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Strengthening power grid projects' governance and sustainability through lifecycle auditing

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Power-grid projects are inherently complex and characterized by significant risks and uncertainties. This study examines the application of lifecycle auditing (LAud) to enhance project management and risk control in power-grid development. Through a qualitative case study approach, the study examines the implementation of a full-process LAud model within a state-owned organization's internal audit framework, analyzing data from 29 completed power-grid projects and incorporating expert interviews. The core outcome is the development of a comprehensive LAud framework that covers all critical stages of power-grid projects' lifecycle, from initiation to post-completion audit. This framework, tested through a pilot program, has led to the creation of a new workflow and a fully functional digital platform for LAud. The results demonstrate that LAud can enhance project governance and sustainability by enabling real-time monitoring, proactive risk mitigation, and continuous data integration, addressing the limitations of traditional auditing methods. The study contributes to the theoretical understanding of continuous auditing in complex infrastructure projects and provides actionable insights for improving governance and sustainability practices in power-grid projects. It also provides actionable insights for improving project oversight in power-grid systems and supports the sustainable development of the electricity sector by fostering transparency, efficiency, and resilience.

Keywords Lifecyle auditing, Power grid enterprises, Engineering projects, Risk management, Digital auditing

Electricity is a vital energy resource for national economic development, playing a critical role in promoting high-quality economic growth, ensuring societal stability, and improving living standards, particularly in developing economies such as Nepal[1], China[2], and Africa[3]. The reliable supply of electricity underpins industrial productivity, commercial operations, and residential consumption, forming the bedrock of economic efficiency[4]. However, electricity supply systems face significant challenges due to widening supply-demand gaps[5]. As investment scales expand and project management complexity increases, power-grid engineering projects confront escalating risks. Power-grid projects are frequently exposed to substantial risks stemming from capital-intensive investments, political conflicts, technological and environmental constraints, and extended construction timelines[6,7]. These factors render such projects vulnerable to capital fraud, cost overruns, schedule delays, and quality deficiencies. Consequently, effective cost control and risk mitigation have become critical challenges for power-grid enterprises. Given the strategic importance of power-grid infrastructure to national economies[8,9], project failures or inefficiencies can have cascading effects, impacting enterprise financial health, consumer power reliability, and macroeconomic stability.

The concept of lifecycle auditing (LAud), is extended from the continuous auditing as defined by the American Institute of Certified Public Accountants (AICPA) and the Canadian Institute of Chartered Accountants (CICA) as "a methodology for issuing audit reports simultaneously with, or shortly after, the occurrence of relevant events"[10], where it further leverages technology to enhance the timeliness and accuracy of financial reporting, detect potential errors and fraud, and provide actionable insights for decision-making in all operations[11,12]. In the context of power-grid engineering, LAud enables project managers and auditors to track progress against planned schedules, budgets, and quality benchmarks, facilitating immediate corrective actions throughout the project lifecycle. It also supports proactive risk identification through data analysis from project management software, financial systems, and operational logs, thereby reducing potential losses. Existing literature highlights the complexities of risk management in power-grid projects. Zhao et al.[13] emphasized the need for comprehensive

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risk management systems in power transmission and transformation projects, noting that traditional methods often lack robust evaluation frameworks. Similarly, Ding et al.[14] developed fuzzy comprehensive evaluation method to evaluate the investment risk in power engineering projects. Moreover, Wu et al.[15] developed a risk management model to promote clean energy in high-permeability power grid projects. However, these studies primarily focus on static, periodic risk assessments, which may fail to capture real-time project dynamics, particularly for integrating continuous, real-time auditing into power-grid project management.

Hence, this study aims to explore the application of LAud in enhancing project governance and sustainability in power-grid projects, thereby addressing the limitations of traditional auditing methods. Utilizing a qualitative research approach, the study examines the implementation of a full-process LAud model within a state-owned organization through an internal audit framework. Specifically, the research analyzes data from 29 completed power-grid projects and incorporates expert interviews to validate the framework and investigate the collaborative governance mechanisms and digital empowerment strategies critical to its success. This comprehensive approach ensures robust validation of the LAud framework while providing actionable insights for improving governance and sustainability practices.

Theoretical foundation

Lifecycle auditing

The concept of LAud emerged as an extension of continuous auditing (CA), building upon foundational work by Groomer and Murthy[16] and Vasarhelyi and Halper[17]. While early definitions of CA focused on financial reporting, LAud broadens this scope to encompass holistic project oversight. Rezaee et al.[18] described CA as a systematic process for gathering electronic audit evidence to evaluate financial statements in real-time systems, a foundation that LAud expands by integrating cross-functional operational data. Eulerich and Kalinichenko[19] framed CA as an automated monitoring system for detecting deviations from standards, a concept LAud extends to track multidimensional performance metrics across project lifecycles. In power-grid engineering contexts, LAud leverages advanced technology to enhance the timeliness and accuracy of financial and operational reporting, detect errors and fraud, and provide actionable insights for decision-making[11,12,20]. This evolution addresses the limitations of traditional risk management methods in power-grid projects, which often lack robust evaluation frameworks[13].

Auditors now face demands for real-time assurance not only over financial data but also operational integrity, requiring continuous assessment of control systems for anomalies and risks[21,22]. Traditional auditing methodologies, designed for periodic reviews, struggle to meet these dynamic requirements[23]. LAud overcomes these constraints by enabling concurrent monitoring of project schedules, budgets, quality benchmarks, and risk indicators throughout the asset lifecycle[24]. In power-grid projects, this facilitates immediate corrective actions and proactive risk mitigation through data integration from project management software, financial systems, and operational logs. The principles of LAud build upon those articulated for CA[25,26], enhanced for lifecycle applications[27]. These include:

- High-frequency audit cycles aligned with project milestones.
- Automated monitoring of technical, financial, and operational parameters.
- Exception-based auditing supplemented by human expertise for complex judgments.
- Integration of predictive analytics for risk identification in engineering workflows.
- Real-time assurance over both financial and non-financial performance indicators.
- Continuous data modeling using inputs from IoT sensors, ERP systems, and maintenance records.

As a technology-dependent methodology, LAud requires sophisticated tools for implementation. Auditors employ computer-assisted audit techniques to analyze heterogeneous data streams, assess risks, and validate compliance across project phases[28]. Successful deployment depends on secure integration with client systems for installing monitoring modules, collecting evidence, and generating alerts[29]. In power-grid contexts, this necessitates interoperability with specialized engineering platforms and Supervisory Control and Data Acquisition (SCADA) systems. Critical success factors include executive sponsorship, mature IT infrastructure, adaptive internal audit structures, and workforce upskilling in both audit principles and engineering operations[26,30].

The implementation of LAud is particularly valuable in addressing the complex risk landscape of power-grid projects. Effective lifecycle risk management requires integrated systems capable of processing technical, environmental, and financial data streams—a capability inherent in LAud frameworks[13]. Adoption success depends on technological readiness, regulatory alignment, and organizational culture[30,31]. Recent studies highlight LAud's growing relevance in critical infrastructure sectors, where it enhances resilience through continuous compliance monitoring and predictive analytics[12,32].

Audit of power grid projects

The audit of power grid projects constitutes a critical mechanism for ensuring operational efficiency, regulatory compliance, and sustainable development in the energy sector. Various dimensions of power-grid auditing emphasize the integration of technical and financial oversight[33], while the role of energy audits in optimizing household electricity consumption in Amman, Jordan—a framework adaptable to broader distribution network efficiency[34]. Zhou et al.[35] advanced risk assessment methodologies through a two-layer neural network model capable of processing multi-attribute, low-correlation data, addressing a key challenge in auditing complex infrastructure projects.

LAud extends these foundations by embedding continuous, technology-driven oversight across all project phases. Abdel-Hadi et al.[36] laid groundwork for this approach through a holistic audit framework that synthesizes financial, technical, and operational metrics—principles now operationalized in LAud through real-time data integration from SCADA systems, IoT sensors, and project management platforms. Energy performance indicators gain enhanced relevance in LAud frameworks[37], where they are dynamically tracked against evolving benchmarks. Early innovations in automation, such as intelligent auditing system[38], foreshadowed LAud's reliance on artificial intelligence (AI) and machine learning to minimize human error and accelerate anomaly detection[33,39,40].

Diverging from prior literature, this research investigates the implementation of LAud based on a full lifecycle model that integrates:

- Design-phase risk forecasting using predictive analytics.
- Construction-phase compliance tracking via IoT-enabled progress monitoring.
- Operational-phase resilience auditing through SCADA system interoperability.
- Post-completion performance evaluation with machine learning-driven benchmarks.

This framework is underpinned by collaborative digital ecosystems that unify stakeholders—engineers, auditors, and policymakers—on shared data platforms. By demonstrating LAud's capacity to synchronize technical specifications (e.g., substation load thresholds) with financial constraints (e.g., budget allocations), our work addresses a critical gap identified by Bosu et al. (2023)[41] in aligning engineering priorities with fiscal accountability. Furthermore, the study elucidates how LAud's proactive risk identification mechanisms, leveraging AI-augmented analysis of operational logs and environmental data, mitigate the systemic vulnerabilities in power transmission systems[13].

Lifecyle audit challenges in power grid projects

As power-grid projects escalate in scale and complexity, traditional auditing approaches struggle to address the multifaceted challenges of modern infrastructure development. These challenges underscore the imperative for adopting LAud frameworks that integrate continuous monitoring and predictive analytics.

Current practices disproportionately focus on post-completion financial reviews, neglecting critical front-end nodes such as design validation, procurement oversight, and contractor selection[35]. This fragmented approach fails to detect risks embedded in early project phases, such as design flaws or bid-rigging, which later manifest as cost overruns or operational failures[13]. LAud addresses this gap through real-time monitoring of all lifecycle stages, leveraging IoT-enabled progress tracking and predictive modeling to identify deviations during design and construction[25]. For instance, SCADA system interoperability allows auditors to validate equipment specifications against live operational data, ensuring alignment between design intent and implementation[36].

Audit findings often remain siloed within departmental boundaries, lacking integration with strategic decision-making processes. This disconnection stems from inadequate digital infrastructure to disseminate insights across engineering, finance, and risk management teams[26]. LAud transforms audit outcomes into actionable intelligence by deploying centralized digital platforms that automate report generation and distribute findings to stakeholders in real time. Machine learning algorithms[33] enable predictive risk scoring, allowing preemptive interventions in procurement or contractor performance. Furthermore, blockchain-based audit trails[32], enhance transparency in corrective action tracking, addressing the feedback loop deficiencies[41].

Last but not least, the exponential growth of audit scope—spanning environmental compliance, cybersecurity, and supply chain ethics—has strained traditional audit teams[39]. While outsourcing to intermediaries temporarily alleviates resource shortages, it introduces governance gaps, such as inconsistent data standards and misaligned incentives[12]. LAud mitigates these issues through digitalization-driven automation, reducing manual workloads by 40–60% in routine compliance checks[40]. For example, natural language processing tools audit contractual documents against regulatory databases, while computer vision systems validate construction milestones via drone-captured imagery. This shift enables internal teams to focus on high-value tasks like fraud pattern analysis and resilience stress-testing, aligning with the proactive risk culture[30].

By transitioning from reactive compliance checks to a lifecycle assurance model, power-grid enterprises can reduce project risks at early stages, as evidenced by pilot implementations in state-owned utilities[37,38]. This evolution positions LAud not merely as an audit methodology but as a cornerstone of sustainable infrastructure governance.

Research methodology

This study employed a qualitative case study approach to investigate the implementation of a full-process LAud model within a state-owned organization's internal audit framework. The research focused on managing power-grid projects and controlling risks throughout the project lifecycle, using 29 completed power-grid projects in 2023 as the primary empirical context. This case study design was selected to enable an in-depth exploration of the LAud framework's operational dynamics and its alignment with audit needs throughout the project lifecycle.

Data collection and analysis

The primary data were collected through two methods, namely, document analysis and expert interviews. Regarding the document analysis, a purposive sample of the completed power-grid projects was selected based on their relevance to the LAud framework's implementation. Internal audit reports, project records, and post-audit evaluations were systematically reviewed to identify patterns in governance practices, digital tool utilization, and audit outcomes[42]. Meanwhile, semi-structured interviews were conducted with 11 stakeholders, including internal auditors, project managers, IT specialists, and senior executives involved in the power-grid company as shown in Table 1. Interviews focused on validating the framework's efficacy, uncovering challenges in collaborative governance, and evaluating the role of digital tools in enhancing audit transparency and efficiency.

Expert role	Number of participants	Average years of experience	Methodological focus
Internal auditors	3	15	To validate the efficacy of the proposed audit framework and understand their roles in ensuring compliance and transparency
Project managers	3	20	To explore systemic challenges in cross-functional collaboration and identify gaps in governance protocols
IT specialists	3	10	To assess the perceived role of technology in enhancing audit efficiency and identify technical barriers to implementation
Senior executives	2	25	To evaluate leadership perspectives on governance alignment and gather insights on the auditing process

Table 1. Backgrounds of experts.

The interviewees were selected purposively to capture audit perspectives from the 29 completed power-grid projects. Selection criteria for these interviewees were (a) direct involvement in at least one of the completed power-grid projects and (b) functional role in internal audit, project management, IT systems, or executive oversight, and with a minimum of five years' experience. Recruitment continued until thematic saturation was reached—no new concepts emerged after the ninth interview, and two confirmatory interviews were added, yielding the final sample of 11 stakeholders.

Thematic analysis was then applied to documentary and interview data. Iterative code development focused on project lifecycle stages. Interview transcripts were triangulated with project documentation for consistency and reliability. Emerging patterns were mapped to the LAud framework's theoretical foundations, with discrepancies resolved through research team discussions.

Case study context, LAud framework Implementation, and digital platform development

The study was conducted at State Grid Jiangsu Electric Power Company, a prominent provincial power grid company within the State Grid Corporation of China. This state-owned enterprise was deliberately chosen because such organizations are both the dominant investors in China's power-grid infrastructure and subject to stringent public-sector auditing standards, thereby providing a high-stakes, high-visibility environment in which the benefits and constraints of a full-process LAud model can be rigorously examined and transparently validated. This company plays a crucial role in the region's energy infrastructure, overseeing 13 municipal and 59 county-level branches, and serving a substantial customer base of over 50.77 million. In 2023, the company successfully completed 29 power-grid projects, which provided a rich empirical context for developing and testing the LAud framework.

The power-grid projects were located across different geographical areas within Jiangsu Province, including urban centers, suburban regions, and rural areas. This geographical diversity posed unique challenges in terms of environmental conditions, land acquisition, and coordination with local stakeholders. For instance, projects in urban areas had to navigate complex underground utility networks and meet higher safety and environmental standards, while rural projects faced challenges related to transportation of materials and limited local infrastructure support.

The company operates in a highly regulated and dynamic environment, with increasing demands for power supply reliability and quality. It faces intense competition in the electricity market and growing expectations from customers and regulators regarding project cost-effectiveness, environmental sustainability, and social responsibility. These factors made the power-grid projects not only technically challenging but also strategically critical for the company's long-term development and reputation.

The successful completion of these projects was essential for enhancing the power supply capacity, improving grid stability, and supporting the economic growth of the region. However, the projects also carried significant risks, such as cost overruns, schedule delays, and quality issues, which necessitated effective governance and risk control mechanisms.

Against this backdrop, the study proposed a holistic LAud framework covering six critical stages of power-grid projects' lifecycle after expert verification: Project Initiation, Survey and Design, Bidding, Tendering and Procurement, Implementation of Engineering Project, Engineering Completion, and Post-Completion Audit.

Throughout the pilot program, the company developed a new workflow to streamline the audit process. This workflow incorporated the principles of the LAud framework and emphasized mid-process and pre-process engagement. It involved various stages, from audit planning and implementation to reporting and follow-up, ensuring continuous tracking and on-site audits throughout the construction process.

Post-pilot, a fully functional digital LAud platform was developed to support the implementation of the LAud framework. This platform enhanced off-site data analysis for engineering audits, characterized by "full-volume scanning, precise positioning, systematic analysis, and focused verification" to accurately identify project issues. It automatically collected data across three layers: decision-making, business, and support, providing a comprehensive digital solution for auditing power-grid projects.

The current study provides an in-depth exploration of implementing the LAud framework in a state-owned power-grid enterprise. By offering detailed insights into the case study background and implementation process, the study highlights the practical application and effectiveness of the LAud framework in enhancing project governance and sustainability through continuous auditing practices and digital innovation.

Results

Backgrounds and cases

State Grid Jiangsu Electric Power Company was selected as the power-grid enterprise in this study, which is a preeminent provincial power grid company within the State Grid Corporation of China. In 2023, they had completed 29 power-grid projects, which were used as the main source of data for developing the LAud framework. Some of the completed power-grid projects included Yangzhou Power Supply Branch Maintenance Facility Project, Zhenjiang Junbei 110 kV Substation Expansion, Nantong Haidong 110 kV Substation Expansion, Qidong Yongyang 220 kV Substation Supporting Grid Project, and so on as illustrated in Fig. 1.

In its pursuit of operational excellence and risk management, they implemented a comprehensive auditing strategy tailored to different types of projects. This strategy ensured rigorous oversight throughout the project lifecycle. Particularly, the tender control price, a critical component of project cost management, was identified as a key focus area for the process tracking management audit, with a separate and detailed audit report issued to provide transparent and actionable insights. These data served as useful information and references in clarifying the process involved in LAud.

Development of LAud framework

As a result, a holistic LAud framework is proposed that covers various critical stages of power-grid projects' lifecycle after verifying the details with the experts in the company. Figure 2 illustrates the details of the LAud framework. The details of each stage and how they should be implemented in power-grid projects throughout the project lifecycle are as follows:

I. Stage 1: Project Initiation.

The project initiation stage establishes the foundational framework for power grid development by addressing planning approvals, feasibility study reviews, and compliance with regulatory prerequisites. During this phase, project teams prepare and submit documentation for land use pre-approval, policy alignment, and investment plan formulation. Auditors rigorously evaluate adherence to national policies and corporate governance mandates, ensuring procedural legality, transparency in fund allocation, and alignment with strategic decisions issued by the organization's leadership. Emphasis is placed on verifying that pre-construction conditions, such as environmental clearances and stakeholder consultations, are fully satisfied before advancing to subsequent stages.

II. Stage 2: Survey and Design.

The survey and design phase focuses on translating conceptual plans into actionable engineering blueprints. Engineers develop preliminary designs and construction drawings, which undergo iterative reviews to optimize technical specifications, cost efficiency, and safety protocols. Auditors assess the adequacy of geological surveys, structural calculations, and risk mitigation strategies embedded within the designs, ensuring alignment with industry standards and project objectives. This stage also involves oversight of third-party design contractors to prevent deviations from approved parameters. Critical attention is directed toward identifying discrepancies between design iterations and their implications for project timelines, budgets, and operational resilience.

III. Stage 3: Bidding, Tendering and Procurement.

Fig. 1. Some of power-grid projects as completed in 2023.

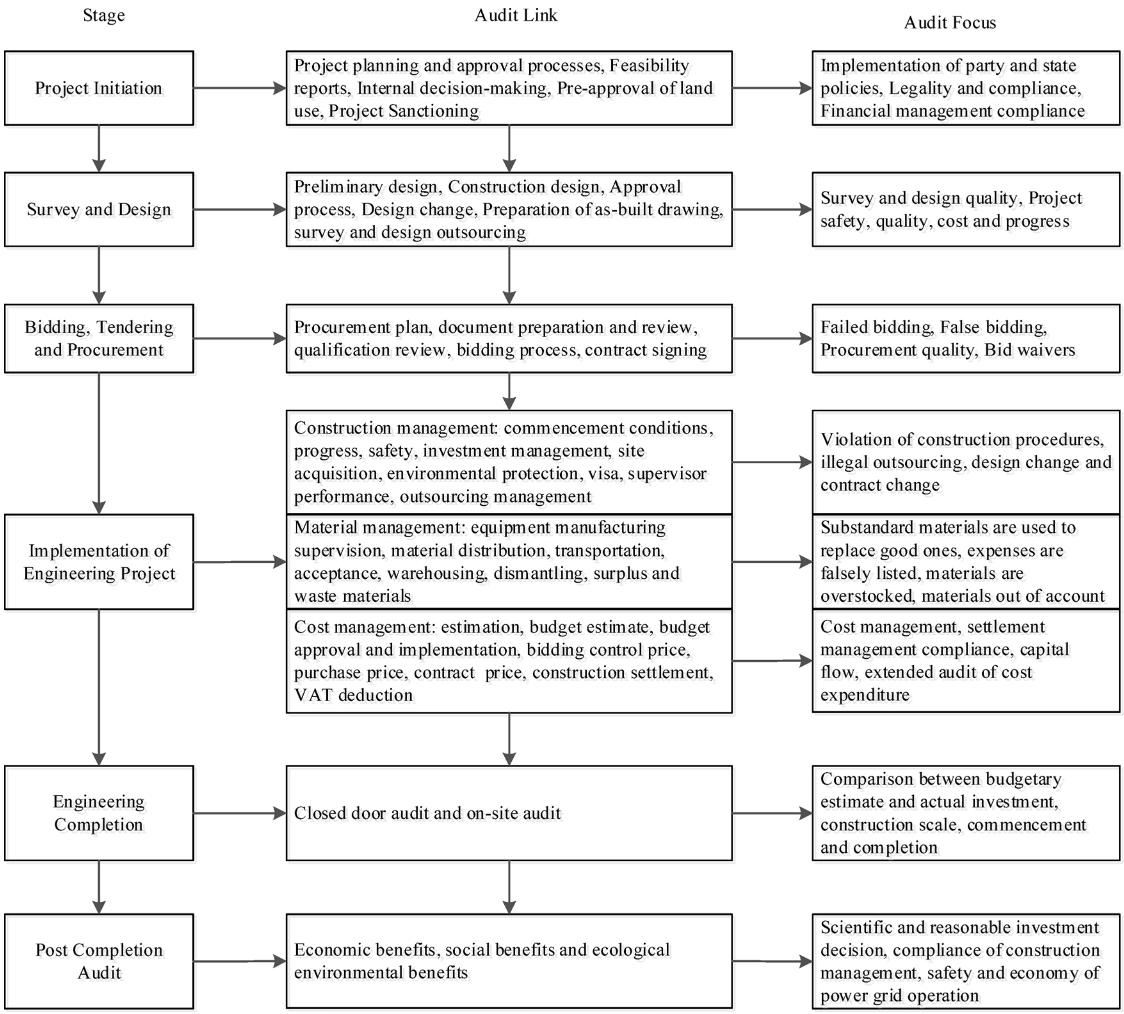

Fig. 2. LAud framework of power grid projects.

During the procurement phase, project managers formulate bidding strategies, draft procurement documents, and evaluate vendor qualifications to secure cost-effective and compliant contracts. Auditors monitor the entire procurement lifecycle, from bid solicitation to contract execution, to prevent irregularities such as collusion, inflated pricing, or non-competitive practices. A key audit activity involves comparing winning bid prices with pre-established control benchmarks to detect anomalies. Additionally, auditors scrutinize the fairness of bid evaluation criteria, the accuracy of technical specifications, and the integrity of award decisions. Post-award audits ensure that contractual terms, including delivery schedules and quality guarantees, are explicitly defined and legally binding.

IV. Stage 4: Implementation of Engineering Project.

The implementation phase prioritizes adherence to safety regulations, contractual obligations, and environmental safeguards. Auditors conduct on-site inspections to verify compliance with land acquisition protocols, migrant worker wage disbursements, and construction quality standards. They validate work volumes through physical measurements, particularly for concealed elements like underground foundations, and assess the legitimacy of design changes or cost adjustments. Contractual deviations, such as unauthorized subcontracting or unapproved scope expansions, are flagged to mitigate financial and operational risks.

Material audits ensure traceability and quality control across the supply chain. Auditors review equipment supervision logs, material distribution records, and storage practices to prevent losses or misuse. They verify tax compliance in material settlements and investigate discrepancies such as inflated procurement costs or off-book inventory. Special attention is given to the disposal of surplus or scrap materials to ensure compliance with waste management regulations.

Financial oversight focuses on budget adherence, tax accountability, and fraud prevention. Auditors reconcile expenditures against feasibility estimates, design budgets, and final settlements to detect overruns. Pre-audit mechanisms are applied to critical payments, including land compensation and contractor invoices, to block unauthorized fund diversion. Rigorous reviews of affiliated entities' expenses, such as subcontractors or design consultants, further safeguard against fraudulent accounting practices. Ensuring compliance in settlement management and providing a sufficient basis for settlements are also critical. To maintain financial transparency and prevent misuse, pre-audit processes are implemented at various payment stages, including land compensation, construction payments, and material payments. Furthermore, extended audits are conducted on the cost expenditures of affiliated construction, design, and supervisory units. This comprehensive approach helps preventing the establishment of unauthorized funds, commonly referred to as "slush funds," ensuring that all financial activities are legitimate and properly accounted for.

V. Stage 5: Engineering Completion.

The completion phase involves a two-tier audit process to finalize project costs and validate deliverables. The settlement audit cross-references completed work with contractual terms through document reviews and on-site inspections, verifying labor costs, material consumption, and scope deviations. The final account audit then reconciles initial budgets with actual expenditures, ensuring adherence to approved scales and timelines. Auditors confirm asset registrations and financial closures, formally certifying the project's readiness for operational handover.

VI. Stage 6: Post Completion Audit.

The post-completion audit evaluates the project's long-term viability and societal impact. Auditors analyze economic returns, environmental sustainability, and grid reliability to identify inefficiencies in planning or execution. Recommendations are formulated to enhance future investment decisions, optimize asset utilization, and align projects with regional development goals. This retrospective assessment ensures accountability, fosters continuous improvement, and strengthens the alignment of power grid investments with national energy strategies.

Testing of LAud framework and proposal of additional workflow

After acceptance of the Laud framework by the power-grid company, a pilot program was initiated to implement full-process auditing using the principles in the LAud framework. This initiative expanded audit supervision to cover the entire project lifecycle, from the initial stages of planning, scheduling, and procurement, through construction, completion, and eventual operation. By adopting an interventionist approach that emphasized mid-process and pre-process engagement, the company carried out ongoing tracking and on-site audits throughout the construction process. As a result, a new workflow was developed to further streamline the audit process. The workflow is illustrated in Fig. 3.

During the project initiation phase, the company's audit department developed an audit work plan based on the annual audit project schedule. In the audit implementation phase, the audit department formed an audit team as required and issued an audit notice to the audited enterprise, which acknowledged receipt. The audit team then prepared an audit implementation plan, conducting pre-audit surveys when necessary to define the audit scope and focus. On-site audits began with an opening meeting, during which the audited enterprise was expected to provide full cooperation. The audit team conducted the on-site audit, generating audit records and working papers, while the audited enterprise supplied the necessary documents and confirmed the accuracy of the working papers. The audit team also conducted interviews as needed, and the audit department provided project guidance when required.

In the audit report phase, the audit team drafted interim audit reports based on the findings from the on-site audit, and the audited enterprise implemented corrective actions accordingly. After project completion, the audit team prepared the engineering tracking audit report, incorporating insights from both on-site and interim reports and seeking input from relevant departments. Management recommendations were provided based on identified issues, and the audit department reviewed the report before finalizing it. The final audit report was then shared with the audited enterprise for feedback before being officially delivered.

In the post-report phase, the audited unit was responsible for implementing the recommended audit corrections and submitting a detailed feedback report to the audit department. Upon receiving the feedback, the audit department archived all audit project materials in accordance with established requirements, thereby concluding the audit process.

Overall, the new workflow had streamlined the auditing process and strengthened risk mitigation strategies, ensuring that projects were completed successfully and in compliance with established standards and regulations. It also facilitated the timely identification and rectification of issues, significantly enhancing the efficiency and effectiveness of project management.

Digital platform of LAud

After successful completion of the pilot program, a full-functional digital platform of LAud was developed to realize all required processes in the practice. It would increase the depth and breadth of off-site data analysis for engineering audit, delving deeper into the value of data. This platform serves as a comprehensive digital audit approach characterized by "full-volume scanning, precise positioning, systematic analysis, and focused verification" to accurately identify issues within engineering projects. It allowed for a comprehensive understanding of the trends in problem risks, providing a basis for targeted tasks in engineering audit. It could

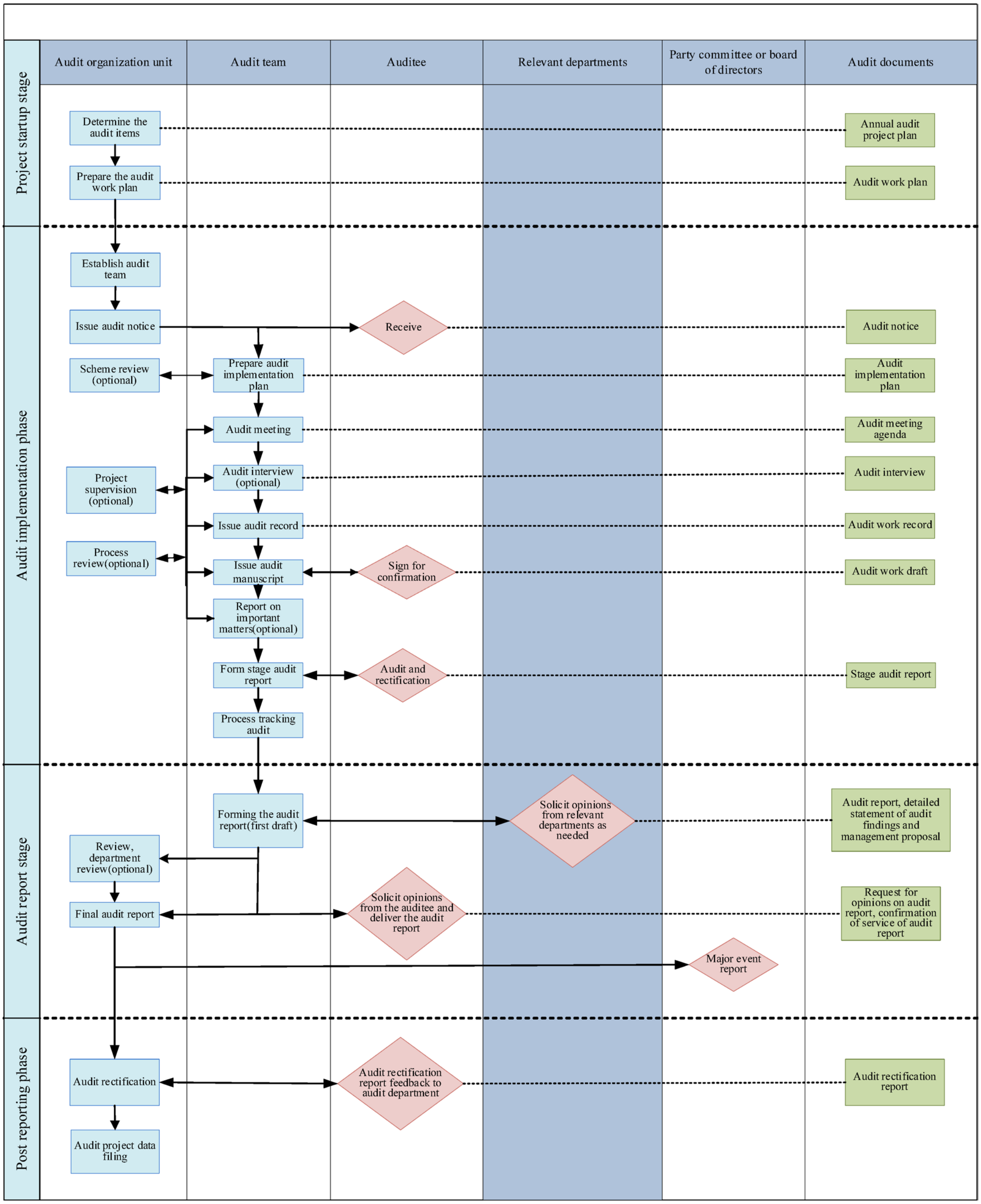

Fig. 3. New workflow incorporating into the LAud framework.

automatically collect the necessary data based on three main layers, namely, decision-making layer, business layer and support layer.

The digital platform of LAud is built on a robust technical architecture that ensures seamless integration with existing enterprise systems. It incorporates advanced integration mechanisms to connect with systems such as ERP (Enterprise Resource Planning) and BIM (Building Information Modeling), enabling smooth data exchange and collaboration. The platform employs standardized interfaces and data protocols to ensure compatibility and efficient data flow between systems. This integration allows for real-time data sharing, eliminating information silos and enhancing the overall efficiency of project management and auditing processes.

In terms of cybersecurity, the platform implements multiple layers of security measures to protect sensitive project and financial data. These include encryption of data in transit and at rest, strict access controls based on user roles and permissions, and continuous monitoring for potential threats. The platform also undergoes regular security audits and vulnerability assessments to ensure its resilience against evolving cyber threats.

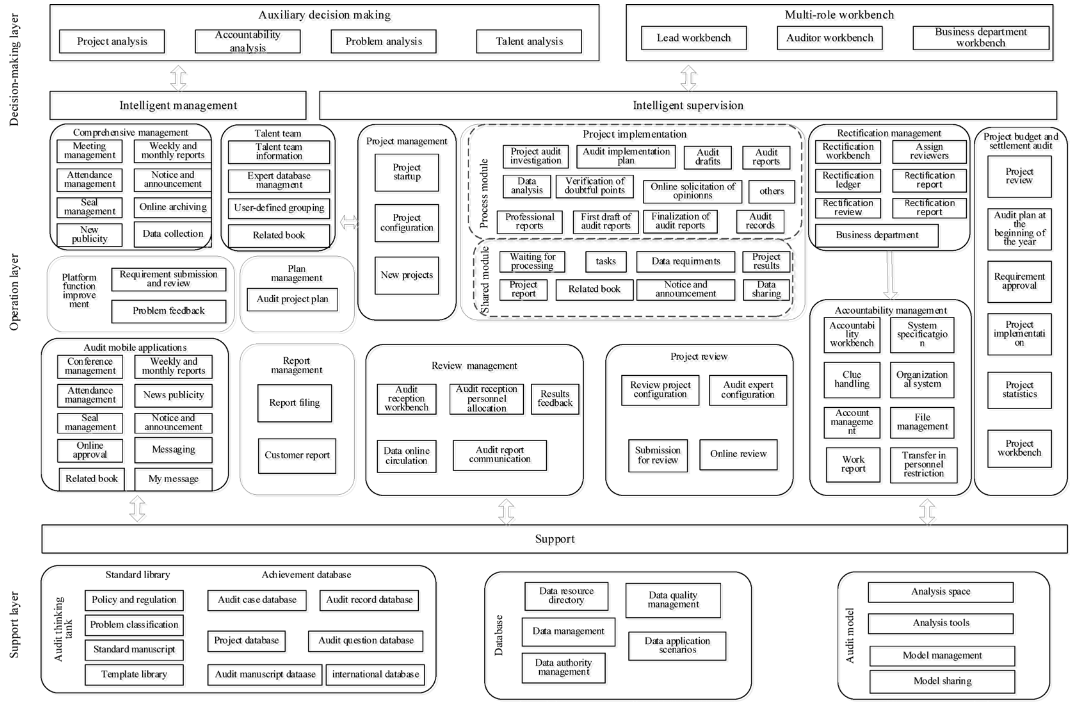

Fig. 4. The technical roadmap of the digital platform for LAud.

Fig. 5. Main interface of the digital platform of LAud.

The technical roadmap of the digital platform of LAud is shown in Fig. 4.

Decision-making layer

The decision making level played a pivotal role in offering high - level guidance and devising strategic plans for audit work in the digital platform. The project analysis module conducted an in - depth examination of various aspects of engineering projects. Cost - benefit analysis was performed to evaluate whether the benefits justified the costs. Schedule control was implemented to ensure projects were completed in a timely manner. Risk assessment was carried out to identify potential threats and develop mitigation strategies. The accountability analysis module functioned to ensure clear assignment of responsibility during the audit process. It accurately identified any violations, enhancing transparency and accountability. The issue analysis module was dedicated to pinpointing and analyzing potential problems within engineering projects, allowing for early detection and mitigation of issues. The talent analysis module assessed the capabilities of the audit team. It ensured that audit tasks were executed by individuals with the right skills and knowledge, sometimes even prompting the organization to tailor training programs and professional development initiatives to enhance the skills of the staff.

Business layer

The business layer constituted the central component of the digital audit platform, directly facilitating the execution of audit workflows. For example, the project management module structured the audit lifecycle by encompassing initiation, planning, execution, and monitoring phases. It ensured adherence to predefined objectives and standards through embedded governance frameworks, enabling systematic progress tracking and resource allocation. The rectification management module prioritized issue resolution through a structured feedback loop. Identified discrepancies were logged, tracked, and validated against corrective actions, ensuring accountability and timely remediation. Collectively, these modules synergized to enhance audit efficiency, compliance, and transparency. The business layer's architecture not only digitized manual processes but also embedded continuous improvement mechanisms, positioning the platform as a scalable solution for evolving audit demands.

Support layer

In the completed platform, the support layer played a crucial in role providing essential backing and resources for the audit work.

The audit knowledge base functioned as a repository. It contained policy regulations, issue classification libraries, and standard working paper templates, serving as a reference and guidance source for auditors. The outcomes repository was utilized to store audit records, issue databases, and international reference materials, supplying historical data and case analyses for future audits. The data resource library, which included a data resource catalog, data quality management, data application scenarios, and data access management, ensured the accuracy and security of audit data.

Within the support and assurance module, the audit knowledge base was divided into a standards library and an outcomes library. The standards library was composed of policy and regulation databases, issue classification libraries, standard working paper templates, template libraries, audit task libraries, standard record templates, audit matter libraries, audit system guidance libraries, rectification standard libraries, regulatory penalty libraries, and rectification standard libraries. The outcomes library consisted of audit case libraries, project material libraries, working paper libraries, audit record libraries, issue libraries, entity material libraries, audit label libraries, audit training libraries, and international reference libraries. It is worth noting that the audit training library had been planned to be launched in the third phase of the platform.

In summary, the digital audit platform had been designed with a multi - role workstation approach, empowered stakeholders to access particular functions and information in line with their needs. This not only enhanced the efficiency and quality of the audit work but also, through in - depth data analysis and mining, lent strong support and assurance to engineering project management. Figure 5 illustrates the main interface of the digital platform of LAud.

Challenges and achievements of the LAud framework

The case study on implementing the LAud framework at State Grid Jiangsu Electric Power Company faced several challenges. The power-grid projects' complexity, varying in scale and technical requirements, demanded auditors to possess extensive technical and managerial knowledge. For instance, substation expansion required coordinating multiple technical systems, while smart grid implementation needed advanced technology integration. Additionally, data integration from diverse sources like project management software and financial systems was hindered by inconsistency and incompatibility, necessitating unified data standards. Resistance to change from staff accustomed to traditional auditing also posed a challenge, requiring extensive communication and training. Ensuring the digital platform's security and stability was another critical concern, demanding significant investment in cybersecurity measures.

However, the LAud framework also brings remarkable achievements. In 2023, State Grid Jiangsu Electric Power Company audited 111,400 engineering projects, covering a total investment of 78.047 billion yuan, and achieved cost savings and revenue increments of 2.902 billion yuan through measures such as reducing engineering costs. The full-process auditing work not only enhanced the efficiency and quality of audits but also significantly improved the management level of engineering projects and the efficiency of fund utilization. Furthermore, the LAud framework played a crucial role in these achievements by providing comprehensive oversight throughout the project lifecycle, enabling early issue identification and risk reduction. The digital platform significantly improved audit efficiency through automated data analysis and report generation, allowing for more accurate and timely project issue identification. The framework strengthened risk control by enabling proactive risk monitoring and mitigation strategies across all project stages, minimizing potential losses. It also supported the company's sustainability goals by ensuring environmental compliance and efficient resource utilization. The post-completion audit offered insights into projects' long-term viability and societal impact, guiding future investment decisions. Furthermore, the digital platform marked a significant step in the company's digital transformation, demonstrating how technology can enhance traditional auditing practices. Finally, the framework fostered better collaboration among stakeholders, improving communication and coordination among various roles within the company.

Discussion

Theoretical contributions

This research has made significant strides in exploring the application of LAud in power-grid projects. Through a qualitative case study approach, we examined the implementation of a full-process LAud model within a state-owned organization's internal audit framework. The study analyzed data from 29 completed power-grid projects and incorporated expert interviews to validate the framework and investigate collaborative governance mechanisms and digital empowerment strategies. The core outcome is the development of a comprehensive LAud framework that covers all critical stages of power-grid projects' lifecycle, from initiation to post-completion audit. This framework has been tested and refined through a pilot program, leading to the creation of a new workflow and a fully functional digital platform for LAud. The results demonstrate that LAud can enhance project governance and sustainability by enabling real-time monitoring, proactive risk mitigation, and continuous data integration, thereby addressing the limitations of traditional auditing methods.

The study advances theoretical discourse by redefining lifecycle auditing as a dynamic, technology-driven governance mechanism rather than a static compliance tool. Traditional auditing frameworks, as critiqued, often prioritize periodic financial reviews, neglecting operational risks embedded in early project phases[23]. By contrast, this research operationalizes LAud as a holistic system that embeds real-time assurance across design, procurement, construction, and operational stages—a paradigm shift aligning the call for resilience-oriented auditing in critical infrastructure[32]. The integration of SCADA systems and IoT sensors for compliance tracking extends foundational work on continuous auditing[25], bridging the gap between financial reporting and engineering integrity. Furthermore, the framework's emphasis on predictive analytics for risk forecasting (e.g., design-phase anomalies) responds to advocacy for AI-enhanced evaluation methods in power projects[14]. This contribution repositions LAud as a cornerstone of sustainable infrastructure governance, harmonizing technical specifications with fiscal accountability.

The second theoretical contribution lies in elucidating the role of collaborative digital ecosystems in overcoming siloed audit practices. Prior studies, such as those by Zhou et al.[35], identified fragmented oversight as a key barrier to infrastructure risk management. This research demonstrates how LAud's digital platform fosters interdisciplinary collaboration among engineers, auditors, and policymakers through shared data interfaces and automated reporting. By aligning real-time audit findings with strategic decision-making, the framework operationalizes the "collaborative assurance" concept proposed by Wahdan et al.[31], which emphasizes cross-functional transparency. These findings extend holistic audit model[36] by embedding stakeholder synergy into lifecycle governance, thereby addressing the feedback loop deficiencies.

The third theoretical contribution is the exploration of the digital empowerment mechanisms within the LAud framework. This research highlights the critical role of technology in enhancing audit efficiency and effectiveness. The developed digital platform for LAud incorporates advanced technologies such as IoT sensors, SCADA systems, and machine learning algorithms. These technologies enable high-frequency audit cycles aligned with project milestones, automated monitoring of technical, financial, and operational parameters, and exception-based auditing supplemented by human expertise for complex judgments[25]. The platform also supports continuous data modeling using inputs from various sources, providing real-time assurance over both financial and non-financial performance indicators. This technological integration addresses the limitations of traditional auditing methods, which often struggle with the dynamic and complex nature of power-grid projects[23,43]. The digital empowerment mechanisms developed in this study provide a theoretical foundation for how technology can transform audit practices in critical infrastructure sectors.

Practical implementations

The implementation of the LAud framework can lead to improved project governance and sustainability by enabling proactive risk identification and immediate corrective actions throughout the project lifecycle. For project managers and auditors, the framework provides a structured approach to tracking progress against planned schedules, budgets, and quality benchmarks, facilitating better decision-making. The digital platform developed in this study offers a scalable solution for continuous auditing and enhances the accuracy and timeliness of audit reports. This can result in significant cost savings and improved project outcomes. Additionally, the collaborative governance mechanisms within the LAud framework promote transparency and accountability among stakeholders, fostering a culture of continuous improvement and alignment with organizational goals.

The LAud framework has enormous potential for widespread application. It can be adapted for use in other types of organizations and industries, though some modifications may be necessary. State-owned enterprises typically prioritize regulatory compliance, public accountability, and long-term societal impacts, aligning with centralized governance structures. In contrast, private enterprises often emphasize cost efficiency, shareholder returns, and agile decision-making, necessitating streamlined audit workflows and faster return-on-investment justification. For example, private enterprises may need to adjust the framework to suit their unique governance models and operational dynamics. Future development of LAud should consider the different needs in private enterprises, while retaining its core principles of real-time monitoring and proactive risk management during its implementation.

The implementation of the LAud framework may encounter several obstacles, such as high costs, training demands, and organizational resistance to innovation. Organizations might be reluctant to invest in new technologies and training programs due to budget constraints. Additionally, integrating the LAud digital platform with existing systems like ERP and BIM can be complex. To address these issues, organizations should conduct thorough cost-benefit analyses to demonstrate the long-term advantages of adopting LAud. Developing comprehensive training programs and effective change management strategies can help overcome resistance and ensure a smooth implementation process.

When compared to other contemporary audit models, the LAud framework offers several advantages. Traditional audit models typically focus on periodic financial reviews, often overlooking operational risks across project phases. In contrast, this framework provides continuous, real-time monitoring across all project stages, from design to operation. This holistic approach enables early risk detection and timely corrective actions. While other models may offer valuable insights, LAud uniquely combines technical, financial, and operational data using advanced technologies like IoT sensors and machine learning algorithms, providing a more comprehensive view of project performance. The framework's emphasis on proactive risk mitigation and continuous improvement further distinguishes it from models that primarily rely on post-hoc analysis. These features make the LAud framework a superior choice for auditing complex infrastructure projects.

Conclusions

This study has made significant progress in exploring the application of Lifecycle Auditing (LAud) in power-grid projects. The research has developed a comprehensive LAud framework that covers all critical stages of power-grid projects' lifecycle, from initiation to post-completion audit. This framework has been tested and refined through a pilot program, leading to the creation of a new workflow and a fully functional digital platform for LAud. The results demonstrate that LAud can enhance project governance and sustainability by enabling real-time monitoring, proactive risk mitigation, and continuous data integration, thereby addressing the limitations of traditional auditing methods.

However, this research also has some limitations. First, the study was conducted in a single state-owned organization, which may limit the generalizability of the findings to other contexts. Particularly, the observed differences between state-owned and privately-owned organizations—such as variance in regulatory pressure and change-management flexibility—suggest that the generalizability of the LAud framework may be context-dependent. Future studies should test the framework across ownership types to delineate how governance structures influence adoption success and required adaptations. Second, while the digital platform for LAud has shown promise, its full potential may not have been fully realized due to the complexity of integrating various technologies and data sources. Further development and testing of the platform are needed to ensure its robustness and scalability. Third, the study primarily focused on the technical and operational aspects of LAud, with limited attention to the human factors and organizational culture that can influence its implementation. Future research could investigate how to foster a culture of continuous auditing and risk management within organizations to fully leverage the benefits of LAud.

Data availability

Data is provided within the manuscript.

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Mo Zhou: Conceptualization, methodology, software, validation, formal analysis. Yinhao Chen: Validation, formal analysis, investigation. Liuzao Zhou: Visualization, supervision, project administration. Jizhou Zhan: Conceptualization, supervision, project administration, funding acquisition, writing—review and editing. Heap-Yih Chong: Conceptualization, supervision, project administration, writing—review and editing.

Declarations

Competing interests
The authors declare no competing interests.

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