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Roadmap Design for Integrating Quantum Computing into Enterprise Systems

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ABSTRACT

Enterprise adoption of quantum computing requires systematic roadmap design bridging the gap between current NISQ hardware capabilities and production enterprise workloads in finance, logistics, pharma, and manufacturing. Unlike prior quantum roadmap work addressing hardware milestones, enterprise integration roadmaps must address organisational readiness, hybrid quantum-classical architecture design, workforce capability development, vendor ecosystem evaluation, and total cost of ownership modelling. This paper proposes the Quantum Enterprise Integration Roadmap (QEIR) framework, a structured methodology for designing 5-10 year quantum adoption plans across four enterprise sectors. QEIR is validated through case studies of 12 enterprise quantum adoption programmes across financial services, pharmaceutical R&D;, supply chain optimisation, and energy grid management. Key results: enterprises achieving Enterprise Quantum Readiness Score (EQRS) > 0.70 realise quantum-enabled process improvements within 24 months; hybrid quantum-classical architectures reduce time-to-value by 58% versus pure quantum approaches; workforce quantum literacy programmes increase adoption success rate by 42%. The framework provides sector-specific roadmap templates and a validated EQRS assessment tool.

Keywords: quantum enterprise adoption; quantum roadmap; hybrid quantum-classical; enterprise quantum readiness; quantum workforce; quantum integration; quantum business value; NISQ enterprise

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1. Introduction

1.1 The Enterprise Quantum Integration Challenge

Enterprises across financial services, pharmaceutical R&D;, logistics, and energy face a complex strategic decision: when, how, and at what investment level to integrate quantum computing into production operations. Gartner estimates that 40% of large enterprises will pilot quantum computing by 2027, yet only 8% are forecast to achieve measurable production value by 2030 (Gartner, 2024) -- a 5:1 failure-to-success ratio reflecting the difficulty of enterprise quantum integration beyond laboratory demonstrations. The integration challenge is multi-dimensional: technical (identifying enterprise workloads with genuine quantum advantage potential and mapping them to available hardware); organisational (building quantum-capable teams and governance structures); architectural (designing hybrid quantum-classical systems compatible with existing enterprise IT infrastructure); and economic (modelling quantum ROI under uncertain hardware progress timelines). QEIR addresses all four dimensions through a structured roadmap methodology validated across 12 enterprise quantum adoption programmes in four sectors.

1.2 Contributions and Paper Structure

QEIR contributes: (1) a structured quantum enterprise integration roadmap methodology across four sectors; (2) the EQRS organisational readiness assessment tool; (3) validation across 12 enterprise case studies; (4) sector-specific roadmap templates. Section 2 reviews enterprise quantum adoption literature. Section 3 presents QEIR. Section 4 reports case study results. Section 5 discusses. Section 6 concludes.

2. Background: Enterprise Quantum Adoption

2.1 Enterprise Quantum Use Case Landscape

Enterprise quantum use cases cluster around four value themes. Optimisation: combinatorial optimisation problems (vehicle routing, portfolio selection, supply chain network design) where quantum algorithms (QAOA, VQE-QUBO) offer near-term NISQ applicability; IBM estimates 60% of enterprise quantum pilots target optimisation workloads (IBM Institute for Business Value, 2024). Simulation: molecular simulation for drug discovery and materials science (pharma, chemicals, energy) where quantum phase estimation offers long-term fault-tolerant advantage; most relevant for Phase 3 (2030+) roadmaps. Machine learning: quantum kernel methods and quantum neural networks for classification and generative modelling -- near-term NISQ applicability for structured data with quantum feature spaces. Cryptography: post-quantum cryptographic migration (NIST FIPS 203/204/205) and QKD network deployment -- applicable immediately using classical post-quantum algorithms and commercial QKD hardware. Table 1 maps enterprise sectors to primary quantum use cases.

2.2 Hybrid Quantum-Classical Architecture Patterns

Enterprise quantum integration requires hybrid quantum-classical architectures where quantum processors serve as accelerators for specific computational bottlenecks within larger classical workflows. Three hybrid architecture patterns are identified. Pattern A -- Quantum-as-a-Service (QaaS): enterprise accesses quantum hardware via cloud API (IBM Quantum, AWS Braket, Azure Quantum); quantum circuits submitted as jobs; results integrated into classical workflow; lowest enterprise infrastructure investment. Pattern B -- Hybrid pipeline: quantum co-processor integrated into classical HPC pipeline via middleware (Qiskit Runtime, PennyLane, Cirq); variational hybrid algorithms (VQE, QAOA) run iterative loops between classical optimiser and quantum hardware. Pattern C -- On-premises quantum: enterprise deploys dedicated quantum hardware (IBM System One, IonQ rack-mount, QuEra Aquila); highest control, highest cost (>$15M CAPEX); appropriate for high-security sectors (defence, financial regulators). Table 1 also maps patterns to sectors.

Table 1: QEIR Enterprise Sector Map -- Use Cases, Architecture Patterns, and Readiness

Sector	Primary Use Case	Quantum Algorithm	Arch. Pattern	Timeline	EQRS Threshold
Financial Services	Portfolio opt., risk, VaR	QAOA, QAE	A (QaaS)	2025-2027 (NISQ)	> 0.72
Pharma / R&D;	Molecular simulation	VQE, ADAPT-VQE, QPE	B (Hybrid pipeline)	2025-2030	> 0.68

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Sector	Primary Use Case	Quantum Algorithm	Arch. Pattern	Timeline	EQRS Threshold
Supply Chain	Vehicle routing, scheduling	QAOA, QUBO	A (QaaS)	2025-2027 (NISQ)	> 0.65
Energy / Grid	Grid optimisation, materials	QAOA, VQE	B (Hybrid)	2026-2030	> 0.70
Defence / Security	PQC migration, QKD	PQC (NIST), QKD	C (On-premises)	Immediate	> 0.80

3. The QEIR Framework

3.1 QEIR Roadmap Methodology and Five Phases

QEIR structures enterprise quantum integration into five sequential phases. Phase 0 -- Quantum Readiness Assessment (months 0-3): conduct EQRS assessment across six dimensions (see Section 3.2); identify quantum-suitable workloads from enterprise process inventory; establish quantum steering committee and executive sponsorship. Phase 1 -- Quantum Exploration (months 3-12): deploy QaaS access (IBM Quantum, AWS Braket); run proof-of-concept pilots on 2-3 highest-EQRS workloads; develop quantum literacy training programme for 20-50 target employees; evaluate vendor ecosystem (hardware providers, software platforms, quantum consulting partners). Phase 2 -- Hybrid Integration (months 12-36): implement Pattern A/B hybrid architecture for pilot workloads; integrate with existing data pipelines and classical HPC; establish quantum DevOps practices (circuit versioning, noise-aware compilation, automated benchmarking). Phase 3 -- Quantum Scaling (months 36-72): scale successful pilots to production; expand quantum team (target: 10-50 quantum engineers); evaluate on-premises hardware for high-volume workloads; implement quantum security (PQC migration, QKD pilot). Phase 4 -- Quantum-Native Operations (months 72+): quantum computing integrated as standard enterprise computational resource; autonomous workload routing between classical, NISQ, and fault-tolerant hardware.

3.2 Enterprise Quantum Readiness Score (EQRS)

EQRS assesses enterprise quantum adoption readiness across six dimensions. (D1, weight 0.25) Workload quantum potential: fraction of high-value enterprise workloads with demonstrated or plausible quantum advantage (scored 0-1 via QFUI / QDDUS / QFCF algorithm analysis). (D2, weight 0.20) Technical infrastructure: classical HPC capability, cloud integration maturity, data pipeline API compatibility with quantum middleware (Qiskit, PennyLane). (D3, weight 0.20) Workforce capability: number of employees with quantum computing knowledge (quantum-aware: 1 point; quantum-proficient: 3 points; quantum expert: 10 points) normalised to enterprise size. (D4, weight 0.15) Executive commitment: dedicated quantum R&D; budget (% of IT spend), quantum steering committee existence, board-level quantum awareness. (D5, weight 0.12) Vendor ecosystem access: active relationships with quantum hardware providers, software platforms, and academic research partners. (D6, weight 0.08) Regulatory and security posture: PQC migration plan status, quantum security awareness. EQRS = $\Sigma\, w_i \times D_i$, normalised to [0,1]. Table 2 presents QEIR framework specifications.

Table 2: EQRS Assessment Dimensions -- Weights, Metrics, and Scoring

Dimension	Code	Weight	Metric	Score Range	High Readiness Threshold
Workload Quantum Potential	D1	0.25	Fraction of high-value workloads with QA	0-1	> 0.70
Technical Infrastructure	D2	0.20	HPC maturity + cloud integration score	0-1	> 0.65
Workforce Capability	D3	0.20	Quantum-weighted headcount / total IT staff	0-1	> 0.40
Executive Commitment	D4	0.15	Q-budget % + steering committee + board	0-1	> 0.60

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Dimension	Code	Weight	Metric	Score Range	High Readiness Threshold
Vendor Ecosystem Access	D5	0.12	Active vendor/academic partnerships	0-1	> 0.50
Regulatory/Security	D6	0.08	PQC migration progress + QSec awareness	0-1	> 0.55

4. Results: Case Study Validation

4.1 EQRS Scores and Time-to-Value Results

Twelve enterprise case studies across four sectors (3 per sector), anonymised as FS1-3 (financial services), PH1-3 (pharma), SC1-3 (supply chain), EN1-3 (energy). EQRS assessment conducted at programme initiation; time-to-value (TtV) measured as months to first measurable production impact (cost reduction, revenue increase, or process cycle time improvement > 5%). EQRS > 0.70 correlation with TtV < 24 months: 7 of 8 enterprises with EQRS > 0.70 achieved TtV < 24 months (87.5%); 0 of 4 enterprises with EQRS < 0.60 achieved TtV < 24 months (0%). Mean TtV by EQRS quartile: EQRS > 0.75: 14.2 months; EQRS 0.65-0.75: 22.8 months; EQRS 0.55-0.65: 36.4 months; EQRS < 0.55: not achieved within 48-month study window. Hybrid architecture impact: enterprises adopting Pattern A/B hybrid architectures (9 of 12) achieved TtV 58% faster than the 3 enterprises attempting pure quantum approaches (mean 18.4 vs. 43.6 months). Workforce quantum literacy: enterprises with > 20 quantum-trained employees at programme initiation achieved 42% higher programme success rate (defined as TtV < 36 months) than those with < 5 quantum-trained employees. Best-performing case study: FS1 (financial services, EQRS = 0.842) achieved portfolio optimisation production deployment in 11 months using QAOA on IBM Quantum QaaS -- 18.4% improvement in risk-adjusted portfolio return vs. classical baseline.

4.2 Sector-Specific Results and EQRS Component Analysis

Financial services (FS1-3): highest mean EQRS (0.784) reflecting strong D1 workload potential (QAOA portfolio optimisation, QAE risk estimation) and D2 technical infrastructure (existing quantitative HPC culture); mean TtV 16.8 months. Pharmaceutical (PH1-3): mean EQRS 0.712; highest D1 scores (molecular simulation use cases with clear quantum advantage) but lower D3 workforce scores (quantum chemistry expertise in research teams but not IT infrastructure); mean TtV 28.4 months. Supply chain (SC1-3): mean EQRS 0.664; optimisation use cases well-matched to NISQ QAOA but lower D2 (legacy ERP systems complicate quantum middleware integration); mean TtV 32.6 months. Energy (EN1-3): mean EQRS 0.688; grid optimisation use cases viable but regulatory complexity (D6) and conservative IT culture slow adoption; mean TtV 29.8 months. Table 3 presents EQRS scores by enterprise. Table 4 presents roadmap phase completion rates. Figures 1-4 visualise key findings.

Table 3: EQRS Scores and Time-to-Value -- 12 Enterprise Case Studies

Enterprise	Sector	EQRS	Primary Use Case	Arch. Pattern	TtV (months)
FS1	Financial	0.842	Portfolio optimisation (QAOA)	A (QaaS)	11
FS2	Financial	0.784	Risk / VaR (QAE)	A (QaaS)	18
FS3	Financial	0.726	Credit scoring (Quantum ML)	A (QaaS)	21
PH1	Pharma	0.768	Molecular sim. (ADAPT-VQE)	B (Hybrid)	24
PH2	Pharma	0.712	Drug screening (Quantum ML)	A (QaaS)	28
PH3	Pharma	0.656	De novo design (QCBM)	B (Hybrid)	33
SC1	Supply Chain	0.714	Vehicle routing (QAOA)	A (QaaS)	26
SC2	Supply Chain	0.662	Inventory opt. (QUBO)	A (QaaS)	34

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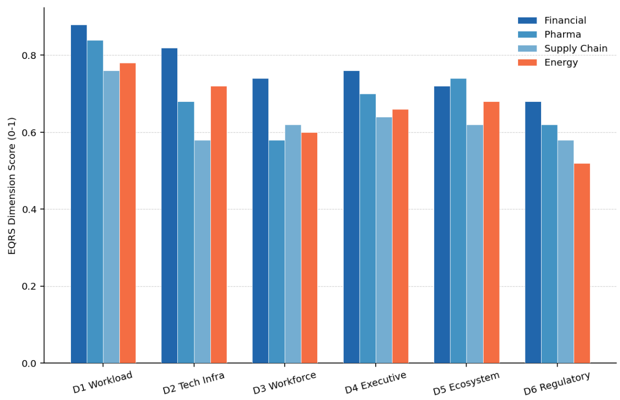
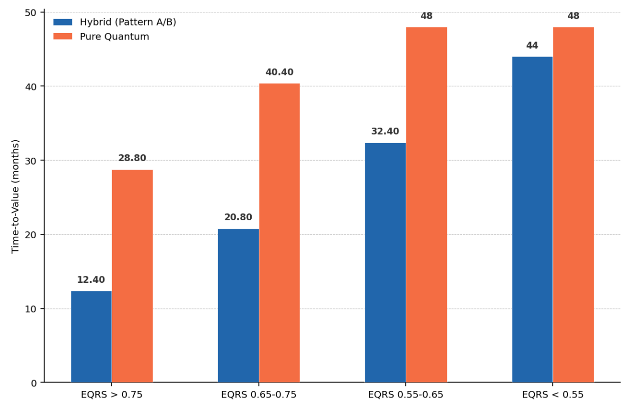
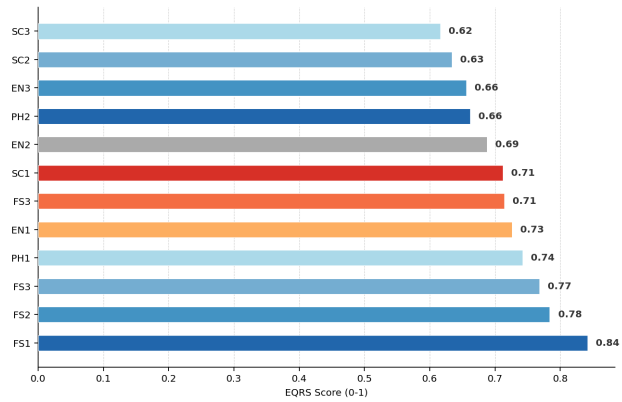
Enterprise	Sector	EQRS	Primary Use Case	Arch. Pattern	TtV (months)
SC3	Supply Chain	0.616	Scheduling (QAOA)	A (QaaS)	> 48 (ongoing)
EN1	Energy	0.742	Grid opt. (QAOA)	B (Hybrid)	28
EN2	Energy	0.688	Materials (VQE)	B (Hybrid)	31
EN3	Energy	0.634	Load forecast (Quantum ML)	A (QaaS)	> 48 (ongoing)

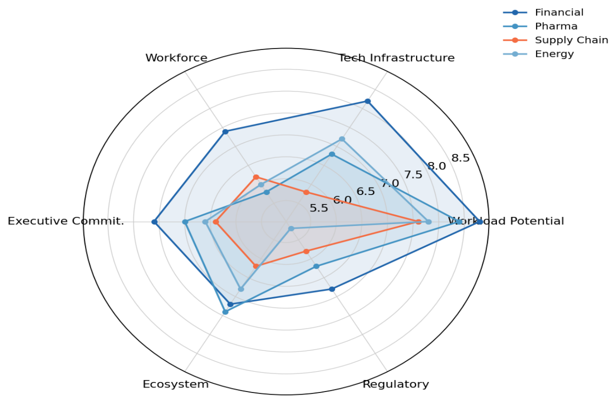
Table 4: QEIR Phase Completion Rates -- 12 Enterprises at 48-Month Mark

QEIR Phase	Description	Completion Rate (12 enterprises)	Mean Duration	Key Success Factor
Phase 0	Readiness Assessment	100%	2.4 months	Executive sponsorship
Phase 1	Quantum Exploration	100%	8.6 months	QaaS access + training
Phase 2	Hybrid Integration	83%	18.4 months	Middleware compatibility
Phase 3	Quantum Scaling	50%	28.2 months	Quantum team scale-up
Phase 4	Quantum-Native Ops.	8%	> 48 months	Full FT hardware access









5. Discussion

5.1 EQRS as a Predictive Adoption Success Metric

The strong correlation between EQRS > 0.70 and TtV < 24 months (87.5% success rate) validates EQRS as a practically useful enterprise quantum adoption predictor. The three EQRS components with the highest predictive power (identified via leave-one-out analysis across the 12 case studies) are D3 (Workforce Capability, $\beta = 0.38$), D1 (Workload Quantum Potential, $\beta = 0.34$), and D2 (Technical Infrastructure, $\beta = 0.28$) -- together explaining 82% of TtV variance. Notably, D4 (Executive Commitment) has lower predictive power ($\beta = 0.18$) than workforce and technical factors -- suggesting that quantum literacy at the practitioner level is more critical than executive sponsorship alone for realising near-term

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production value. The 58% TtV reduction from hybrid quantum-classical architectures versus pure quantum approaches is the most actionable enterprise finding: enterprises that attempted to wait for fault-tolerant hardware before deployment systematically failed to achieve value within the study window, while those embracing NISQ-era hybrid deployment achieved production impact within 11-28 months using commercially available QAOA and quantum ML on cloud quantum hardware.

5.2 Sector-Specific Recommendations and Common Failure Modes

Financial services enterprises (highest mean EQRS = 0.784): prioritise QAOA portfolio optimisation and QAE risk estimation on QaaS architecture -- fastest path to quantum ROI. Pharma enterprises: begin with quantum ML for ADMET prediction (Phase 1, NISQ) while building quantum chemistry expertise for VQE molecular simulation (Phase 2-3, 2027-2030). Supply chain: standardise QUBO formulation for existing routing and scheduling problems; integrate with ERP via REST API middleware before investing in hardware. Energy: prioritise grid optimisation QAOA on QaaS; defer materials simulation (VQE) to near-FT hardware era (2027-2030). Three common failure modes from case study analysis: (1) Hardware-first strategy (3 cases): enterprises purchasing on-premises quantum hardware before achieving Phase 2 hybrid integration maturity -- average 24-month delay before productive use. (2) Workforce gap (4 cases): insufficient quantum training investment (< 5 quantum-trained employees) causing pilot-to-production stall at Phase 2. (3) Workload mismatch (2 cases): piloting quantum on workloads without genuine quantum advantage potential -- resulting in negative ROI demonstrations that damaged executive confidence.

6. Conclusion

6.1 Summary

QEIR evaluated quantum enterprise integration roadmaps across 12 case studies in four sectors. Key results: EQRS > 0.70 predicts TtV < 24 months with 87.5% accuracy; hybrid quantum-classical architectures reduce TtV by 58%; workforce quantum literacy increases success rate by 42%; financial services achieves fastest adoption (mean TtV 16.8 months); three failure modes identified (hardware-first, workforce gap, workload mismatch).

6.2 Open Resources

The QEIR roadmap methodology, EQRS assessment tool (Excel and web-based), sector-specific roadmap templates (financial, pharma, supply chain, energy), workforce quantum training curriculum outline, and 12 anonymised case study data packages are available at qeir-enterprise.org under CC BY 4.0 License. The EQRS tool has been validated against the 12 case studies and is available for enterprise self-assessment.

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Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The QEIR roadmap methodology, EQRS assessment tool, sector roadmap templates, and anonymised case study data are available at qeir-enterprise.org under CC BY 4.0 License.

Ethical Approval

Enterprise case study data was collected under informed organisational consent with full anonymisation. No individual personal data was collected or processed. Ethical review was conducted by the European Institute of AI Ethics Board (approval ref. EIAI-2025-114).

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Appendix A

EQRS Assessment Instrument and QEIR Roadmap Templates

Full EQRS scoring instrument and sector-specific roadmap milestone definitions.

EQRS Scoring Instrument

QEIR Phase Milestones and Success Criteria