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The Role of Engineering Leadership in Delivering National Power Infrastructure Projects: An Archival Multi-Case Study of Eight Large-Scale Projects

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ABSTRACT

Background: National power infrastructure projects combine high capital intensity, tightly coupled technical systems, public accountability, long asset lives and extensive inter-organizational interfaces. Although megaproject research has documented persistent cost and schedule underperformance, the specific contribution of engineering leadership - understood as a project-level socio-technical integration capability rather than the traits of a single manager - remains under-specified.

Objective: This study examined how engineering leadership architecture relates to delivery outcomes in nationally significant power projects.

Methods: A comparative archival case study was conducted across eight projects in Pakistan, the United Arab Emirates, Morocco, the United States, Finland, France and South Africa. Publicly verifiable regulatory, sponsor, government, multilateral and peer-reviewed records were coded using a six-domain Engineering Leadership Integration Index (ELII; range 0-12): technical authority and systems integration; interface and stakeholder coordination; risk and quality escalation; learning and knowledge transfer; supply-chain and workforce capability; and governance and change control. Delivery was coded independently using a three-domain Delivery Performance Index (DPI; range 0-6) covering schedule, cost stewardship and functional commissioning. Cross-case pattern matching and Spearman rank analysis were used.

Results: ELII scores ranged from 3 to 12 and DPI scores from 1 to 5. Projects with explicit technical integration, early regulator/stakeholder interfaces, institutionalized learning and capability development, and disciplined change governance showed stronger delivery profiles. The ELII was strongly associated with the DPI (Spearman rho=0.900; exact two-sided permutation p=0.0048). Because cost data were not comparably disclosed for three projects, a sensitivity analysis excluding the cost component remained positive (rho=0.710; exact p=0.0417). The strongest contrast was between projects characterized by proactive integration and learning and those in which design defects, fragmented interfaces and corrective action became prominent late in delivery.

Conclusions: Engineering leadership appears to function as an integrative delivery system that connects technical authority, governance, learning and organizational interfaces. The findings do not establish causality, but they provide a reproducible framework for studying engineering leadership in power megaprojects and suggest that owner organizations should institutionalize technical authority, interface governance, early risk escalation and learning before construction intensity peaks.

Keywords: engineering leadership; megaprojects; power infrastructure; systems integration; project governance; energy infrastructure; project performance; comparative case study

1. INTRODUCTION

Electric-power infrastructure is among the most consequential classes of public and quasi-public capital investment. Large generating assets must convert policy objectives, financing structures, engineering designs, regulatory requirements, procurement packages, construction work fronts, commissioning procedures and long-term operating obligations into a single functioning socio-technical system. The resulting projects are exposed simultaneously to technological novelty, interface density, stakeholder conflict, supply-chain constraints and political scrutiny. These features place many power developments within the broader megaproject literature, where large scale, long duration and organizational complexity repeatedly generate schedule slippage, cost escalation and benefit uncertainty [1-4].

Research on megaproject performance has moved beyond the idea that underperformance is explained simply by weak scheduling or inaccurate estimating. Systems integration, contracting arrangements, governance, risk allocation, institutional incentives, learning and inter-organizational coordination all shape outcomes [2-6]. In complex projects, technical subsystems are frequently delivered by separate organizations, yet they must work as one operational whole. This makes integration a management problem and an engineering problem at the same time. Studies of the London 2012 programme, Heathrow Terminal 5 and other complex projects show that effective delivery depends on organizational capabilities that connect technical knowledge with cross-boundary decision making [5,6].

Leadership is therefore relevant, but the usual treatment of project leadership is incomplete for national power infrastructure. Project-management studies have linked leadership competencies and transformational leadership to project success, team building and context-specific performance [7-10]. Engineering-leadership research additionally emphasizes technical credibility, systems thinking, ethical accountability, problem framing and resource stewardship [11-14]. Recent work on large complex projects argues explicitly that systems-engineering capability is central to effective leadership because leaders must manage requirements, interfaces, verification and emergent system behavior, not only motivate teams [12].

A further limitation is the tendency to conceptualize leadership as an attribute of an individual project manager. National power projects are rarely controlled by one individual. Authority is distributed across owners, engineering functions, EPC contractors, regulators, financiers, original equipment manufacturers, operators and public agencies. The practical question is therefore not only whether a project has a capable leader, but whether the project has a leadership architecture that can maintain an authoritative technical baseline, integrate interfaces, escalate quality and risk information, preserve institutional learning, develop the workforce and govern consequential changes. This paper uses the term engineering leadership architecture to describe that project-level capability.

Contemporary evidence strengthens the case for this system-level view. Planning affects megaproject performance partly through process and information integration [16]. Recent studies also show that governance, trust and stakeholder integration influence performance across large public and construction projects [17,18]. Risk research similarly demonstrates that project threats are interconnected across technical, economic, environmental, social and political domains [19,20]. Recent reviews and empirical and theoretical studies continue to identify governance, accountability, complexity management, early project conception and organizational integration as recurring weaknesses in megaproject delivery [21-27].

Power infrastructure provides a useful setting for testing these ideas because the sector contains highly visible contrasts. Some projects have achieved rapid construction or systematic capability transfer, while others have experienced prolonged delays, major cost escalation, design non-conformances, contractual disputes or post-commissioning defect remediation. Importantly, these differences cannot be reduced to one technology: nuclear, coal and concentrating-solar projects all face distinct but comparable integration challenges. The comparison therefore allows engineering leadership to be examined as a cross-technology delivery capability rather than as a technology-specific practice.

This study addresses two research questions. RQ1: Which project-level engineering leadership practices distinguish stronger from weaker delivery profiles in national power infrastructure projects? RQ2: Is a higher level of engineering leadership integration associated with stronger schedule, cost and commissioning outcomes across a diverse set of large power projects? The study contributes by developing and applying an original Engineering Leadership Integration Index (ELII), triangulating it against verifiable project records, and comparing it with an independently coded Delivery Performance Index (DPI). Figure 1 summarizes the conceptual model.

2. METHODS

2.1 Study design and unit of analysis

An embedded comparative archival case-study design was used [42,43]. The unit of analysis was the project-level engineering leadership architecture during development, construction, commissioning and early operational transition. The design is deliberately distinct from a biographical leadership study: it does not infer personality, motivation or competence of named individuals. Instead, it codes observable organizational arrangements and documented delivery practices that reflect how technical authority and coordination were structured.

Case selection followed maximum-variation logic. Projects were eligible when they were nationally significant grid-scale generation investments; had substantial construction and commissioning activity during the twenty-first century; had reached commercial operation or a sufficiently mature commissioning state by the evidence cutoff of 10 December 2025; and had enough public documentation to separate leadership-process evidence from outcome evidence. Eight cases were selected: Sahiwal Coal Power Project (Pakistan), Barakah Nuclear Energy Plant (United Arab Emirates), Noor Ouarzazate II-III (Morocco), Plant Vogtle Units 3-4 (United States), Olkiluoto 3 (Finland), Flamanville 3 (France), Medupi (South Africa) and Kusile (South Africa). This produces variation in technology, contracting model, regulatory regime and delivery performance while retaining a common requirement for complex engineering integration.

Evidence was collected through targeted searches of regulator and government portals, project-owner repositories, multilateral development-bank records, nuclear and energy agencies, and peer-reviewed publisher platforms. Searches were completed and verified through 10 December 2025. Preference was given to primary or authoritative institutional records for dates, capacities, budgets, commissioning milestones, defects and regulatory events. Peer-reviewed literature was used primarily to define the leadership and integration constructs and, where available, to contextualize documented mechanisms. Secondary media reports were not used to establish primary numeric outcomes when an official or institutional source was available.

Documentary content was analyzed using directed qualitative content analysis [44]. A priori dimensions were derived from engineering-leadership, systems-integration, governance, project-risk and organizational-learning literature [5-14,16-31]. Each case was first summarized in a factual extraction sheet containing technology, capacity, baseline or announced completion expectations, commercial-operation dates, cost evidence, major technical or governance events and evidence of organizational integration. Leadership domains were then coded separately from delivery outcomes to reduce circularity. After all cases were scored, every score was rechecked against its cited evidence and the same decision rules were re-applied across cases.

2.2 Engineering Leadership Integration Index

The ELII operationalized engineering leadership as six observable project-system capabilities. Each dimension received 0, 1 or 2 points. A score of 0 indicated documented material deficiency or fragmentation; 1 indicated partial, mixed, late or inconsistently institutionalized evidence; and 2 indicated proactive and project-wide institutionalization during a consequential delivery phase. The total range was 0-12. Table 1 provides the coding rubric. The index is an author-constructed research instrument, not an official project metric.

2.3 Delivery Performance Index and statistical analysis

The DPI was coded independently from ELII evidence and combined three ordinal domains: schedule, cost stewardship and functional commissioning, each scored 0-2 (total 0-6). Schedule thresholds were anchored to the earliest sufficiently explicit public baseline or announced commercial-operation target available in the reviewed records. Cost scores used comparable baseline/final values where available. When a project did not have a publicly comparable final cost series, it was assigned the conservative midpoint score of 1 rather than being classified as on-budget. Functional commissioning captured whether the delivered asset reached its intended operational state and whether material design defects or prolonged technical outages remained evident at case closure.

Analysis proceeded in three stages. First, cross-case pattern matching compared leadership architecture with documented delivery mechanisms. Second, dimensional profiles were visualized to identify recurring strengths and deficits. Third, the association between ELII and DPI was estimated with Spearman's rank correlation because both variables are ordinal and the sample is small. Statistical significance was evaluated using an exact two-sided permutation test over all 40,320 permutations of the observed DPI scores. A pre-specified sensitivity analysis removed the cost component, because comparable cost disclosure was incomplete for Sahiwal, Barakah and Noor. Statistical results are treated as exploratory; the study is not powered for causal estimation and does not assume independence of national institutional contexts.

2.4 Ethics and research integrity

The study used publicly available organizational, regulatory, audit, institutional and peer-reviewed documents and did not involve human participants, personal data or intervention; formal human-subject ethics approval was therefore not required. No interviews, questionnaires or unpublished participant data were fabricated or inferred. All numerical outcome claims are linked to the sources listed in the references, while the ELII and DPI are explicitly identified as researcher-constructed coding instruments.

3. RESULTS

3.1 Case characteristics and delivery outcomes

The eight projects span three major generation technologies and seven national contexts. Their delivery trajectories vary markedly (Table 2). Sahiwal reached commercial operation on 28 October 2017 after both 660 MW units were inaugurated earlier that year [45]. Barakah established the Arab world's first multi-unit nuclear power programme, with the four 1,400 MW APR1400 units moving into commercial operation sequentially between 2021 and 2024; however, initial public schedules had anticipated the first unit in 2017 and the fourth in 2020 [47-49]. Noor II became operational in April 2018 and Noor III completed performance testing in October 2018, with the latter documented as approximately 12 months behind schedule [50].

The European and U.S. nuclear cases experienced much larger baseline deviations. Vogtle Units 3-4 were originally expected to cost about US$14 billion and enter commercial operation in 2016 and 2017; the project ultimately exceeded US$30 billion, with Units 3 and 4 entering commercial operation in July 2023 and April 2024, respectively [51-53]. Olkiluoto 3 began regular electricity production in April 2023, roughly fourteen years later than the original 2009 commercial-operation target; OECD-NEA documentation records an estimated project cost approximately EUR8 billion above initial projections [54,55]. Flamanville 3 moved from an original approximately EUR3.3 billion estimate and 2012 operating target to a EUR13.2 billion completion estimate (2015 euros), first grid connection in December 2024, followed by staged commissioning and power ascension during 2025 [56,57].

South Africa's Medupi and Kusile eventually achieved full fleet commercial operation, but official Eskom records acknowledge design and execution shortcomings, schedule delays, labour disruption, contractual disputes, corruption-related matters and cost escalation [58-60]. Medupi's last unit entered commercial operation in July 2021, while agreed technical solutions for boiler design defects still required implementation [58]. Kusile Unit 6 entered commercial operation on 29 September 2025 [59]. These cases therefore provide a useful contrast between completion as an administrative milestone and the deeper engineering question of whether defects, reliability and system integration have been stabilized.

3.2 Engineering leadership profiles

ELII scores ranged from 3 to 12 (median 6.5). Barakah scored highest (12), followed by Noor II-III (11) and Sahiwal (10). Olkiluoto 3 scored 7; Vogtle and Flamanville 3 scored 6; and Medupi and Kusile scored 3. The dimension with the lowest cross-case mean was risk and quality escalation (0.875/2), while interface coordination, learning and supply-chain/workforce capability each averaged 1.375/2. The distribution is shown in Figure 2 and the underlying scores in Table 3.

The high-ELII cases shared several features despite different technologies. At Barakah, the programme deliberately combined a reference-plant strategy, a prime contractor with prior APR1400 experience, early regulatory institution-building, international expert recruitment, workforce nationalization and a formal roadmap organized around plant, people and processes [48,49]. The IAEA record explicitly identifies early regulator engagement, milestone-based planning, international peer support, mentoring and structured development of domestic expertise as good practices [49]. Noor similarly demonstrates coordinated owner-level implementation and project learning across phases; World Bank reporting documents satisfactory implementation progress overall while also recording a one-year delay for Noor III [50]. Sahiwal combined compressed execution with supplier and logistics coordination in a context where rapid delivery was strategically important [45,46].

By contrast, the middle- and low-ELII cases show recurring evidence of corrective rather than anticipatory integration. Vogtle ultimately completed successfully from an operational standpoint, but its delivery history includes first-of-a-kind design maturation, contractor and vendor-management challenges, quality-assurance/testing pressures and schedule instability [51-53]. Olkiluoto 3 and Flamanville 3 similarly demonstrate the consequences of design maturity, manufacturing quality, contract boundaries and late technical remediation in early EPR deployments [54-57]. Eskom's own retrospective statements on Medupi and Kusile emphasize the need for more planning and design effort upfront and acknowledge design/execution shortcomings, labour disruption and contractual problems [60].

3.3 Association between engineering leadership integration and delivery performance

DPI scores ranged from 1 to 5 (median 2.0). Sahiwal recorded the highest DPI (5), followed by Barakah and Noor II-III (3 each); Vogtle, Olkiluoto 3 and Flamanville 3 each scored 2; Medupi and Kusile each scored 1 (Table 4). Across all eight cases, ELII and DPI were strongly positively associated (Spearman rho=0.900; exact two-sided permutation $p=0.0048$). The relationship is shown in Figure 3. The result should be interpreted as cross-case pattern evidence, not as an estimate of the causal effect of leadership.

The three projects with ELII >=10 had a mean DPI of 3.67, compared with 1.60 among the remaining five cases. Importantly, Barakah illustrates why leadership should not be equated with schedule success alone: its ELII is high because of documented integration, capability development and governance practices, while its DPI is moderated by a multi-year delay relative to the original announced unit schedule. This divergence supports the conceptual separation between leadership-process quality and outcome realization.

Because comparable final cost disclosure was incomplete for Sahiwal, Barakah and Noor, cost-indeterminate projects were conservatively assigned the midpoint cost score of 1. When the cost component was removed entirely, the association remained positive (Spearman rho=0.710; exact $p=0.0417$). The reduced magnitude is expected because schedule dominates the residual two-component outcome score and because several technically successful nuclear projects were substantially late. The sensitivity result nonetheless indicates that the primary finding is not solely an artifact of how missing cost data were handled.

3.4 Cross-case mechanisms

Pattern matching identified four mechanisms that repeatedly separated the stronger leadership architectures from weaker ones. First, technical authority had to operate across organizational boundaries. A design may be locally correct while the plant-level system remains unintegrated; therefore, the relevant leadership task is to maintain system requirements, interfaces, verification logic and configuration decisions across packages. This pattern is consistent with systems-integration research in other megaproject settings [5,12,31,37,41].

Second, early escalation was more valuable than late technical heroics. The low-scoring cases are not devoid of engineering expertise; indeed, large technical teams eventually solved many difficult problems. The distinction is temporal and institutional. Where defects or interface failures became visible after substantial construction, correction required redesign, rework, additional outages, contract negotiation and schedule re-baselining. The practical leadership advantage therefore appears to lie in creating forums and authority paths that surface weak signals before they become embedded physical work [19,20,30,31].

Third, capability development mattered where the owner or national system was initially inexperienced. Barakah is the clearest example: foreign subject-matter experts were paired with deliberate national workforce development, regulator capacity-building, mentoring and recurring international review [49]. This is different from simple staff augmentation. It creates a learning system that can absorb specialist knowledge while preserving owner accountability. Noor and Sahiwal also show evidence of local supplier/workforce integration, although the documentation is less extensive [46,50].

Fourth, governance and contracting shaped whether engineering information could trigger action. Fixed-price or turnkey arrangements can clarify responsibility but do not eliminate technical interdependence, as illustrated by Olkiluoto 3's long-running disputes and the wider megaproject literature on risk transfer [3,55]. Likewise, owner-contractor relationships that rely primarily on formal allocation without relational integration can allow local optimization to undermine project-system performance. Recent evidence on trust, hybrid governance and stakeholder integration supports this interpretation [17,18,24,36].

4. DISCUSSION

4.1 Principal findings

This study set out to examine the role of engineering leadership in national power infrastructure delivery without reducing leadership to the personality of a project manager. The principal finding is that projects with stronger documented engineering leadership architectures also tended to have stronger delivery outcomes. The observed rank association is large, remains positive when the cost component is removed, and is supported by qualitative mechanism evidence. However, the most important contribution is not the correlation coefficient. It is the identification of a recurring delivery architecture: authoritative technical integration, structured interfaces, early risk and quality escalation, deliberate learning, capability development, and governance that can convert engineering evidence into timely decisions.

This interpretation aligns with the broader shift in megaproject scholarship from isolated success factors toward systems of interdependent capabilities. Denicol et al. [2] synthesize poor performance as a multi-dimensional problem involving behavior, strategy, governance, risk and supply chains. Sanderson [3] emphasizes uncertainty and governance rather than assuming that more detailed ex ante control is sufficient. Davies and Mackenzie [5] show how system integration becomes an organizational capability, while Brady and Davies [6] distinguish structural complexity from dynamic complexity. The present study extends these arguments into power infrastructure by positioning engineering leadership as the coordinating capability that holds these elements together.

The findings are also consistent with engineering-leadership literature. Technical credibility, systems thinking and problem framing distinguish engineering leadership from generic managerial leadership [11-14]. Yet the power-project cases suggest that these competencies only matter at scale when they are institutionalized. A highly competent chief engineer cannot compensate indefinitely for fragmented governance, immature design interfaces, weak supplier quality or incentives that delay bad news. Engineering leadership in megaprojects must therefore be designed into the project organization through decision rights, assurance processes, integration offices, interface registers, configuration control, technical review forums and learning routines.

The contrast between Barakah and the European first-of-a-kind EPR projects is instructive but should not be simplified into a technology verdict. Barakah benefited from a reference-plant strategy and repeat-unit learning, but it also built regulatory and workforce capability deliberately and engaged international institutions early [48,49]. Olkiluoto 3 and Flamanville 3 confronted first-of-a-kind design, manufacturing and regulatory challenges in settings where late technical remediation and contractual boundaries became consequential [54-57]. The implication is not that standardization guarantees success. Rather, standardization creates value when leadership protects configuration discipline, captures lessons across units and prevents design changes from fragmenting the system baseline.

Sahiwal provides a different pattern. Its rapid execution indicates that decisive coordination, logistics and supply-chain mobilization can compress delivery time [45,46]. However, fast completion should not be interpreted as proof of globally superior project performance because the present study does not evaluate environmental externalities, fuel-price exposure, financing sustainability or long-term policy value. This distinction is important. The DPI measures delivery execution, not whether the underlying investment was socially optimal. Megaproject research increasingly recognizes that success has multiple dimensions beyond the traditional cost-time-scope triangle [26,34,35].

Similarly, the South African cases demonstrate why commercial operation is not an adequate standalone success criterion. Medupi and Kusile ultimately added large amounts of generation capacity, and later recovery programmes improved important technical problems. Nevertheless, official records describe design and execution shortcomings, boiler defects, contractual disputes and other governance challenges that extended beyond nominal unit completion [58-60]. Engineering leadership should therefore be evaluated through the lifecycle transition from design to construction, commissioning and stable operation. An asset that reaches a contractual milestone while carrying major unresolved defects transfers project risk into operations rather than eliminating it.

The quantitative result requires restraint. With only eight purposively selected cases, the correlation can be influenced by case composition, ordinal scoring and common institutional features. In addition, ELII is partly reconstructed from retrospective documents, which may selectively report successful initiatives or failures. The analysis cannot establish that increasing ELII by one point would cause a predictable increase in delivery performance. The correct interpretation is configurational: stronger leadership integration co-occurs with stronger delivery outcomes in this sample and the underlying documentary mechanisms are theoretically coherent with prior research.

4.2 Implications for engineering leaders and owner organizations

The first practical implication is to establish a project-level technical authority model before high-volume construction begins. The model should specify who owns the system architecture, who approves deviations from requirements, how package-level engineering decisions are reconciled, and how commissioning feedback changes the design baseline. In projects delivered through multiple EPC packages or major subcontractors, interface authority should be explicit rather than assumed. Systems integration is an owner capability even when design and construction are outsourced.

Second, risk governance should privilege early escalation over optimistic schedule preservation. A project culture that penalizes the reporting of non-conformances can create the appearance of progress while increasing latent rework. Engineering leaders should define objective escalation triggers for safety-significant quality issues, interface deviations, vendor performance deterioration, configuration changes and test failures. Independent design assurance and constructability/commissionability reviews should have direct access to executive governance rather than being filtered exclusively through delivery organizations whose incentives are tied to short-term progress.

Third, capability-building should be tied to the project learning curve. New nuclear programmes illustrate this most clearly, but the principle applies to any country introducing unfamiliar technology. Workforce plans should identify which capabilities must be permanently resident in the owner/operator, which can remain supplier-provided and how knowledge will be transferred between them. Repeat-unit programmes should make lesson capture an engineered process: issue taxonomies, root-cause repositories, design freeze criteria, standardized work packages and formal feedback from commissioning to engineering can turn experience into measurable schedule and quality gains.

Fourth, governance should align commercial incentives with system performance. Contracts define responsibilities, but complex projects inevitably generate uncertainty that no contract can fully specify in advance [3,27]. Owner organizations therefore need both contractual clarity and relational mechanisms for joint problem solving. Governance forums should distinguish ordinary commercial disputes from urgent technical decisions so that the latter are not delayed by unresolved allocation of financial liability. In safety-critical projects, the authority to stop, investigate and correct work must be insulated from pressure to preserve milestone optics.

Fifth, project dashboards should include leading integration indicators, not only lagging cost and schedule indicators. Useful measures include open high-severity technical decisions, ageing interface actions, repeat non-conformances, unresolved configuration deviations, verification backlog, engineering change churn, vendor quality escapes, commissioning retest rates, turnover of critical technical roles and closure time for independent assurance findings. These indicators translate engineering leadership into operational signals that boards and programme executives can govern.

4.3 Theoretical contribution

The study contributes a project-system interpretation of engineering leadership. Existing leadership research often begins with leader behavior and examines downstream team or project outcomes [7-10]. The ELII instead begins with the socio-technical functions that must be performed for a complex engineered asset to cohere. This shifts the theoretical emphasis from who the leader is to what leadership architecture enables the project system to do. It is compatible with competency theories - because technical, adaptive and relational capabilities are still required - but it locates those competencies within distributed organizational structures.

The framework also provides a bridge between leadership and systems-integration research. Systems integration explains how technically interdependent components are coordinated [5,31,37,41]; leadership research explains how direction, influence, judgment and collective action are generated [7,14]. In national power projects, these domains converge because technical decisions carry commercial, regulatory and political consequences. Engineering leadership is therefore best conceptualized as a boundary-spanning capability that converts technical knowledge into coordinated organizational action under uncertainty.

4.4 Limitations and future research

Several limitations should guide interpretation. First, the case sample is small and purposive. It is suitable for analytical comparison but not population-level inference. Future studies should apply the framework to larger samples of generation, transmission and grid-modernization projects and use multilevel models that account for country, technology and procurement regime.

Second, the ELII is a new researcher-constructed index. Although its dimensions are grounded in established literature and the coding rules are transparent, formal validation is required. Future research should test content validity with expert panels, inter-rater reliability with independent coders, convergent validity against systems-engineering maturity measures and predictive validity using prospectively collected project data.

Third, documentary evidence is uneven. Projects differ in transparency, accounting conventions and the level at which costs are reported. The midpoint treatment of unclassifiable cost data was intentionally conservative and a sensitivity analysis was provided, but harmonized cost databases would improve comparability. Future work should distinguish overnight construction cost, financing cost, owner cost, contractor loss, regulated recovery and lifecycle cost.

Fourth, leadership and delivery are endogenous. Stronger projects may create conditions in which leadership practices are easier to institutionalize, while crises can trigger later governance improvements. Longitudinal process tracing is needed to establish temporal sequencing - for example, whether the introduction of a systems-integration office precedes improvements in interface closure and commissioning performance.

Finally, the DPI deliberately focuses on delivery execution. It does not measure full public value, carbon performance, affordability, environmental justice, political legitimacy or long-term reliability. These outcomes matter for national infrastructure and should be added in future benefit-realization research rather than conflated with construction delivery [26,34].

5. CONCLUSION

National power infrastructure is delivered through engineered systems and organizational systems at the same time. This archival multi-case study suggests that engineering leadership is most useful when understood as the architecture that integrates those two systems. Across eight projects, stronger technical authority, interface coordination, risk and quality escalation, institutional learning, capability development and change governance were associated with stronger delivery outcomes. The cross-case association was substantial, but the small, heterogeneous sample and researcher-coded measures mean the result should be treated as hypothesis-strengthening rather than causal proof.

For practice, the implication is clear: engineering leadership should be designed before construction intensity peaks. Owners should establish technical decision rights, systems-integration capability, independent assurance, escalation pathways, learning routines and workforce-development mechanisms as core elements of project governance. Contracting can distribute work and risk, but it cannot substitute for owner-level integration. In complex power programmes, the ability to make technically credible decisions early - and to make them across organizational boundaries - is itself a strategic delivery capability.

For research, the ELII offers a reproducible starting point for measuring that capability. Larger prospective studies, independent coding and project-level leading indicators can test whether the architecture identified here predicts delivery performance across technologies and countries. Such work would help move engineering leadership research from generalized prescriptions toward empirically testable mechanisms for delivering infrastructure on which national energy systems depend.

DECLARATIONS

Ethics approval

Not required; the study used publicly available documentary data and involved no human participants or identifiable private data.

Consent for publication

Not applicable.

Data availability

All case-level scores used in the analysis are reported in Tables 3 and 4. Source records supporting the factual case data are cited in the reference list.

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APPENDIX A. REPRODUCIBILITY NOTE FOR CASE CODING

The coding in Tables 3 and 4 is intended to be auditable. ELII scores represent the strength of documented project-level practices, not judgments about the personal ability of named leaders. A score of 2 requires affirmative evidence that a practice was institutionalized before or during a consequential delivery phase; a score of 1 is used for partial, mixed or substantially corrective evidence; and a score of 0 requires documentary evidence of a material deficiency or breakdown. DPI scores are based on observed project outcomes using the thresholds in Table 1. Researchers replicating the study should retain the same thresholds, independently code the project documents, record the specific source passage used for each score and report any disagreement before consensus. The present analysis should be considered an initial validation exercise for the ELII rather than a finalized psychometric instrument.

Table 1. Operational definitions and scoring rules for the Engineering Leadership Integration Index and Delivery Performance Index.

Domain	0 points	1 point	2 points
Technical authority & systems integration	Material design/integration deficiencies; unclear or fragmented technical authority.	Mixed or corrective integration; authority exists but is late, partial or inconsistently effective.	Clear technical authority, requirements discipline and proactive system/interface integration.
Interface & stakeholder coordination	Persistent interface fragmentation or unresolved cross-organizational coordination failures.	Coordination mechanisms exist but are uneven or substantially reactive.	Formal, early and recurring coordination across owner, contractors, regulator and/or public stakeholders.
Risk & quality escalation	Material risks/non-conformances remain unaddressed or surface late without effective escalation.	Risk/quality systems exist but show delayed or mixed escalation performance.	Early identification, independent challenge, transparent escalation and closure of technical/quality risk.
Learning & knowledge transfer	Little evidence of systematic learning or transfer across units/phases.	Some training/learning or late corrective learning.	Institutionalized lessons learned, reference-plant/unit learning, mentoring or deliberate knowledge transfer.
Supply-chain & workforce capability	Capability gaps materially constrain delivery.	Capability development is present but uneven or largely corrective.	Structured supplier development, workforce qualification and capacity-building aligned with project needs.
Governance & change control	Weak accountability/change control or material governance breakdowns documented.	Formal governance exists but major instability, dispute or corrective intervention is evident.	Clear accountability, stage-gate/change discipline and timely governance of consequential decisions.
DPI - Schedule	>25% slippage or >2 years beyond announced/baseline target.	Approximately 5-25% slippage or moderate delay.	On/before baseline or <=5% slippage.
DPI - Cost stewardship	>30% over baseline/comparable estimate.	10-30% overrun OR final comparable cost not publicly classifiable.	Within 10% of comparable baseline.
DPI - Functional commissioning	Major unresolved functionality shortfall or not operational.	Operational but material defect remediation/recurrent major outage affects intended function.	Commercially operational with intended core function demonstrated and no material unresolved design defect identified at case closure.

Table 2. Comparative profile of the eight national power infrastructure cases.

Project / country	Technology; capacity	Initial public target / baseline	Observed commissioning status	Cost / delivery evidence	Key sources
Sahiwal / Pakistan	Supercritical coal; 1,320 MW	Implementation milestones 2015-2017; rapid CPEC delivery window	Commercial operation 28 Oct 2017	Public project cost about US$1.912bn; no comparable final overrun series used in DPI	[45,46]
Barakah / UAE	Nuclear APR1400 x4; 5,600 MW	Unit 1 completion announced for 2017; Unit 4 for 2020	Units entered commercial operation 2021-2024	Comparable final programme cost not used; strong evidence of staged capability and regulatory development	[47-49]
Noor Ouarzazate II-III / Morocco	Concentrating solar power; 350 MW combined	World Bank programme schedule; Noor III target earlier than actual	Noor II operational Apr 2018; Noor III performance tests Oct 2018	Noor III documented ~12 months late; later technical/storage issues affected availability	[50]
Vogtle 3-4 / USA	Nuclear AP1000 x2; ~2,234 MW	Commercial operation 2016/2017; ~US$14bn	Unit 3 Jul 2023; Unit 4 Apr 2024	Total project estimate >US$30bn; major prudency and cost-recovery proceedings	[51-53]
Olkiluoto 3 / Finland	Nuclear EPR; ~1,600 MW	Commercial operation Apr 2009	Regular production 16 Apr 2023; commercial operation May 2023	~14 years late; estimated project cost ~EUR8bn above initial projections	[54,55]
Flamanville 3 / France	Nuclear EPR; 1,669 MW gross	Commercial operation 2012; ~EUR3.3bn	Grid connection Dec 2024; staged commissioning and power ascension during 2025	Completion estimate EUR13.2bn (2015 euros); weld-related remediation and added studies	[56,57]
Medupi / South Africa	Supercritical coal; 4,764 MW	Build began 2007; earlier completion expectations substantially missed	Last unit commercial Jul 2021	Approved construction budget later R145bn; boiler/design defect remediation continued after unit handover	[58,60]
Kusile / South Africa	Supercritical coal; 4,800 MW	Build programme experienced prolonged delay	Unit 6 commercial 29 Sep 2025	Approved construction budget R160.5bn; design/execution, labour, contract and governance problems acknowledged	[59,60]

Table 3. Engineering Leadership Integration Index scores by case.

Project	TA/SI	IC	RQ	LK	SC/WC	GA/CC	ELII total
Sahiwal	2	2	1	1	2	2	10
Barakah	2	2	2	2	2	2	12
Noor II-III	2	2	1	2	2	2	11
Vogtle 3-4	1	1	1	1	1	1	6
Olkiluoto 3	1	1	1	2	1	1	7
Flamanville 3	1	1	1	1	1	1	6
Medupi	0	1	0	1	1	0	3
Kusile	0	1	0	1	1	0	3

Abbreviations: TA/SI, technical authority and systems integration; IC, interface coordination; RQ, risk and quality escalation; LK, learning and knowledge transfer; SC/WC, supply-chain and workforce capability; GA/CC, governance/accountability and change control.

Table 4. Delivery Performance Index scores and outcome interpretation.

Project	Schedule	Cost	Functional commissioning	DPI total	Interpretive basis
Sahiwal	2	1	2	5	Rapid completion; comparable final cost variance not independently classifiable; commercial operation achieved.
Barakah	0	1	2	3	Original unit schedule slipped by several years; final comparable programme cost not used; all four units commercially operational.
Noor II-III	1	1	1	3	Noor III about 12 months late; cost variance not comparably classifiable; later thermal-storage/availability issues.
Vogtle 3-4	0	0	2	2	~6-7+ year delay and >2x initial aggregate estimate; both units commercially operational.
Olkiluoto 3	0	0	2	2	~14-year delay and major cost increase; regular/commercial operation achieved in 2023.
Flamanville 3	0	0	2	2	~12+ year delay vs initial target and large cost increase; grid connection achieved and staged commissioning continued through the evidence cutoff.
Medupi	0	0	1	1	Long delay/cost escalation; all units commercial but material boiler/design defect remediation documented.
Kusile	0	0	1	1	Long delay/cost escalation; all units commercial by 2025 but major design/execution and project challenges documented.

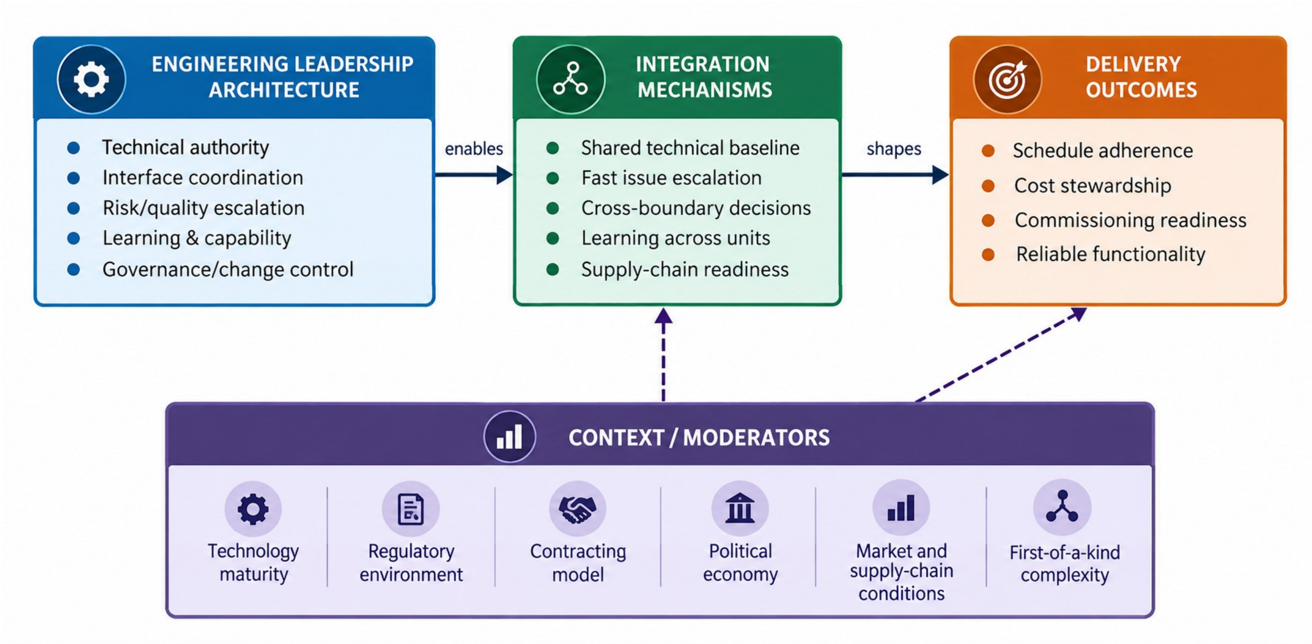
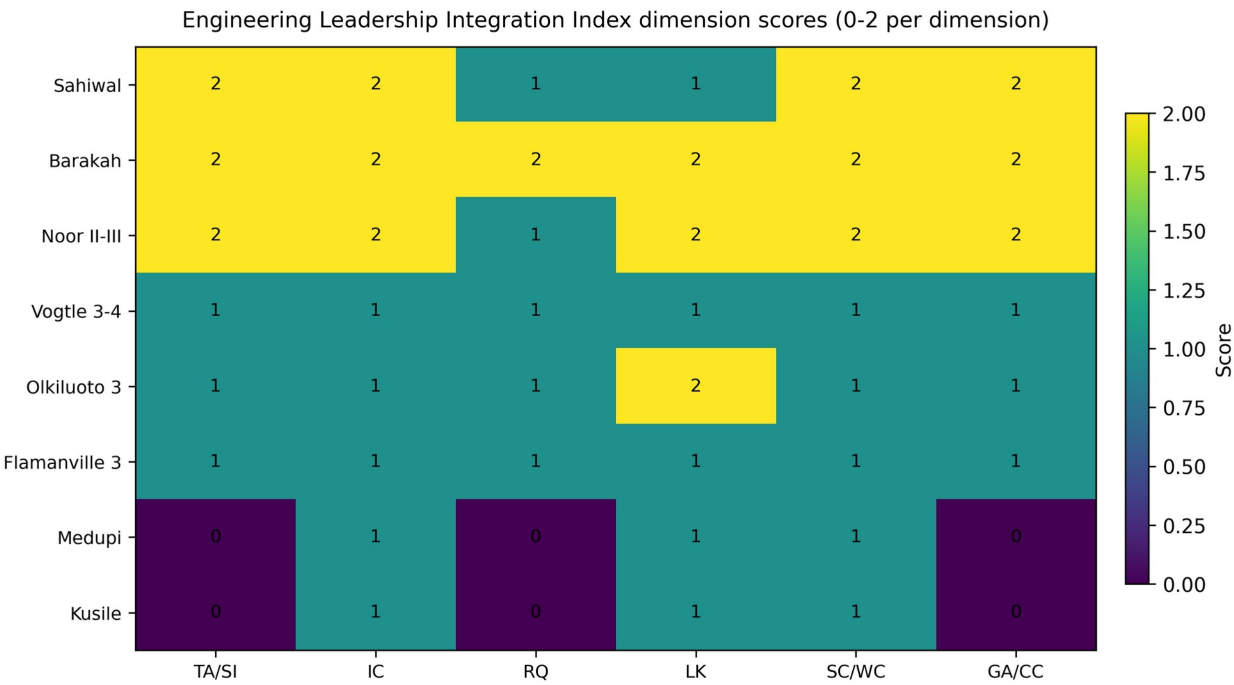


Figure 1. Conceptual model linking engineering leadership architecture to integration mechanisms and delivery outcomes. Contextual factors are treated as moderators rather than as components of leadership.



TA/SI = technical authority & systems integration; IC = interface coordination; RQ = risk & quality escalation;
LK = learning & knowledge transfer; SC/WC = supply-chain & workforce capability; GA/CC = governance & change control.

Figure 2. Heatmap of researcher-coded Engineering Leadership Integration Index dimensions. Scores: 0 = material deficiency/fragmentation; 1 = partial or mixed evidence; 2 = proactive and institutionalized evidence.

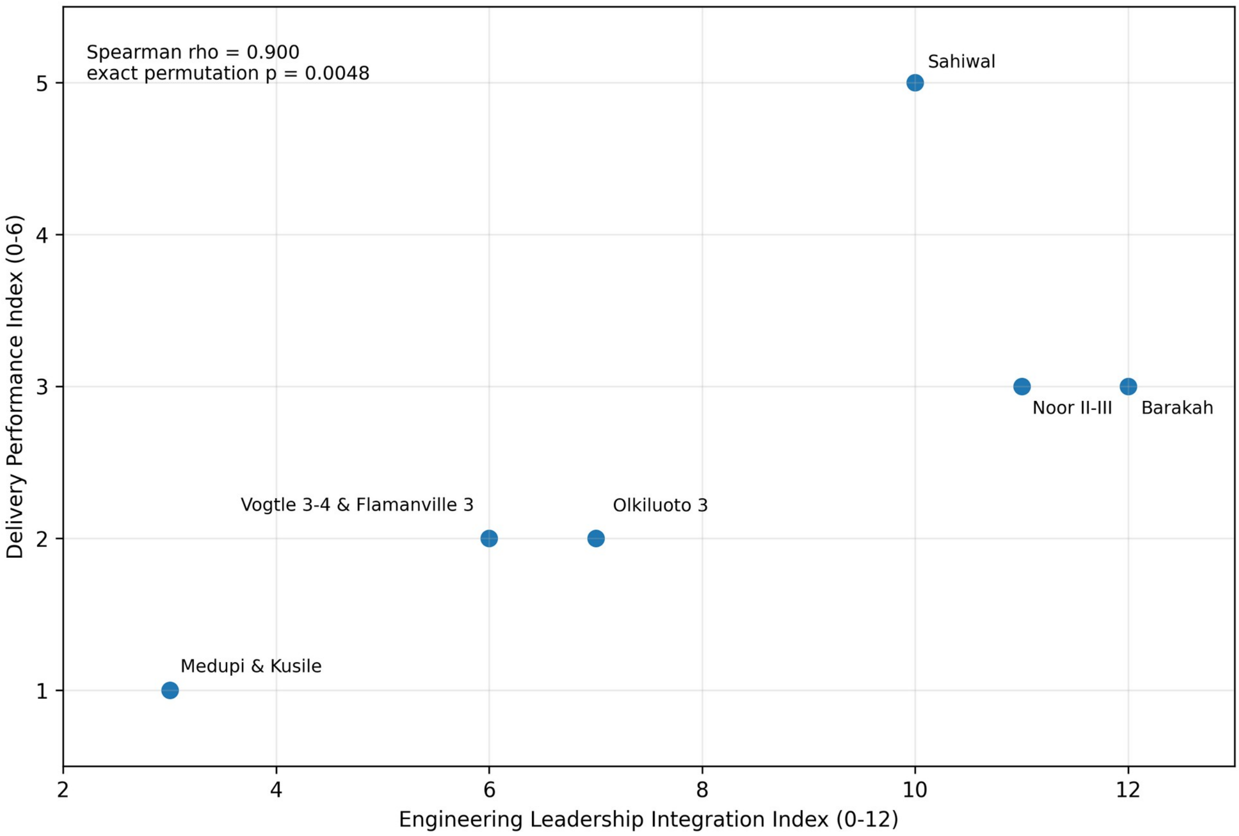


Figure 3. Relationship between Engineering Leadership Integration Index and Delivery Performance Index across eight cases. The association is exploratory and does not imply causation.

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