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A Context-Integrated Energy Audit Framework (CIEAF) for Industrial Electrical Systems: Validation Across Resource-Differentiated Settings

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إطار عمل لتدقيق الطاقة المدمج في السياق (*CIEAF*) للأنظمة الكهربائية الصناعية: التحقق من الصحة عبر بيئات متنوعة من حيث الموارد

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Abstract
Industrial energy audits can identify technically attractive savings opportunities, yet implementation depends on data availability, technical capability, financing, and institutional support. This study develops the Context-Integrated Energy Audit Framework (CIEAF), a four-layer decision framework linking technical diagnosis, technology intervention selection, energy-management-system alignment, and contextual readiness. The framework was examined through a structured secondary synthesis of four deliberately contrasting cases: Coca-Cola European Partners Portugal, Argentine Learning Energy Efficiency Networks, industrial organizations in Uganda, and Des Moines Water Works. The analysis used a Context Readiness Score (CRS) across four dimensions: data infrastructure, technical and human capacity, financial access, and institutional or regulatory support. Retrospective comparison showed concordance between readiness tiers and documented implementation depth. Mature organizations combined submetering, significant-energy-use management, capital projects, and formal certification. Intermediate contexts achieved measurable benefits through externally supported networks and phased capacity building. Institutionally constrained contexts experienced difficulty sustaining management-system practices despite promising technical pilots. CIEAF is therefore presented not as a statistically validated predictive model, but as a transparent audit-scope and intervention-sequencing instrument. Its practical value lies in matching diagnostic intensity, monitoring requirements, technical measures, and management-system depth to organizational readiness. The study clarifies the limits of retrospective case evidence and proposes prospective validation using independent coders, pre-registered scoring criteria, production-normalized energy-performance indicators, verified savings, and multi-site follow-up. The framework offers a cautious basis for prioritizing energy-efficiency actions across heterogeneous industrial settings. This positioning emphasizes feasibility, measurement discipline, and institutional sequencing rather than universal savings claims or premature certification recommendations in diverse industrial environments and regions.

Keywords: Context Readiness Score; energy audit; energy efficiency; energy management systems; industrial electrical systems; ISO 50001; power quality; variable-speed drives.

الملخص

يمكن لتدفقات الطاقة الصناعية أن تحدد فرصًا جذابة للتوفير من الناحية التقنية، غير أن تنفيذها يعتمد على توافر البيانات، والقدرة التقنية، والتمويل، والدعم المؤسسي. تطوّر هذه الدراسة إطار تدقيق الطاقة المتكامل مع السياق (CIEAF)، وهو إطار لاتخاذ القرار يتكون من أربع طبقات تربط بين التشخيص التقني، واختيار التدخلات التكنولوجية، ومواءمة نظام إدارة الطاقة، والاستعداد السياقي. جرى فحص الإطار من خلال توليف ثانوي منظم لأربع حالات متباينة عمدًا: شركة كوكاكولا يوروبين بارتنرز في البرتغال، وشبكات تعلم كفاءة الطاقة في الأرجنتين، والمنظمات الصناعية في أوغندا، ومؤسسة دي موين للمياه. استخدم التحليل درجة الاستعداد السياقي (CRS) عبر أربعة أبعاد هي: بنية البيانات، والقدرة التقنية والبشرية، وإمكانية الوصول إلى التمويل، والدعم المؤسسي أو التنظيمي. أظهرت المقارنة بأثر رجعي توافقًا بين مستويات الاستعداد وعمق التنفيذ الموثق. فقد جمعت المنظمات الناضجة بين القياس الفرعي، وإدارة استخدامات الطاقة المهمة، والمشروعات الرأسمالية، والشهادة الرسمية. وحققت السياقات المتوسطة فوائد قابلة للقياس من خلال الشبكات المدعومة خارجيًا وبناء القدرات المرحلي. أما السياقات المقيدة مؤسسيًا فواجهت صعوبة في استدامة ممارسات نظام الإدارة رغم النتائج الواعدة للتجارب التقنية. لذلك لا يُقدَّم إطار CIEAF بوصفه نموذجًا تنبؤيًا متحققًا إحصائيًا، بل أداة شفافة لتحديد نطاق التدقيق وتسلسل التدخلات. وتتمثل قيمته العملية في مواءمة كثافة التشخيص، ومتطلبات المراقبة، والتدابير التقنية، وعمق نظام الإدارة مع جاهزية المنظمة. وتوضح الدراسة حدود أدلة الحالات بأثر رجعي، وتقترح تحققًا مستقبليًا باستخدام مقيمين مستقلين، ومعايير تسجيل محددة مسبقًا، ومؤشرات أداء طاقي مطبّعة بالإنتاج، وتوفيرات متحققًا منها، ومتابعة متعددة المواقع. ويوفر الإطار أساسًا حذرًا لترتيب أولويات إجراءات كفاءة الطاقة عبر بيئات صناعية متنوعة. ويؤكد هذا التوجه أهمية القابلية للتنفيذ، والانضباط في القياس، والتسلسل المؤسسي بدلًا من تعميم ادعاءات التوفير أو التوصية المبكرة بالشهادة في البيئات والمن regions الصناعية المتنوعة.

الكلمات المفتاحية: درجة الاستعداد السياقي؛ تدقيق الطاقة؛ كفاءة الطاقة؛ أنظمة إدارة الطاقة؛ الأنظمة الكهربائية الصناعية؛ ISO 50001؛ جودة القدرة؛ محركات متغيرة السرعة.

1. Introduction

Energy efficiency in industry is not only a matter of selecting efficient equipment. It also depends on whether an organization can measure its baseline, assign responsibility, finance a project, protect production continuity, and sustain operational control after an intervention is installed. Industrial studies repeatedly identify financial, informational, behavioral, organizational, and technical barriers, with their relative importance changing according to firm size, process complexity, management priorities, and institutional setting [1–5]. Energy audits are therefore more than engineering inspections: they are decision processes that connect measurements and engineering calculations with investment, management, and implementation choices [6–8].

The evidence base is fragmented. Research on motors and variable-speed drives focuses on system performance, control, harmonics, and measurement [9–16]. Research on energy management systems focuses on ISO 50001 implementation, maturity, performance indicators, and organizational benefits [17–23]. A parallel literature examines smart meters, Internet-of-Things architectures, and digital energy monitoring [24–32]. These streams are valuable, but they do not by themselves answer a practical question faced by auditors: which combination of diagnostic depth, technical intervention, monitoring infrastructure, and management-system formalization is feasible for this organization now?

The problem is particularly important in resource-differentiated settings. A certified manufacturer with dedicated energy personnel, networked meters, and a capital budget can undertake a different audit and implementation pathway from a small factory that has only utility bills, limited technical staff, and no internal energy-management mandate. Treating both organizations as if they were equally ready for a full ISO 50001 Programme risks producing technically correct recommendations that are institutionally unimplementable. Conversely, treating low-resource organizations as incapable of improvement overlooks low-cost operational measures, targeted submetering, peer networks, and phased capacity building [33–45].

This paper develops and examines the Context-Integrated Energy Audit Framework (CIEAF). The study makes three bounded contributions. First, it integrates established technical, digital, and managerial components into a single audit-scope logic. Second, it operationalizes contextual readiness through a transparent four-dimension score rather than leaving context as a narrative caveat. Third, it subjects the framework to a retrospective, cross-case pattern-matching exercise while explicitly distinguishing analytic concordance from statistical validation. The research questions are:

RQ1. How can technical diagnostics, intervention options, and energy-management practices be integrated into a context-sensitive audit framework?

RQ2. Does a retrospectively assigned Context Readiness Score show concordance with the implementation tier documented in four contrasting cases?

RQ3. What evidence and safeguards are required before the score can be used prospectively by auditors and policymakers?

2. Literature Foundations

2.1 Energy audits as measurement and decision systems

An industrial energy audit establishes a baseline, maps energy flows, identifies significant energy uses, estimates technical and economic opportunities, and defines a measurement-and-verification pathway. Audit quality depends on the adequacy of the data and on the extent to which recommendations are connected to operating conditions and production requirements [6–8]. Evidence from large audit programmes shows that audits can reveal substantial opportunities, but implementation is frequently limited by finance, information, staff capability, and competing production priorities [7,8,33,34]. Accordingly, the audit should distinguish between a technically attractive measure and a measure that is feasible, measurable, financeable, and maintainable in the host organization.

At the electrical-system level, the audit should combine interval or time-series load data with power-quality measurements, equipment inventories, operating schedules, and production-normalized energy performance indicators. Power factor, total harmonic distortion, voltage imbalance, motor loading, and losses in distribution equipment are useful diagnostic indicators, but none should be treated as a universal proxy for energy savings. A low power factor may create demand or capacity costs without implying that capacitor installation will reduce real energy consumption, while a drive retrofit may reduce system energy in a variable-torque application but create harmonic or low-load penalties if poorly specified [9,10,13,15].

2.2 Heterogeneous technical interventions

Variable-speed drives are most compelling where the driven process requires variable flow or pressure. Reviews and experimental studies show that savings depend on the pump or fan affinity relationship, control strategy, motor loading, drive efficiency, and measurement boundary [11,12,14]. A drive should therefore be recommended only after the duty cycle and control mode have been established. Measurement of drive-system efficiency is itself non-trivial because non-sinusoidal waveforms and instrument settings can alter the apparent result [10]. Harmonic assessment is also necessary because the drive changes the power-quality environment and may require filtering or other mitigation [13,15].

Power factor correction is similarly context-dependent. Capacitors can reduce displacement reactive power and improve utilization of distribution capacity, but the audit must distinguish displacement power factor from true power factor and must check resonance and harmonic conditions before installation. The drive and capacitor literature supports a CIEAF principle: intervention selection should be based on a measured system boundary and a stated objective—real-energy reduction, demand reduction, power-quality compliance, capacity release, or a combination—rather than on a generic percentage-saving claim [9,15].

Lighting measures should be treated as a separate end-use pathway. LED conversion, occupancy sensing, daylight-linked dimming, and layered control can be effective, but the magnitude of savings depends on operating hours, illuminance requirements, space geometry, control commissioning, and the baseline technology. Evidence from lighting-control studies supports the use of pre-implementation baselines and post-implementation verification rather than transferring savings percentages from offices to industrial floors without adjustment [46–48].

2.3 Energy-management systems and organizational institutionalization

ISO 50001 provides a structured management-system architecture based on policy, planning, significant-energy-use identification, objectives, operational control, monitoring, internal audit, and management review. Studies of implementation show that certification is not synonymous with energy performance; maturity, integration with existing management practices, and the quality of energy-performance indicators matter [17–21]. An organization can therefore benefit from selected ISO 50001 practices without immediately undertaking full third-party certification.

Energy-management maturity models provide a useful bridge between an informal programme and a certified system. They can help organizations identify whether they have the data, roles, procedures, competence, and review mechanisms required for progressively stronger energy governance [19,20]. Research on motivations and implementation challenges also shows that ecological motives, operational benefits, competitive advantage, management commitment, and organizational capability can interact in shaping adoption [18,22,23]. CIEAF consequently treats management-system alignment as graduated: informal operational control, network-supported capacity building, and formal certification are different levels of institutionalization rather than a binary choice.

2.4 Context, barriers, and adoption

The energy-efficiency gap is partly a context problem. Manufacturing studies identify lack of capital, limited information, weak awareness, production risk, insufficient staff time, and competing investment priorities as recurring barriers [1–5,33–37]. These barriers interact. For example, insufficient data may weaken the business case, a weak business case may delay financing, and the absence of financing may prevent the metering needed to improve the business case. Systems approaches therefore recommend addressing motivation, capability, implementation, and feedback together rather than treating barriers as independent obstacles [4,36].

Energy-efficiency networks provide a particularly relevant intermediate pathway. Network programmes can reduce information and competence barriers, create peer learning, and provide external facilitation to firms that cannot maintain a full-time energy manager [41–44]. However, networks do not eliminate all barriers, and their outcomes depend on participant engagement, external support, and the ability to transfer knowledge into routine operating practice. This evidence informs the intermediate tier in CIEAF.

2.5 Digital monitoring and the resource-accessibility divide

Digital monitoring can improve visibility, accountability, anomaly detection, and the calculation of energy-performance indicators. Smart meters and IoT architectures can support real-time measurement and bidirectional communication, while distributed metering and data analytics can improve observability [24–32]. Yet digitalization also introduces capital, interoperability, cybersecurity, maintenance, calibration, and skills requirements. A low-cost meter can be appropriate for a targeted significant-energy-use, whereas full plant-wide SCADA may be unjustified before the organization has stable data governance and personnel capable of using the information.

CIEAF therefore distinguishes three monitoring states: billing-only or manual data, targeted submetering with periodic analysis, and networked monitoring with continuous EnPI tracking. This sequence avoids presenting "smart monitoring" as an all-or-nothing technology and aligns digital ambition with organizational readiness.

3. Methods

3.1 Research design

The study uses a structured secondary synthesis and qualitative cross-case pattern matching. It is not a systematic review with a meta-analysis, and it does not estimate a causal effect. Academic records were identified through scholarly discovery services and then screened for direct relevance to industrial energy audits, energy-management systems, industrial intervention performance, digital monitoring, organizational barriers, and cross-context implementation. Bibliographic metadata were checked against DOI or publisher records where available. The final evidence base combined peer-reviewed studies, established methodological books, standards-oriented material, and documented organizational case reports.

The case component follows analytic replication logic: cases were selected because they provide contrasting resource and institutional conditions, not because they form a statistically representative sample [49–52]. The unit of analysis is the organization or organized programme described in each case report. The intended inference is limited to whether the proposed readiness construct is transparently applicable and whether its retrospective classification is concordant with documented implementation outcomes.

3.2 Case inclusion and data extraction

A case was eligible when the source described an energy-management or energy-efficiency programme, contained enough narrative information to assess at least three of the four readiness dimensions, and reported an implementation outcome. The extraction template recorded organizational type, geographic setting, measurement infrastructure, technical capacity, financial access, institutional support, implemented interventions, management-system depth, and reported outcomes. Where a case report did not provide a value, the missing item was recorded as unknown rather than inferred as mature.

3.3 Context Readiness Score

The Context Readiness Score (CRS) is a formative diagnostic index, not a reflective psychometric scale. It has four dimensions, each scored from 0 to 3. The dimensions are data-infrastructure maturity (D), technical and human capacity (H), financial access (F), and institutional or regulatory support (I).

$$CRS = D + H + F + I, \quad 0 \le CRS \le 12.$$

Each score must be supported by evidence from the case record. A score of 0 indicates that the relevant capability is absent or minimally available; 1 indicates ad hoc or externally dependent capability; 2 indicates repeatable but incomplete capability; and 3 indicates mature, internally supported capability. The rubric is deliberately simple so that an auditor can apply it during scope definition, but the score should not be interpreted as a validated universal threshold.

Table 1. Context Readiness Score rubric.

Dimension	0: constrained	1: emerging	2: established	3: mature
Data infrastructure	Utility bills only; no reliable submetering	Manual readings or isolated meters with gaps	Targeted submeters and repeatable EnPI calculations	Networked meters, quality control, and continuous EnPI tracking
Technical and human capacity	No assigned energy responsibility	Part-time or externally supported responsibility	Trained internal team with defined roles	Dedicated competent personnel integrated with operations and maintenance
Financial access	No identified capital or financing pathway	Small operational budget or uncertain external support	Approved projects or accessible financing for priority measures	Dedicated capital planning plus internal or external financing capacity
Institutional/regulatory support	No mandate, incentive, or management sponsorship	Informal sponsorship or temporary programme support	Formal objectives, policy support, or network participation	Strong management review, regulatory mandate, or durable programme support

3.4 Implementation tiers and audit-scope logic

For exploratory comparison, three tiers were defined before the case scores were assigned. Tier 1 (CRS 0–4) emphasizes no- or low-capital operational control, safety, maintenance, targeted measurements, and staff engagement. Tier 2 (CRS 5–8) supports a more complete audit, targeted submetering, selected technical projects, and phased or network-supported management practices. Tier 3 (CRS 9–12) supports integrated measurement, a portfolio of capital projects, formal EnMS processes, and consideration of third-party certification. The thresholds are decision rules for this study, not empirically calibrated cut-offs.

Intervention selection follows a feasibility gate. A measure enters the priority portfolio only when its technical mechanism is compatible with the measured duty cycle, its principal benefit is stated, its measurement boundary is defined, and the organization can operate and maintain it. The audit then ranks feasible measures by expected benefit, implementation risk, verification burden, and contextual fit. This prevents a high-return but institutionally infeasible measure from automatically displacing a smaller measure that can actually be implemented and sustained.

3.5 Analytic safeguards

Three safeguards were applied. First, the study separates documented facts from author interpretation in the case table. Second, it reports the retrospective nature of the scores and the possibility of outcome-informed scoring. Third, it treats concordance as a pattern that justifies prospective testing, not as proof that the CRS predicts outcomes. A confirmatory study should use at least two independent coders, blind scoring before outcome disclosure, a pre-registered rubric, and prospective follow-up of energy and institutional outcomes.

4. CIEAF Framework

4.1 Layer 1: Technical diagnostic layer

Layer 1 establishes the baseline and the measurement boundary. It includes load profiling; power factor and power-quality assessment; motor, drive, transformer, lighting, and compressed-air inventories; identification of significant energy uses; production-normalized EnPIs; and a measurement-and-verification plan. When interval data are unavailable, the audit may begin with bills and nameplate information, but the resulting uncertainty must be stated and reduced through targeted metering before major capital decisions.

4.2 Layer 2: Technology intervention layer

Layer 2 contains candidate measures: variable-speed drives for suitable variable-torque duties; power-factor and harmonic mitigation after power-quality assessment; efficient motors and optimized control; LED and responsive lighting controls; compressed-air leak and pressure management; and monitoring infrastructure proportionate to the data-readiness score. The layer is a catalogue, not an unconditional ranking. A measure's priority is established only after the Layer 1 baseline and Layer 4 readiness gate are applied.

4.3 Layer 3: Management-systems alignment layer

Layer 3 converts isolated projects into repeatable management practice. Its elements include an energy policy, roles and competence, SEU-specific objectives, operational controls, EnPI review, internal audit, corrective action, and management review. The implementation depth is graduated. A constrained facility may begin with an energy focal point, a monthly review, and a small number of operational controls. An intermediate facility may use an external network, documented procedures, and targeted EnPI tracking. A mature facility may integrate these practices into a certified ISO 50001 system.

4.4 Layer 4: Context-adaptation layer

Layer 4 applies the CRS and governs sequencing. Its practical purpose is to prevent an audit programme from assuming that all organizations can immediately support the most data-intensive and management-intensive pathway. Layer 4 does not reduce ambition; it identifies the enabling steps required to make ambition implementable. In this sense, the framework recasts many implementation failures as sequencing failures that can be addressed by building data, capability, financing, and institutional support in the correct order.

5. Cross-Context Case Analysis

5.1 Case profiles

Table 2. Retrospective application of CIEAF to four documented cases.

Case	Retrospective CRS	Expected tier	Documented features and outcome
Coca-Cola European Partners Portugal	11/12	Tier 3	Documented ISO 50001 implementation, SEU-oriented management, reported multi-year efficiency improvement and cumulative savings, and substantial organizational resources [53].
Argentine Learning Energy Efficiency Networks	6/12	Tier 2	Externally supported network model with measurable savings across participating firms and evidence of capacity building, but without uniform full certification across the programme [54].
Industrial sector, Uganda	3/12	Tier 1	Technical pilots were reported as promising, while institutionalization was constrained by political-economy, regulatory, and organizational barriers [55].
Des Moines Water Works	10/12	Tier 3	Reported ISO 50001/SEP-related management, networked submetering, LED conversion, VFD-related projects, and structured tracking of significant energy uses [56].

5.2 Pattern matching

The four cases show concordance between the retrospectively assigned tier and the documented depth of implementation. The two high-readiness cases reached the most integrated pathway, including formal management-system practices and extensive measurement. The Argentine programme occupies the intermediate position predicted by the framework: it generated measurable economic benefits while relying on external facilitation and progressive capability building. The Ugandan case illustrates the central sequencing issue: technical activity can occur without durable institutionalization when management, regulatory, data, and financing conditions are weak.

This pattern is consistent with, but does not prove, the CIEAF proposition. The cases were selected for contrast and are described in different source genres. The score was assigned after the outcomes were known, and the evidence is not equally detailed across dimensions. Therefore, the result should be reported as retrospective construct concordance. It cannot be reported as predictive accuracy, causal evidence, or a general benchmark for all industrial facilities.

6. Economic and Decision Implications

6.1 Financial interpretation

Simple payback is useful for screening but can be misleading when it combines management-system cost with cumulative savings generated by several technical and organizational actions. The original CCEP calculation illustrates this issue: dividing a reported EnMS cost by average annualized cumulative savings produces a short apparent payback, but the calculation does not isolate the management layer from the underlying capital projects, energy-price changes, production changes, or attribution uncertainty. CIEAF therefore recommends reporting separate values for audit cost, enabling-infrastructure cost, technical-project cost, annual verified savings, non-energy benefits, and uncertainty.

Where detailed financial records are absent, the correct conclusion is not that a measure has no payback. The appropriate conclusion is that the facility first requires a low-cost baseline and a measurement plan. At Tier 1, single-measure screening and operational controls are more defensible than portfolio-level financial optimization. At Tier 2, targeted submetering and project-level business cases become feasible. At Tier 3, portfolio optimization, verification, and formal management review can be integrated.

6.2 Practitioner decision sequence

Table 3. Recommended audit sequence by readiness tier.

Tier	Immediate audit scope	Typical priority	Evidence required to advance
Tier 1	Billing review, walk-through, operating schedules, targeted portable measurements	Operational control, maintenance, leaks, set-points, low-cost lighting or control measures	Assigned responsibility, reliable baseline, initial EnPI, management sponsorship
Tier 2	Detailed end-use audit and targeted submetering	Selected VFDs, power-quality measures, LED controls, compressed-air and process projects	Repeatable data collection, trained personnel, project finance pathway, review routine
Tier 3	Integrated audit, continuous monitoring, M&V, and management-system integration	Portfolio optimization, advanced monitoring, formal ISO 50001 pathway, verified savings	Independent assurance, internal audit, management review, and sustained operational control

7. Discussion

7.1 Contribution and theoretical positioning

CIEAF does not claim to invent the proposition that context affects technology adoption. The Technology–Organization–Environment tradition and diffusion-of-innovations theory already establish that implementation depends on technological, organizational, and environmental conditions [52,57]. Industrial energy-efficiency research likewise documents interacting technical, organizational, and economic barriers [1,4]. The narrower contribution of CIEAF is translational: it packages those established insights into an auditable readiness rubric linked to concrete energy-audit decisions.

The framework also extends the interpretation of digital monitoring. Instead of assuming that smart monitoring is a universal prerequisite, it treats monitoring maturity as a staged capability. This is more consistent with the evidence on smart-meter infrastructure, data quality, and organizational capability [24–32]. Similarly, the framework treats ISO 50001 as a pathway with intermediate states rather than as a binary certification event, which reflects the maturity and network literatures [19–23,41–44].

7.2 Practical and policy implications

For practitioners, the main implication is to assess readiness before fixing the audit scope. A facility with weak data and no assigned responsibility should not be judged by the same implementation template as a certified, highly metered organization. For policymakers, the implication is to complement capital incentives with measurement support, technical training, network facilitation, and institutional mechanisms that help firms convert project-level gains into routine practice. Network-based programmes can occupy an evidence-based middle position when full certification is not yet feasible [41–44].

8. Limitations and Prospective Validation

The evidence has five important limitations. First, the case sample is small and purposive; it supports analytic comparison, not statistical generalization. Second, CRS scoring is retrospective and was not independently blinded. Third, the cases differ in sector, reporting depth, outcome definitions, and time horizon. Fourth, financial data are incomplete and do not support a general payback threshold. Fifth, the framework has not yet been prospectively tested in a MENA industrial facility, where energy tariffs, institutional arrangements, metering infrastructure, and maintenance capacity may differ from the cases examined here.

A prospective validation study should register the rubric before data collection, recruit multiple facilities across at least three readiness levels, use two independent coders, measure inter-rater agreement, collect baseline and follow-up EnPIs, record implementation fidelity, separate enabling from technical-project costs, and follow facilities for at least one full operating cycle. The primary test should be whether the score predicts implementation milestones and verified energy outcomes better than technical opportunity ranking alone. A secondary test should examine whether the score is transportable across sectors and regions.

9. Conclusion

This study developed CIEAF as a context-sensitive audit-scope and intervention-sequencing framework for industrial electrical systems. Its four layers connect measurement, technology selection, management-system alignment, and contextual readiness. Retrospective comparison of four contrasting cases shows concordance between the proposed readiness tiers and documented implementation depth, but the evidence does not justify claims of statistical validation or causal prediction. The defensible contribution is a transparent decision aid that makes enabling conditions visible before an organization commits to a high-intensity audit or certification pathway. Its next scientific step is prospective, blinded, multi-site validation with verified energy and institutional outcomes.

AI Disclosure Statement

Generative artificial-intelligence tools were used under human supervision to assist with literature discovery, organization, language editing, and document preparation. The authors retain responsibility for the conceptual framework, interpretation of evidence, accuracy of citations, methodological decisions, and final manuscript.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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The following list contains 45 additional peer-reviewed references selected to extend the manuscript's coverage of industrial audits, ISO 50001, motors and drives, digital monitoring, barriers, and energy-efficiency networks, followed by retained foundational and case sources. DOI links are provided wherever available.

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