioning, human override, drift monitoring, auditability, and protection of customer or infrastructure data.

Open research data are essential but should not mean unrestricted publication of sensitive network details. A tiered architecture can publish cleaned resource and performance datasets while protecting personally identifiable information, precise vulnerability information, and critical operational configurations. Universities, utilities, regulators, and project developers should agree common metadata, data-quality flags, licences, and retention rules.

Table 8. AI and smart-grid evidence and validation requirements

Study/application	Claimed or plausible value	Evidence concern	Review score / quality	Minimum validation for Libya
Almonier (2025), solar-grid PINN	Physically constrained prediction of dissipation pathways	Spain-based telemetry; transfer, reproducibility, and uncertainty need testing	10/18, moderate	Open protocol; physical/statistical baselines; out-of-sample Libyan plant

Study/application	Claimed or plausible value	Evidence concern	Review score / quality	Minimum validation for Libya
Ammar et al. (2020), ANN motor identification	Nonlinear system identification for control	Limited hardware, noise, and stability evidence	10/18, moderate	Hardware test and conventional-identification benchmark
Huang & Wang (2023), PINN review	Organizes power-system applications and challenges	Review evidence, not operational proof	High external evidence	Application-specific benchmark and constraint audit
Battery-state ML	Faster or more accurate state estimation	Chemistry and climate domain shift	Application-dependent	Cross-season, cross-pack external validation
Digital-twin maintenance	Earlier fault detection and decision support	Often ambiguous scope and weak causal benefit evidence	Application-dependent	Registered asset, synchronized data, intervention baseline, cyber controls

8. Power quality, protection, and converter-dominated grids

Renewable integration changes both steady-state and dynamic network behaviour. Voltage rise, reactive-power demand, harmonics, flicker, unbalance, reverse power flow, and thermal loading can appear at distribution level. At transmission and system level, reduced synchronous inertia, weak-grid interactions, converter control coupling, frequency response, and fault-current limitations become important. The appropriate study sequence is feeder and system data validation, scenario definition, load flow, short circuit, harmonic and protection analysis, dynamic simulation, controller or relay testing, and staged commissioning.

Khalifa and Alatai (2026) model capacitor-switching overvoltages. Although the study is not a renewable-energy experiment, it is directly relevant because reactive-compensation devices, cables, filters, transformers, and converters can interact during switching. Model credibility depends on component frequency dependence, closing-angle variability, trapped charge, breaker behaviour, grounding, and comparison with disturbance recordings or controlled tests. The study receives a moderate quality score (11/18) in this review: it provides a useful modelling basis, but system-specific validation is needed before settings or equipment ratings are changed.

Grid-following converters regulate current relative to a measured grid voltage and can face synchronization or control problems in weak systems. Grid-forming converters establish a voltage/frequency reference and can contribute fast frequency and voltage support, but their protection behaviour, current limiting, control interactions, and fault recovery require careful testing (Song et al., 2022; Zhang et al., 2021). Libya should avoid adopting a control label as a substitute for performance requirements. Grid codes should specify measurable capabilities, test procedures, ride-through, reactive power, frequency response, model delivery, and compliance monitoring.

Protection modernization should proceed with renewable connection studies. Lower and control-dependent converter fault currents can reduce the reliability of overcurrent schemes, while bidirectional flows can invalidate coordination assumptions. Pilot studies should use validated network models and, for critical controllers, controller- or power-hardware-in-the-loop testing. Wide-area or adaptive protection may eventually add value, but basic asset data, relay-setting governance, time synchronization, and disturbance recording are prerequisites.

9. Emerging technologies: fuel cells, hydrogen, and superconductors

Sghayer et al. (2020) modelled the influence of catalyst-layer composition on polymer-electrolyte-membrane fuel-cell performance using a percolation-based approach. The study identifies an important design trade-off: catalyst-layer composition affects reaction sites, transport pathways, conductivity, water management, and cost. Its review score is 11/18 (moderate) because it offers a technically relevant model but requires experimental polarization, impedance, durability, and parameter-sensitivity validation. For Libya, fuel cells should be assessed as part of an energy chain rather than as a stand-alone source. Hydrogen production, compression or conversion, storage, transport, stack efficiency, degradation, heat recovery, water, safety, and end-use value all affect the case.

International reviews identify hydrogen as a potential link among variable electricity, industry, transport, seasonal storage, and export markets, but also stress conversion losses, infrastructure, and the importance of the production pathway (Staffell et al., 2019; Yue et al., 2021). Libya may possess strategic advantages in renewable resources, geography, and existing energy-sector skills. These advantages are hypotheses to be tested, not proof of competitiveness. A green-hydrogen pilot should report the source and quality of water, desalination and compression energy, hourly renewable matching, electrolyser loading and degradation, storage, delivered cost, lifecycle emissions, safety case, and the value of the target product. Direct electrification should remain the comparator wherever it can deliver the same service.

Barnos (2025) reviews high-temperature superconductors and their applications. The topic is relevant to future cables, machines, magnetic systems, and fault-current limiters. The article receives 7/18 (low) for deployment inference because it is a broad review without a Libya-specific engineering or economic case. Superconducting applications require cryogenic systems, high reliability, specialized maintenance, and a compelling density or loss advantage. They should remain a horizon-scanning research area rather than a near-term pillar of Libya's renewable strategy.

10. Comparison of local and international evidence

The local corpus is strongest as an agenda-setting body of work. It identifies relevant problems—PV temperature, orientation, wind-curve mismatch, battery degradation, intelligent models, switching transients, and fuel-cell materials—and demonstrates local analytical capacity. It is weaker as a basis for national deployment because many studies are reviews, simulations, or short experiments; dataset and code availability are uncommon; uncertainty is rarely a central output; and external or operational validation is limited.

Stronger international evidence differs less in topic than in **evidence architecture**. High-value studies define a protocol, preserve temporal resolution, quantify uncertainty, validate models outside the training or calibration set, state system boundaries, and connect outcomes to decisions. Libya-specific studies by Lagili et al. (2023) and Nassar et al. (2024) move in this direction through measured-data comparison and lifecycle boundaries. The next step is a coordinated national evidence infrastructure that allows multiple researchers to reuse quality-controlled measurements rather than repeatedly building isolated small datasets.

Table 9. Local–international comparison and transfer conditions

Theme	Core local evidence	Stronger comparator practice	Transfer condition for Libya
PV orientation	Site simulations and microclimate optimization	Measured plane-of-array and AC-yield validation across seasons	Publish input provenance, uncertainty, horizon, soiling and curtailment
PV cooling	Small module and short observations	Controlled seasonal trials with flow, auxiliary power, water, and economics	Report net energy and water productivity, not temperature alone
PV soiling	Recognized but weakly measured in core corpus	Paired sensors, deposition/meteorology, cleaning experiments	Multi-site open soiling network and standardized protocol
Wind	Small-turbine curve and CFD; growing resource studies	Bankable hub-height campaigns and uncertainty-based yield	Met mast/lidar, long-term correction, wakes, extremes, grid access
Storage/EVs	Reviews and power-management simulation	Pack/fleet field data, degradation-aware optimization, safety testing	Local duty cycles, hot climate, warranties, fire and end-of-life plans
AI/PINNs	Promising identification and prediction models	Reproducible baselines, external validation, drift and uncertainty tests	Local operational dataset, model governance, cyber controls
Grid integration	Individual transient and converter topics	Validated network models, hardware-in-loop, compliance testing	Grid-code requirements, relay governance, disturbance recorders
Hydrogen/fuel cells	Component modelling and broad opportunity	Full-chain efficiency, lifecycle, water, safety and offtake analysis	Pilot only after equal-service comparison and bankable offtake

11. Research gaps

11.1 Data and reproducibility

The largest cross-cutting gap is not a missing algorithm; it is the absence of sustained, quality-controlled, reusable data. Resource measurements, asset registers, topology, outages, power quality, inverter alarms, maintenance, battery cycling, and project costs are fragmented or unavailable. Studies consequently depend on default software inputs, limited campaigns, or external datasets. Reproducibility is also constrained when code, model parameters, sampling intervals, missing-data rules, or calibration records are not reported.

The remedy is a federated energy-data program with common metadata and governance. A minimum public layer should include meteorology, irradiance, wind, aggregated load, and anonymized renewable-performance data. A protected operational layer can serve utilities, regulators, and approved researchers. Every funded pilot should include a data-management plan, calibration schedule, data-quality flags, and a publication package.

11.2 Technical and environmental gaps

Long-duration PV studies must integrate heat, soiling, cleaning, corrosion, salt exposure near the coast, inverter reliability, cable and connector faults, and degradation. Wind research needs multi-year campaigns, extremes, turbulence, wakes, availability, and logistics. Storage studies need thermal propagation safety, auxiliary loads, degradation, spares, and disposal or second-life pathways. Grid models need validation against measured disturbances. Environmental studies should assess land, biodiversity, water, materials, end of life, and cumulative—not merely project-by-project—impacts.

11.3 Economic and institutional gaps

Levelized cost is useful but insufficient. Reliability benefits, fuel savings, capacity contribution, curtailment, network upgrades, financing, foreign-exchange exposure, availability, and replacement risk should be represented. The institutional questions are equally consequential: who owns and operates the asset, who pays for balancing, how connection queues are managed, how performance is verified, how land and permits are secured, and what happens if a vendor exits. Bankability requires stable procurement rules, transparent risk allocation, credible offtake, and enforcement.

Table 10. Research-gap map and evidence needed

Gap	Present evidence maturity	Decision consequence	Evidence needed	Priority
Multi-site solar/soiling records	Low–moderate	Yield and cleaning OPEX remain uncertain	≥2 years of standardized monitoring across coastal/inland/desert climates	Immediate
Bankable wind measurements	Low–moderate	Financing and turbine choice remain uncertain	Hub-height met mast/lidar, long-term correction, extremes and uncertainty	Immediate
Storage field performance	Low	Sizing, safety and lifetime value uncertain	Instrumented microgrids and feeder pilots with degradation and incidents	Immediate
Validated network model	Low	Connection limits and protection risks poorly quantified	Asset/topology audit, state-estimation checks, disturbance validation	Immediate
AI reproducibility	Low	Accuracy claims may not transfer to operation	Data cards, baselines, code/protocol, external and drift tests	High
Techno-economic and lifecycle integration	Moderate but fragmented	Projects may optimize energy while externalizing system cost	Common scenarios, probabilistic finance, LCA and water accounting	High
Cybersecurity and data governance	Low	Digitalization may introduce unmanaged risk	Architecture, roles, incident exercises, supplier and update controls	High

Gap	Present evidence maturity	Decision consequence	Evidence needed	Priority
Workforce and supply chains	Low	Availability and warranties may fail after commissioning	Skills inventory, certification, spares and service-market study	High

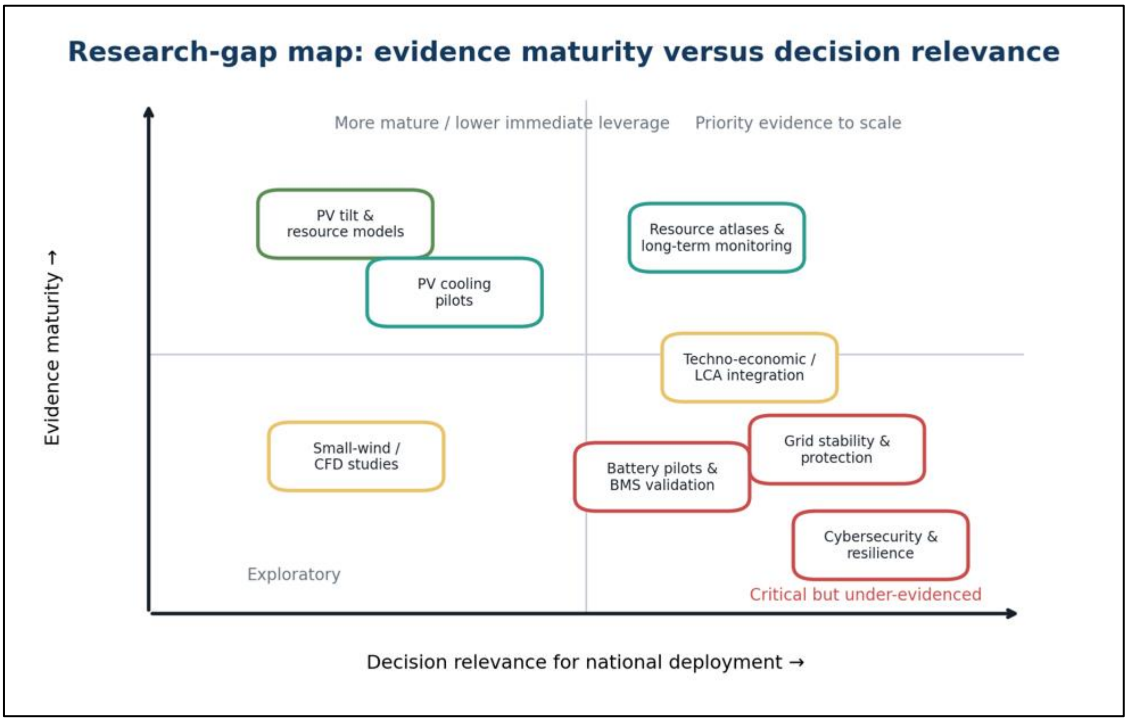

Figure 3. ***Research-gap map.***

12. Integrated conceptual framework

Figure 4 organizes the findings as an integrated development framework. Solar, wind, and longer-duration options form the supply layer. A digital energy hub coordinates forecasting, dispatch, battery management, power-quality control, maintenance, and cybersecurity. Electricity and energy services flow to utilities, industry and desalination, cities and remote loads, and mobility. The entire structure rests on regulation, finance, standards, open but governed data, workforce capability, and university–industry collaboration.

The hub is a functional concept, not a proposal for a single centralized platform. Functions may be distributed among plant controllers, utility control centres, aggregators, and protected research environments. Its value is the use of shared definitions and interfaces: time-synchronized measurements, model version control, asset identifiers, event records, service-level metrics, and cyber responsibilities. A modular architecture limits vendor lock-in and allows capability to grow from monitoring to forecasting, then to closed-loop optimization after validation.

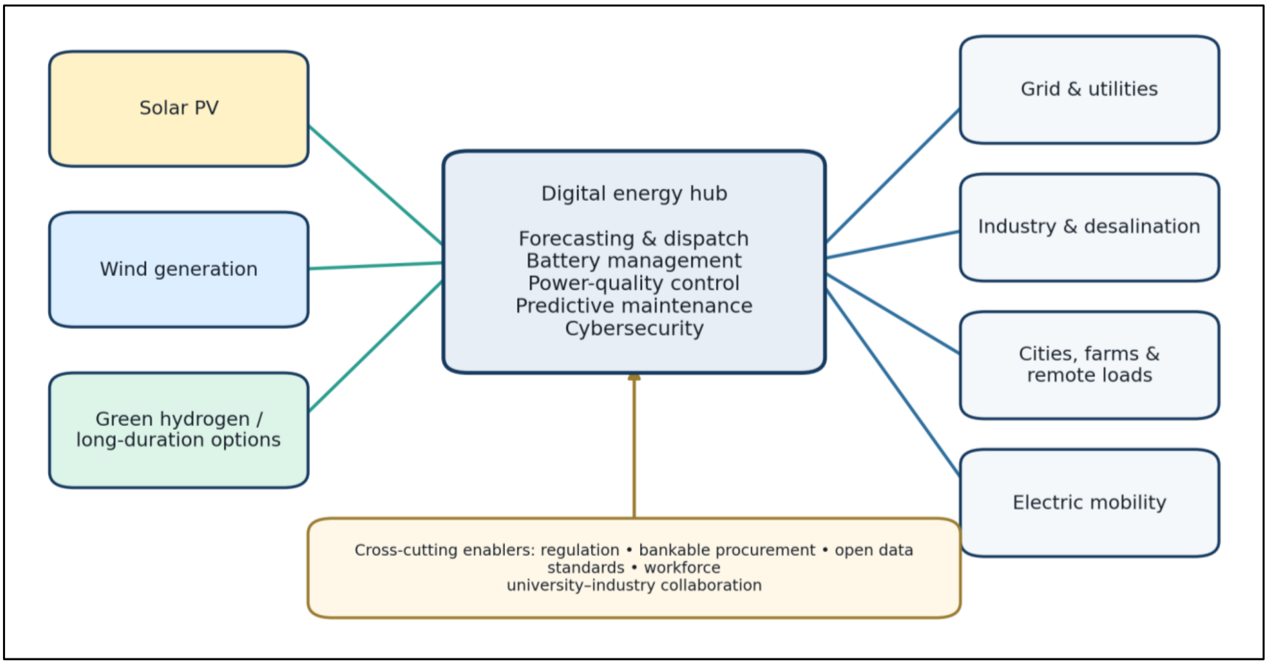

Figure 4. *Integrated renewable-energy development framework for Libya.*

13. Discussion

13.1 A deployment hierarchy emerges from the evidence

The evidence supports a clear hierarchy. **PV is ready for accelerated but measured deployment.** Hardware is mature, the resource is favourable, and local studies address orientation and thermal performance. The unresolved questions concern operating practice and system integration rather than basic feasibility. Deployment should therefore proceed with standardized monitoring, climate-adapted specifications, soiling management, independent performance verification, and feeder or plant-level connection studies.

Wind is ready for resource de-risking and staged projects, not indiscriminate scaling. Multi-source studies identify promising areas, but utility-scale investment needs local campaigns and uncertainty-based energy estimates. Small turbines and Savonius concepts may serve niche loads, yet they should be judged against PV-plus-storage and conventional alternatives on delivered-service reliability and cost.

Battery storage is ready for service-defined pilots. It should not be treated as a generic symbol of modernization. The pilot must specify which service creates value, how dispatch is controlled, how degradation and safety are managed, and how success is measured. Remote or critical-load microgrids and constrained feeders provide particularly useful learning environments.

AI is ready for decision-support pilots with baseline comparison, not autonomous critical control by default. Forecasting, anomaly detection, and maintenance triage are suitable early applications because human operators can review outputs. Protection and safety-critical closed-loop control require stronger verification, cyber assurance, and fallback modes. PINNs are an interesting research direction, but their added value must be established against simpler models.

Hydrogen and high-temperature superconductors are longer-term options. Hydrogen pilots may be justified where a credible industrial offtaker, water strategy, and renewable-matching case exist. Superconductors require a specific engineering bottleneck that outweighs cryogenic and maintenance complexity. Neither option should displace near-term work on grid observability, network reinforcement, PV operations, or resource measurement.

13.2 Climate adaptation changes technology ranking

A technology that performs well in a standard test environment may not offer the best lifetime value in Libya. Heat lowers PV power and accelerates battery ageing; dust reduces optical transmission and adds cleaning requirements; coastal salt and humidity can promote corrosion; water scarcity changes cooling and cleaning decisions; high windblown particles may affect mechanical assets and sensors. Climate adaptation must therefore be included in tender specifications, warranty terms, spares, and acceptance tests.

For PV, the correct comparison is among alternative system designs, not simply "cooling versus no cooling." Module technology, mounting clearance, bifacial design, inverter loading, passive heat transfer, cleaning, water spray, and demand alignment interact. A seasonal or annual net-energy and cost model can identify whether active cooling is justified. For storage, thermal management should be evaluated across standby, cycling, outage, and fire scenarios. For wind, air density, turbulence, erosion, temperature limits, and access should inform turbine selection.

13.3 Reliability is the organizing outcome

Renewable-energy analysis often prioritizes annual kilowatt-hours. In Libya, reliability may be the more useful organizing outcome. A project can reduce fuel use yet fail to improve service if it is frequently unavailable, curtailed, disconnected by protection, or unsupported by spares. Research and procurement should therefore report availability, forced outages, mean time to repair, energy not served, voltage and frequency excursions, recovery after disturbances, and the fraction of maintenance resolved locally.

This framing also improves technology comparison. A battery at a hospital can be evaluated by avoided interruption and generator runtime; a hybrid microgrid by loss of load and fuel savings; a PV feeder project by voltage compliance and peak reduction; a wind plant by dependable energy and availability rather than nameplate capacity. Reliability metrics create a bridge between engineering, economics, and public value.

13.4 Uncertainty should be a decision variable

Many reviewed studies provide point estimates—an optimal tilt, an efficiency improvement, a maximum turbine output, or a model error. Investment decisions require distributions and scenario ranges. Resource interannual variability, measurement error, degradation, availability, curtailment, fuel price, exchange rates, financing, demand, and replacement all affect outcomes. Uncertainty analysis should distinguish variability that can be measured, epistemic uncertainty that can be reduced through research, and structural uncertainty arising from institutional or market change.

Decision-making under uncertainty does not imply waiting for perfect information. It supports staged commitments. A low-cost measurement campaign can precede a wind project; a 100–500 kWh storage pilot can precede a portfolio; a feeder digital model can precede a wide-area platform. Each stage should have predefined evidence gates. Failure to meet a gate should lead to redesign or termination rather than automatic scale-up.

13.5 Apparent disagreements are usually differences in boundaries

Several findings appear inconsistent until their boundaries are aligned. Tilt studies may recommend different angles because they optimize different weather files, angular steps, seasons, array geometries, or performance objectives. A geometry that maximizes annual plane-of-array irradiance may not maximize AC revenue, daytime reliability, or output in a critical demand season. Jumaa and Adbar (2020) and Muftah and Alzaaluk (2025) should therefore be treated as site-specific estimates under stated assumptions. The scientific advance required is not another isolated optimum; it is a sensitivity map that reports how much yield is lost around the optimum and whether cleaning, row spacing, diffuse radiation, and seasonal demand change the preferred design.

Cooling studies similarly report gains under different denominators. Some compare instantaneous electrical power; others compare daily energy, net energy, electrical efficiency, or combined electrical and thermal output. Flow rate, inlet-water temperature, heat-recovery value, and pump consumption change the result (Alami, 2014; Bahaidarah et al., 2013; Bevilacqua et al., 2020; Hadipour et al., 2021). The Benghazi pilot by Hamad et al. (2025) supports the physical relationship between lower module temperature and higher power, but it does not establish an annual economic optimum. Agreement on mechanism should not be mistaken for agreement on deployability. Libya-focused replication should use a common system boundary and report water per net kilowatt-hour gained.

Wind results also depend on scale and measurement convention. A small turbine at a research centre experiences local turbulence and electrical loading that differ from a utility-scale rotor, while CFD of a Savonius rotor addresses aerodynamic design rather than regional energy potential (Basher & Hamdan, 2022; Elsheikhi et al., 2025). Resource studies using satellite or reanalysis products address spatial screening, whereas bankability requires site measurement and loss analysis (Lagili et al., 2023; Nassar et al., 2024). These are complementary levels of evidence, not competing estimates of one quantity. The practical implication is to match every study to the decision scale it can legitimately support.

13.6 Economics, institutions, and engineering are coupled

Technical efficiency has no single economic meaning. A more efficient PV module may reduce land and balance-of-system requirements, but a less efficient technology could be preferable if it offers lower degradation, better temperature behaviour, a stronger warranty, or easier replacement. A battery may appear expensive on energy arbitrage alone yet valuable when avoided outages, fast reserve, voltage support, and deferred reinforcement are included. Conversely, a positive modelled net present value can disappear under high financing cost, foreign-exchange risk, curtailment, delayed interconnection, or weak availability.

These interactions explain why project finance and institutional design belong inside the technical review. The World Bank (2017a, 2017b) reports show that electricity-sector structure, procurement, connection rules, and planning have long been recognized as constraints. The reviewed literature adds a technology-specific interpretation: performance warranties require credible metering; auctions require defined grid access and curtailment; storage revenues require service definitions; and AI-based operation requires accountable data and control rights. Engineering variables become contract variables, and contract ambiguity returns as technical underperformance.

For decision-makers, the appropriate economic method is a set of linked analyses. A project model should include probabilistic resource and availability, degradation and replacement, local taxes and currency exposure, connection and balancing, environmental mitigation, and decommissioning. A system model should estimate fuel and capacity effects and reliability. A distributional assessment should identify who bears cost and who receives improved service. Local-content goals should be tied to quality and lifecycle value rather than a nominal percentage. This structure would allow Libya to compare projects on risk-adjusted delivered service instead of optimistic levelized-energy estimates alone.

13.7 The energy–water–land–materials nexus constrains scale-up

Renewable energy reduces fuel combustion during operation, but it does not eliminate environmental trade-offs. Utility-scale projects occupy land, use materials, require roads and substations, and eventually generate waste. PV cleaning and active cooling can create water demand; hydrogen production requires a water source and treatment; batteries introduce mineral, fire, and end-of-life considerations; and wind projects can affect habitats and landscapes. Nassar et al. (2024) demonstrate the value of expanding system boundaries to manufacturing and transport rather than reporting operational emissions alone.

The nexus is particularly important for evaluating technological responses to heat and dust. Water cooling can raise PV output but should be compared with passive design and alternative water uses. Desalination powered by renewables can reduce freshwater constraints, yet the energy, brine, intake, and coastal impacts remain part of the boundary. Dry or robotic cleaning can reduce water use but adds capital, maintenance, abrasion, and electricity. The correct indicator set therefore includes net energy, water consumption and quality, land transformation, lifecycle emissions, material recovery, and reliability.

Cumulative assessment is preferable to project-by-project isolation. Concentrating projects in renewable zones may reduce transmission and road duplication but can concentrate land and ecological impacts. Distributed projects may use existing roofs and loads but require stronger distribution visibility and many small maintenance relationships. The framework in Figure 4 does not predetermine the balance; it requires each pathway to pass common environmental and reliability gates. This supports comparisons across different technologies and prevents a narrow efficiency metric from shifting burdens outside the project boundary.

13.8 The contribution is an evidence chain, not a technology ranking alone

The principal scientific contribution of this review is the reconstruction of an evidence chain for Libya. Previous work has reviewed PV applications and opportunities (Maka et al., 2021), assessed particular resources and sites (Lagili et al., 2023), or evaluated wind-energy lifecycle performance (Nassar et al., 2024). The present synthesis connects these advances with the local device, simulation, storage, AI, and grid literature and then asks which inference each study can support. This exposes a recurring "scale gap" between a valid component result and a national deployment claim.

The framework also distinguishes three types of relevance that are often conflated. **Libya-based evidence** uses local resources, assets, loads, or institutions. **Libyan-authored capability evidence** shows methods that local researchers can develop even when the dataset is external, as in Almonier (2025). **Transfer evidence** comes from comparable climates or international technology research and requires explicit adaptation. This distinction prevents a Spain-based solar-grid dataset from being presented as Libyan field validation while preserving its methodological relevance.

Finally, the review advances a falsifiable deployment logic. Each recommendation has an observable gate: PV operations should demonstrate net yield and water performance; wind sites should produce uncertainty-based energy estimates; battery pilots should reduce a specified reliability or fuel metric without unacceptable degradation or safety events; AI should outperform a baseline prospectively; and grid controls should pass validated simulations and staged tests. This converts broad calls for "more research" into decision-linked experiments. It also limits causal overreach: a correlation, simulation improvement, or short test becomes a hypothesis for the next gate, not proof of national impact.

13.9 A stronger research ecosystem is as important as a stronger grid

The verified *Albahit* corpus demonstrates an active local research community, but bibliographic inconsistencies and limited reporting reduce discoverability and reuse. Journals can improve value by requiring structured abstracts, data-availability statements, conflict-of-interest disclosures, funding statements, clear units, uncertainty, limitation sections, complete author metadata, DOI consistency, and reporting checklists. Authors should deposit non-sensitive datasets and code or provide a reproducible protocol.

Universities and utilities need durable collaboration rather than one-off access. Joint laboratories could maintain reference PV systems, battery cyclers, power-quality recorders, weather stations, and real-time digital simulators. Students could work on utility-defined problems while publishing de-identified data. Independent verification bodies could support calibration, commissioning, and performance audits. These institutions turn individual papers into cumulative evidence.

14. Practical and policy implications

14.1 Government and regulator

National planning should identify renewable zones and distributed-energy opportunities using resource, network, land, environmental, water, and demand data. Procurement should reward delivered and verified performance rather than equipment supply alone. Standard contracts should allocate resource, curtailment, currency, connection, and availability risks explicitly. Grid-code revisions should be staged and accompanied by compliance-test procedures and model requirements.

14.2 Utility and project developers

The utility should establish a validated network-model program, a disturbance-recording strategy, and transparent connection-study procedures. Developers should supply plant models, controller settings, protection data, cybersecurity documentation, commissioning records, and performance guarantees. Operations and maintenance plans should be evaluated alongside capital cost, including training, diagnostic access, spares, warranty response, and end of life.

14.3 Universities, funders, and journals

Research funding should favour multi-institution datasets, replicated field studies, and clearly specified decision outcomes. Funding calls can require pre-registered protocols for experiments, common metadata, uncertainty analysis, and a dissemination package. Journals should correct metadata promptly and enforce complete author and page information because citation reliability is part of research infrastructure.

15. Future research agenda and roadmap

The proposed agenda is deliberately sequential. Short-term actions build observability and test bounded use cases. Medium-term actions integrate assets and validate controls. Long-term actions scale only those solutions that pass reliability, affordability, environmental, and institutional gates.

Table 11. Prioritized future research questions

Rank	Research question	Preferred design	Core outputs	Decision enabled
1	How do heat, dust, humidity and cleaning interact across Libyan climates?	Multi-site ≥2-year paired PV monitoring	Soiling rate, net yield, water, degradation, uncertainty	Climate-specific PV O&M standard
2	Which wind sites support bankable projects?	Hub-height campaigns plus validated long-term correction	P50/P90 energy, extremes, wakes, losses, grid/access screen	Site tender and turbine class
3	Which battery services create highest reliability value?	Instrumented microgrid/feeder randomized or matched pilots	Unserved energy, fuel, response, ageing, safety, cost	Storage procurement and dispatch
4	What renewable hosting capacity is available by feeder and zone?	Validated load-flow, fault, harmonic and dynamic models	Hosting limits, upgrades, protection changes	Connection planning

Rank	Research question	Preferred design	Core outputs	Decision enabled
5	Can AI improve operational decisions beyond simple baselines?	Prospective external validation with drift monitoring	Error, constraint violations, operator action, avoided loss	Scaled decision-support deployment
6	Which localization steps are technically and economically defensible?	Supply-chain, quality, market and workforce analysis	Cost, scale, certification, jobs, warranty and risk	Industrial policy
7	Where can green hydrogen outperform direct electrification?	Hourly system model plus pilot and lifecycle/water analysis	Delivered cost, efficiency, emissions, water, offtake	Go/no-go on specific value chains
8	Which institutional reforms most improve project performance?	Comparative case studies and contract-performance data	Delays, availability, risk allocation, enforcement	Regulatory and procurement reform

Table 12. Actionable recommendations by stakeholder and horizon

Stakeholder	0–2 years	3–5 years	6–10 years	Success indicator
Government/regulator	Publish roadmap, procurement rules, data governance and pilot safeguards	Competitive procurements; updated grid code; environmental and recycling rules	Integrated power/industry/mobility planning	Projects procured transparently and meeting verified service levels
Utility	Asset/topology audit; metering and disturbance-recording plan	Validated digital network model; storage and microgrid operations	Advanced system operations and regional coordination	Lower unserved energy and faster fault recovery
Developers	Climate-adapted design and independent baseline	Local service chains and performance guarantees	Portfolio optimization and repowering	High availability and auditable lifetime performance

Stakeholder	0–2 years	3–5 years	6–10 years	Success indicator
Universities	Reference monitoring sites and common protocols	Hardware-in-loop and interdisciplinary field labs	Long-term cohort datasets and technology certification support	Reusable datasets and externally validated results
Funders	Prioritize measurements, replication, safety and open outputs	Fund multi-site demonstrators against decision gates	Support scale-up only after measured benefits	Funding follows evidence maturity rather than novelty alone
Journals	Enforce metadata, methods, limitations and data statements	Registered reports and replication tracks	Linked datasets and living evidence syntheses	Higher reproducibility and citation accuracy

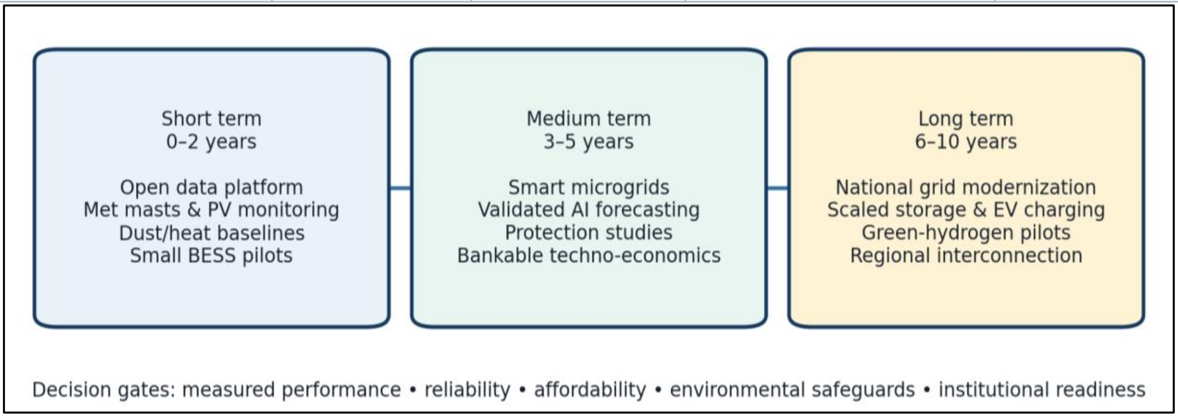

Figure 5. ***Phased research and implementation roadmap***.

16. Limitations of this review

This manuscript has four important limitations. First, the sixteen core local studies were supplied in advance; their inclusion was not the result of an exhaustive database search. Second, the broader literature was purposively selected from verifiable publisher and institutional sources to support critical comparison, so selection bias cannot be excluded. Third, access to methods and supplementary material varied, and several *Albahit* records contain metadata inconsistencies. Quality scores therefore reflect information accessible for this draft and should be updated by two independent reviewers using the final full-text corpus. Fourth, the review does not provide pooled effect estimates because study designs and outcomes are heterogeneous.

The transparent response is to label the work a structured critical review. Before submission as a systematic review, the authors should execute Table 1 in Scopus and Web of Science, export complete records, register a protocol, document de-duplication and full-text exclusions, use independent screening and appraisal, and update all evidence through the submission date. A real PRISMA flow diagram should then replace Figure 1.

17. Conclusions

Libya has a credible opportunity to use renewable energy to diversify supply and improve electricity-service resilience, but its decisive constraint is the conversion of resource potential into verified, maintainable, grid-compatible assets. The local literature identifies the right technical themes and demonstrates growing research capability. Its dominant limitations are short or simulated evidence, inconsistent metadata, weak uncertainty treatment, and limited operational validation.

PV should lead near-term deployment, supported by climate-specific design, measured soiling and degradation, net-benefit cooling analysis, and feeder or plant integration studies. Wind should advance through bankable measurement and staged demonstration. Batteries should be piloted against explicit reliability services and hot-climate safety and degradation requirements. AI should begin with observable, human-supervised decisions and must outperform simple baselines on local external data. Grid modelling, protection, converter performance, cybersecurity, data governance, finance, and workforce development are not supporting details; they are core renewable-energy infrastructure.

The proposed framework links generation, storage, digital intelligence, end uses, and cross-cutting enablers. Its central principle is evidence-gated scale-up: measure first, validate under local conditions, quantify uncertainty and lifecycle effects, demonstrate service value, and expand only when technical and institutional readiness are aligned.

18. Consolidated recommendations

1. Establish a national, quality-controlled renewable-resource and asset-performance data program with public and protected tiers.
2. Standardize PV field protocols for irradiance, temperature, soiling, cleaning, water use, degradation, availability, and AC energy.
3. Commission bankable hub-height wind campaigns at screened priority sites and publish uncertainty-based energy estimates.
4. Deploy service-defined battery microgrids and feeder pilots with thermal safety, degradation, cybersecurity, and end-of-life plans.
5. Create and continuously validate network models for hosting capacity, protection, power quality, and converter dynamics.
6. Require AI studies to report baselines, external validation, uncertainty, drift, reproducibility, and operational decision benefit.
7. Integrate techno-economic, reliability, lifecycle, water, land, and institutional analysis in every scale-up decision.
8. Phase grid-code and procurement reform around measurable capabilities, compliance testing, transparent risk allocation, and performance guarantees.
9. Build joint university–utility laboratories and independent calibration, commissioning, and verification capability.
10. Treat green hydrogen, advanced fuel cells, and superconductors as evidence-gated options tied to specific end uses, not as substitutes for near-term grid and operational priorities.

Suggested target journals

1. **Energy Strategy Reviews** — strong fit for the integrated technology, governance, and implementation framework; the manuscript should emphasize national transition strategy and decision sequencing.
2. **Sustainable Energy Technologies and Assessments** — suitable for a technology-assessment review that connects PV, wind, storage, and grid performance; full systematic-search documentation would strengthen fit.

3. **Energy Reports** — broad energy-system scope and regional relevance; the manuscript's critical synthesis and roadmap align with applied energy research.
4. **Cleaner Engineering and Technology** — appropriate for the engineering and deployment focus and for continuity with published Libya-focused PV scholarship.
5. **Renewable and Sustainable Energy Reviews** — topically aligned but highly selective; submission would require a fully executed systematic protocol, stronger quantitative synthesis where feasible, and a sharper globally novel theoretical contribution.

Journal scope, article type, length, and open-access charges should be checked against current author guidelines immediately before submission.

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