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Post-Quantum Cryptography and Digital Resilience: Preparing Critical Infrastructure for Emerging Security Threats

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Abstract

The development of large-scale quantum computing presents a fundamental challenge to contemporary cybersecurity because widely deployed public-key cryptographic systems may become vulnerable to quantum algorithms. Critical infrastructure—including energy, healthcare, telecommunications, financial services, transportation, water, government, and industrial control systems—faces particular exposure because these systems often combine long operational lifetimes, legacy technologies, interconnected networks, and sensitive information. Post-quantum cryptography (PQC) provides a pathway for transitioning from quantum-vulnerable cryptographic mechanisms toward algorithms designed to withstand attacks from both classical and quantum-capable adversaries. This paper examines the relationship between PQC and digital resilience, focusing on cryptographic migration, infrastructure inventories, algorithm agility, hybrid cryptographic architectures, key management, legacy-system constraints, supply-chain risks, and organisational preparedness. The paper proposes an integrated Post-Quantum Digital Resilience Framework comprising asset discovery, cryptographic inventory, risk prioritisation, hybrid migration, algorithm-agile architecture, continuous monitoring, and recovery planning. Particular attention is given to the "harvest now, decrypt later" threat, in which encrypted information collected today may be decrypted in the future if sufficiently capable quantum computers become available. The analysis argues that post-quantum migration should not be treated as a one-time algorithm replacement project but as a long-term resilience programme involving governance, technology, procurement, workforce development, testing, and continuous adaptation. The paper concludes that organisations responsible for critical infrastructure should begin quantum-readiness activities well before cryptographically relevant quantum computing becomes operational, because migration across complex infrastructure can require substantial time.

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1. Introduction

Critical infrastructure increasingly depends on interconnected digital technologies.

Modern infrastructure systems rely on:

- Public-key cryptography.
- Digital signatures.
- Secure communications.
- Identity management.
- Authentication.
- Digital certificates.
- Cloud services.
- Industrial control systems.

These mechanisms protect the confidentiality, integrity, and authenticity of digital information.

However, the emergence of sufficiently capable quantum computers could undermine several widely used public-key cryptographic algorithms.

The challenge is therefore not simply the arrival of a new computing technology.

It is a long-term infrastructure security problem.

2. Quantum Computing and Cybersecurity

Quantum computers exploit quantum-mechanical principles to process certain classes of problems differently from classical computers.

Two algorithms are particularly important to cybersecurity discussions:

- **Shor's algorithm**, which threatens widely used public-key cryptography based on integer factorisation and discrete logarithms.
- **Grover's algorithm**, which can provide a quadratic speedup for certain brute-force search problems.

The practical implications differ by cryptographic system.

3. Cryptographic Systems at Risk

Many existing systems depend on algorithms such as:

- RSA.
- Diffie–Hellman.
- Elliptic-curve cryptography.
- Elliptic-curve digital signatures.

A sufficiently capable fault-tolerant quantum computer could make several of these public-key mechanisms computationally insecure.

Symmetric cryptography is generally affected differently and can often be strengthened through larger security parameters.

4. The Post-Quantum Cryptography Approach

Post-quantum cryptography involves cryptographic algorithms designed to remain secure against attacks from:

Classical Computers + Quantum Computers

The goal is to replace vulnerable public-key mechanisms while maintaining compatibility with conventional computing environments.

PQC is therefore different from quantum cryptography.

5. PQC Versus Quantum Key Distribution

These technologies should not be confused.

Post-Quantum Cryptography

Uses mathematical algorithms that run on conventional computers.

Quantum Key Distribution

Uses quantum communication properties to establish cryptographic keys.

PQC is particularly attractive for large-scale migration because it can generally be deployed through software and hardware updates without requiring quantum communication infrastructure.

6. Why Critical Infrastructure Is Vulnerable

Critical infrastructure presents unique cybersecurity challenges because systems may remain operational for decades.

Examples include:

- Power-grid equipment.
- Railway systems.
- Medical equipment.
- Industrial control systems.
- Telecom infrastructure.
- Aircraft systems.
- Water-treatment facilities.

Replacing cryptographic mechanisms in such systems can be difficult.

7. Long System Lifetimes

A conventional IT system might be upgraded relatively frequently.

Critical infrastructure may have much longer lifecycles.

For example:

Procurement → Deployment → Operation → Maintenance → Retirement
can extend over many years.
Cryptographic decisions made today may therefore remain relevant long into the future.

8. Harvest Now, Decrypt Later
One of the most important quantum-related threats is the possibility that attackers collect encrypted information today and decrypt it later.
This is often described as:

Harvest Now, Decrypt Later (HNDL)
The risk is particularly important for information requiring long-term confidentiality.
Examples may include:
- Government information.
- Intellectual property.
- Strategic infrastructure data.
- Healthcare records.
- Financial information.

9. Critical Infrastructure Risk
Critical infrastructure contains both operational technology (OT) and information technology (IT).

IT Systems
Include:
- Servers.
- Databases.
- Cloud platforms.
- Business applications.

OT Systems
Include:
- Sensors.
- Controllers.
- Industrial equipment.
- Supervisory control systems.

The interaction between IT and OT increases the complexity of cryptographic migration.

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10. Industrial Control Systems

Industrial control systems often prioritise:

- Availability.
- Safety.
- Reliability.
- Deterministic operation.

Security upgrades cannot disrupt essential operations.

Consequently, PQC deployment must be carefully tested.

11. Legacy Technology

Legacy infrastructure can create significant migration barriers.

Older systems may:

- Support limited cryptographic algorithms.
- Have constrained processing power.
- Lack update mechanisms.
- Depend on proprietary protocols.
- Have unsupported operating systems.

These systems may become the weakest points during PQC migration.

12. Cryptographic Inventory

One of the first steps toward quantum readiness is understanding where cryptography is being used.

Organisations should identify:

- Algorithms.
- Key lengths.
- Certificates.
- Digital signatures.
- Cryptographic libraries.
- Protocols.
- Hardware security modules.
- Embedded systems.

Without such an inventory, organisations cannot reliably assess quantum exposure.

13. Cryptographic Bill of Materials

A useful organisational capability is a Cryptographic Bill of Materials (CBOM).

A CBOM can document:

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Element	Example
Application	Banking platform
Algorithm	RSA
Key size	2048-bit
Usage	Authentication
Certificate	TLS
System owner	IT security
Risk	High
Migration status	Planned

This creates visibility into cryptographic dependencies.

14. Risk-Based Prioritisation

Not every cryptographic system requires immediate replacement.

Prioritisation should consider:

- Data sensitivity.
- Data lifetime.
- System criticality.
- Exposure.
- Algorithm vulnerability.
- Migration complexity.

A high-priority asset could therefore be defined as:

High Sensitivity + Long Data Lifetime + Quantum-Vulnerable Cryptography

15. Post-Quantum Algorithms

Modern PQC research has produced several algorithm families.

Important approaches include:

- Lattice-based cryptography.
- Hash-based signatures.
- Code-based cryptography.
- Other structured mathematical constructions.

Different algorithms provide different performance and security characteristics.

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16. Standardisation

The standardisation of post-quantum algorithms is essential because critical infrastructure operators require confidence in:

- Security.
- Interoperability.
- Implementation.
- Long-term support.

The standardisation process has therefore become an important component of global cybersecurity planning.

17. Hybrid Cryptography

During migration, organisations may use hybrid mechanisms.

A hybrid design combines:

Classical Cryptography + Post-Quantum Cryptography

This can provide protection against weaknesses in either component during the transition period.

18. Why Hybrid Migration Matters

Replacing every cryptographic mechanism simultaneously may be unrealistic.

Hybrid approaches can provide a transition pathway while organisations:

- Test PQC.
- Upgrade systems.
- Validate performance.
- Replace legacy infrastructure.

19. Algorithm Agility

A resilient architecture should allow cryptographic algorithms to be changed without redesigning the entire system.

This property is known as cryptographic agility or algorithm agility.

An agile system can transition:

Algorithm A → Algorithm B → Algorithm C

with minimal architectural disruption.

20. Importance of Algorithm Agility

Future cryptographic standards may evolve.

A system designed around a single fixed algorithm could become difficult to update.

Algorithm agility therefore supports:

- Future upgrades.

- Vulnerability response.
- Regulatory compliance.
- Technology evolution.

21. Digital Certificates

Digital certificates are deeply integrated into modern infrastructure.

PQC migration may require changes to:

- Certificate authorities.
- Certificate formats.
- Key-generation systems.
- Authentication protocols.
- Certificate-management platforms.

This can make certificate infrastructure a major migration dependency.

22. Public-Key Infrastructure

Public-Key Infrastructure (PKI) supports:

- Authentication.
- Digital signatures.
- Secure communications.
- Identity management.

PQC migration therefore requires organisations to examine their entire PKI ecosystem rather than individual applications.

23. Digital Signatures

Digital signatures provide:

- Authentication.
- Integrity.
- Non-repudiation.

Critical infrastructure relies on signatures for:

- Software updates.
- Device authentication.
- Secure communications.
- Firmware verification.

Quantum-resistant signature systems are therefore especially important.

24. Software Supply Chains

Modern infrastructure increasingly depends on software from multiple suppliers.

A compromised or quantum-vulnerable cryptographic component can create downstream risks.

Organisations should therefore evaluate:

- Software libraries.
- Vendor products.
- Firmware.
- Dependencies.
- Update mechanisms.

25. Vendor Risk

Critical infrastructure operators often cannot independently modify every component.
They therefore need suppliers to provide information about:

- Cryptographic algorithms.
- PQC roadmaps.
- Software-update capabilities.
- Certification.
- Algorithm agility.

Quantum readiness should become part of technology procurement.

26. Cloud Infrastructure

Cloud environments may contain:

- APIs.
- Certificates.
- Encryption systems.
- Identity services.
- Databases.

Organisations must therefore assess quantum readiness across both internal and cloud infrastructure.

27. Network Security

Network protocols may depend on vulnerable public-key mechanisms.
Migration may involve:

- TLS.
- VPNs.
- Secure email.
- Authentication protocols.
- Network-device management.

Testing is required because larger PQC keys or signatures can affect bandwidth and latency.

28. Performance Considerations

PQC algorithms can differ from classical cryptography in:

- Key sizes.
- Signature sizes.

- Computational requirements.
- Memory consumption.
- Network overhead.

Critical infrastructure must evaluate these differences before deployment.

29. Resource-Constrained Devices

Some infrastructure devices have limited:

- CPU capacity.
- Memory.
- Storage.
- Network bandwidth.

PQC deployment in such environments may require specialised optimisation.

30. Internet of Things

IoT devices create a particularly difficult migration challenge because organisations may operate thousands or millions of devices.

A resilient IoT architecture should support:

- Secure firmware updates.
- Strong device identity.
- Cryptographic agility.
- Key rotation.
- Long-term maintenance.

31. Smart Grids

Electricity systems increasingly use:

- Smart meters.
- Distributed energy resources.
- Digital substations.
- Remote monitoring.
- Automated control.

These systems depend on secure communication and authentication.

PQC migration can therefore become part of long-term smart-grid cybersecurity planning.

32. Healthcare Infrastructure

Healthcare systems contain highly sensitive information.

Potential targets include:

- Electronic health records.
- Medical devices.
- Hospital networks.
- Research data.

- Genomic information.

Long-term confidentiality makes quantum-resilient encryption particularly relevant.

33. Financial Infrastructure

Financial systems rely extensively on:

- Digital signatures.
- Authentication.
- Encryption.
- Secure transactions.

PQC migration will require coordination across:

- Banks.
- Payment providers.
- Exchanges.
- Regulators.
- Technology vendors.

34. Telecommunications

Telecommunications infrastructure provides connectivity for virtually every other sector.

Quantum-resilient security is therefore strategically important for:

- Mobile networks.
- Fibre networks.
- Data centres.
- Core network systems.
- Satellite communications.

35. Transportation Systems

Transportation systems increasingly rely on digital technology.

Examples include:

- Railway signalling.
- Aviation systems.
- Connected vehicles.
- Intelligent traffic management.
- Port logistics.

PQC deployment must account for safety and operational continuity.

36. Government Systems

Government infrastructure often contains information requiring long-term confidentiality.

Migration planning should include:

- Government networks.
- Digital identity systems.

- Citizen services.
- Secure communications.
- Archival systems.

37. Digital Resilience

Digital resilience is broader than cybersecurity.

It includes the ability to:

1. Anticipate threats.
2. Resist attacks.
3. Detect anomalies.
4. Respond effectively.
5. Recover quickly.
6. Adapt to changing threats.

PQC should therefore be integrated into a wider resilience strategy.

38. PQC as a Resilience Capability

A resilient organisation should be able to:

Identify → Prioritise → Migrate → Test → Monitor → Adapt

This is more sustainable than treating PQC as a one-time technology replacement.

39. Governance

Successful migration requires organisational ownership.

Responsibilities should be assigned to:

- Chief information security officers.
- IT teams.
- OT teams.
- Procurement teams.
- Risk managers.
- Compliance teams.
- Senior management.

40. Workforce Development

PQC migration requires expertise in:

- Cryptography.
- Network security.
- PKI.
- Systems engineering.
- Risk management.
- Compliance.

Training programmes should therefore be established before large-scale migration begins.

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41. Procurement Strategy

Future technology procurement should require vendors to demonstrate:

- PQC readiness.
- Algorithm agility.
- Cryptographic inventories.
- Secure update mechanisms.
- Long-term support.

This can prevent organisations from acquiring new systems that become difficult to migrate later.

42. Testing and Validation

PQC systems should be tested through:

- Laboratory testing.
- Performance testing.
- Interoperability testing.
- Penetration testing.
- Failover testing.
- Operational pilots.

Testing should occur before production deployment.

43. Migration Roadmap

A practical roadmap can contain seven stages:

Stage 1: Discover

Identify cryptographic dependencies.

Stage 2: Classify

Determine criticality and quantum exposure.

Stage 3: Prioritise

Identify high-risk systems.

Stage 4: Design

Develop PQC and hybrid architectures.

Stage 5: Test

Evaluate performance and interoperability.

Stage 6: Deploy

Migrate systems incrementally.

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Stage 7: Monitor

Continuously evaluate cryptographic risk.

44. Integrated Post-Quantum Digital Resilience Framework

The proposed framework consists of:

Asset Discovery

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Cryptographic Inventory

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Quantum Risk Assessment

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Priority Classification

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Hybrid/PQC Architecture

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Algorithm Agility

↓

Testing & Validation

↓

Migration

↓

Continuous Monitoring

↓

Recovery & Adaptation

45. Risk Matrix

Risk Factor	Low	Medium	High
Data sensitivity	Public	Internal	Confidential
Data lifetime	Short	Moderate	Long
System criticality	Low	Important	Essential
Legacy dependency	Limited	Moderate	Extensive
Cryptographic exposure	Low	Partial	High
Migration complexity	Low	Moderate	High

Systems scoring highly across multiple categories should receive priority.

46. Economic Considerations

PQC migration creates costs related to:

- Hardware replacement.
- Software development.
- Testing.
- Certification.
- Workforce training.
- Vendor upgrades.

However, delaying migration can increase future costs.

47. Cost of Delayed Migration

Late migration may create:

- Emergency replacement requirements.
- Operational disruptions.
- Compliance problems.
- Increased cybersecurity risk.
- Supply-chain bottlenecks.

Early planning can reduce these risks.

48. International Coordination

Critical infrastructure often crosses national borders.

Examples include:

- Internet infrastructure.
- Financial networks.
- Global supply chains.
- Telecommunications.
- Cloud services.

Interoperable PQC standards are therefore important.

49. Research Challenges

Major research challenges include:

1. Efficient PQC implementations.
2. Resource-constrained deployment.
3. Cryptographic agility.
4. Legacy-system migration.
5. Quantum-resistant PKI.
6. Secure software updates.
7. Hybrid cryptography.
8. Long-term algorithm confidence.
9. Supply-chain visibility.

10. Automated cryptographic discovery.

50. Future Research Directions

Future studies should investigate:

- AI-assisted cryptographic inventories.
- Automated vulnerability discovery.
- PQC for industrial control systems.
- Quantum-safe IoT.
- PQC-enabled smart grids.
- Quantum-resistant digital identity.
- Secure satellite communications.
- Automated algorithm migration.
- Post-quantum cloud security.
- Cryptographic resilience metrics.

51. Role of Artificial Intelligence

AI can support quantum-readiness programmes by automatically discovering cryptographic dependencies.

Potential capabilities include:

- Code scanning.
- Dependency analysis.
- Certificate discovery.
- Risk classification.
- Migration recommendations.

This could significantly reduce manual inventory efforts.

52. Automated Cryptographic Discovery

An AI-assisted system could analyse:

Applications + Source Code + Network Traffic + Certificates + Devices

and generate:

Cryptographic Dependency Map → Risk Score → Migration Priority

Such tools could become an important component of large-scale PQC migration.

53. Cybersecurity Operations

Security operations centres could incorporate quantum-risk indicators into existing monitoring.

Examples include:

- Detection of vulnerable algorithms.

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- Expiring certificates.
- Unapproved cryptographic libraries.
- Unsupported devices.

This would integrate PQC into continuous cybersecurity operations.

54. Digital Resilience Metrics

Organisations could evaluate quantum readiness using indicators such as:

Metric	Example
Crypto inventory coverage	95%
PQC migration coverage	60%
Algorithm-agile systems	80%
Legacy exposure	15%
High-risk assets migrated	90%
Vendor PQC readiness	75%

These metrics can support executive-level risk management.

55. Strategic Recommendations

Critical infrastructure organisations should:

1. Begin cryptographic discovery.
2. Develop a quantum-risk register.
3. Identify long-lived sensitive data.
4. Require PQC roadmaps from vendors.
5. Build algorithm-agile architectures.
6. Test hybrid cryptographic approaches.
7. Upgrade PKI infrastructure.
8. Address legacy systems.
9. Train cybersecurity personnel.
10. Establish continuous quantum-readiness monitoring.

56. Discussion

The quantum threat should not be understood simply as a future event.

For critical infrastructure, the preparation period itself is strategically important.

Migration can involve thousands of systems, multiple vendors, embedded devices, certificates, protocols, and operational dependencies.

The central problem is therefore:

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How can organisations transition securely before existing cryptographic protections become inadequate?

The answer requires a lifecycle approach.

PQC migration should be integrated into:

- Enterprise architecture.
- Cybersecurity governance.
- Procurement.
- Risk management.
- Digital transformation.
- Infrastructure modernisation.

57. Conceptual Model

The relationship can be expressed as:

Quantum Threat

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Cryptographic Exposure

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Infrastructure Vulnerability

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PQC Migration

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Algorithm Agility

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Resilience Governance

↓

Quantum-Ready Digital Infrastructure

58. Conclusion

Post-quantum cryptography represents an essential component of long-term digital resilience.

Critical infrastructure organisations face particular challenges because their systems often have:

- Long operational lifetimes.
- Complex dependencies.
- Legacy technologies.
- High availability requirements.
- Sensitive information.
- Extensive supply chains.

PQC migration should therefore begin with visibility.

Organisations need to know where cryptography is used, which algorithms are deployed, what information they protect, and how difficult each system will be to migrate.

The most resilient approach combines:

Cryptographic Inventory + Risk Prioritisation + Hybrid Migration + Algorithm Agility + Continuous Monitoring

The transition to post-quantum security should not be treated as a single replacement exercise. It should become a continuing organisational capability that allows critical infrastructure to adapt as cryptographic technologies, quantum computing capabilities, standards, and threats evolve.

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