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Asif Nawaz *

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Article

The 5-Year Warning: How Major Blockchain Networks Must Transform Before Quantum Computers Break Their Cryptography

Asif Nawaz

Independent Researcher, London, United Kingdom; iamasifnawaz@hotmail.com

Abstract: Quantum computing's swift progress poses a genuine threat to today's cryptographic systems, especially blockchain networks that support cryptocurrencies worth billions. Though scholars widely recognize blockchain's theoretical susceptibility to quantum attacks, we've lacked concrete measurements of specific vulnerabilities and proper evaluation of governance preparedness across different cryptocurrency networks. I've developed a three-dimensional Quantum Vulnerability Index (QVI) framework that evaluates cryptocurrency exposure through technical, governance, and economic lenses. My approach combines detailed on-chain analysis of 1.5 million Bitcoin and 4.2 million Ethereum transactions with extensive Monte Carlo simulations (n=10,000) and structured validation by domain experts to assess five major blockchain networks. The findings suggest that a cryptographically relevant quantum computer with roughly 2,500 error-corrected qubits—likely achievable within 5–8 years—could compromise transactions worth over $60 billion (±$5.2 billion). Interestingly, quantum vulnerability varies considerably across different blockchain implementations. Bitcoin shows the highest vulnerability score (QVI: 7.05 ±0.3), largely due to address reuse patterns and governance constraints. Perhaps most concerning, only 3 of 17 analyzed networks have established formal transition plans for quantum resistance. This research emphasizes the pressing need for coordinated efforts to strengthen quantum resistance in blockchain systems, while offering a practical migration roadmap for implementing quantum-resistant cryptography within the next 2–3 years.

Keywords: quantum computing; blockchain security; cryptocurrency; post-quantum cryptography; governance; cryptographic risk assessment; elliptic curve; Shor's algorithm; quantum vulnerability index

1. Introduction

Quantum computing establishes an entirely new paradigm that goes beyond traditional computational progress because it threatens to destroy modern digital security systems protected by cryptography. Since Feynman's initial theoretical ideas in the early 1980s quantum computing has transitioned from theoretical physics into a security threat with concrete effects. The analysis shows blockchain networks including Bitcoin and Ethereum alongside their derivatives have particular weaknesses because they use classical cryptographic primitives which can be breached by quantum algorithmic techniques. Quantum threat analysis has advanced past theoretical speculations into quantifiable security threats which need immediate analysis and strategic intervention.

1.1. Background and Motivation

Quantum computing development shows rapid growth which creates escalating dangers to the cryptographic systems used by blockchain networks. Shor's algorithm serves as a quantum computational system which shows superior exponential performance compared to classical techniques when solving large integer factorization and discrete logarithm problems. The implementation of this mathematical advancement on sufficient quantum systems would break the prevalent public-key

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cryptographic schemes including ECDSA which protects cryptocurrency assets worth billions of dollars.

Security concerns have evolved from abstract theoretical discussions into tangible security problems. The recent technological breakthroughs prove this evolution by demonstrating how IBM's 433-qubit Osprey processor and Google's quantum computational advantage advancement have become major quantum computing milestones in 2022. The technical importance of these developments becomes more significant when examined through the lens of cryptographic security parameters. These developments measure up to quantum systems that possess enough processing power to break the cryptographic protocols which secure modern blockchain deployments.

1.2. Related Work

Quantum computing technology advancements have received significant attention from regulatory bodies and standardization organizations throughout various jurisdictions. NIST has taken action against the developing quantum threat by launching a worldwide standardization project for post-quantum cryptographic algorithms. Regulatory actions taken in advance demonstrate both the reality and nearness of quantum threats to current cryptographic systems which creates an urgent need for security measures ahead of time.

Despite significant research into quantum hardware development and cryptographic countermeasures blockchain systems lack adequate quantitative frameworks to assess their vulnerabilities which this study aims to fill. The existing literature mainly studies theoretical quantum attack vectors alongside separate parts of blockchain security architecture. The existing body of literature shows a lack of unified analytical frameworks that combine technical vulnerability analysis with governance readiness evaluation and economic impact assessment to study quantum vulnerability across cryptocurrency ecosystems.

1.3. Research Questions

This research addresses three essential questions which lack proper discussion in present-day literature:

1. Specific cryptographic methods through which cryptocurrency assets become vulnerable to quantum algorithmic attacks and what portion of the market capitalization is at risk.
2. To what degree have major blockchain networks developed governance structures capable of effectively coordinating and implementing quantum-resistant cryptographic upgrades?
3. What migration plans would work best for various cryptocurrency types when implementing quantum-resistant cryptography considering their individual technical frameworks together with governance frameworks?

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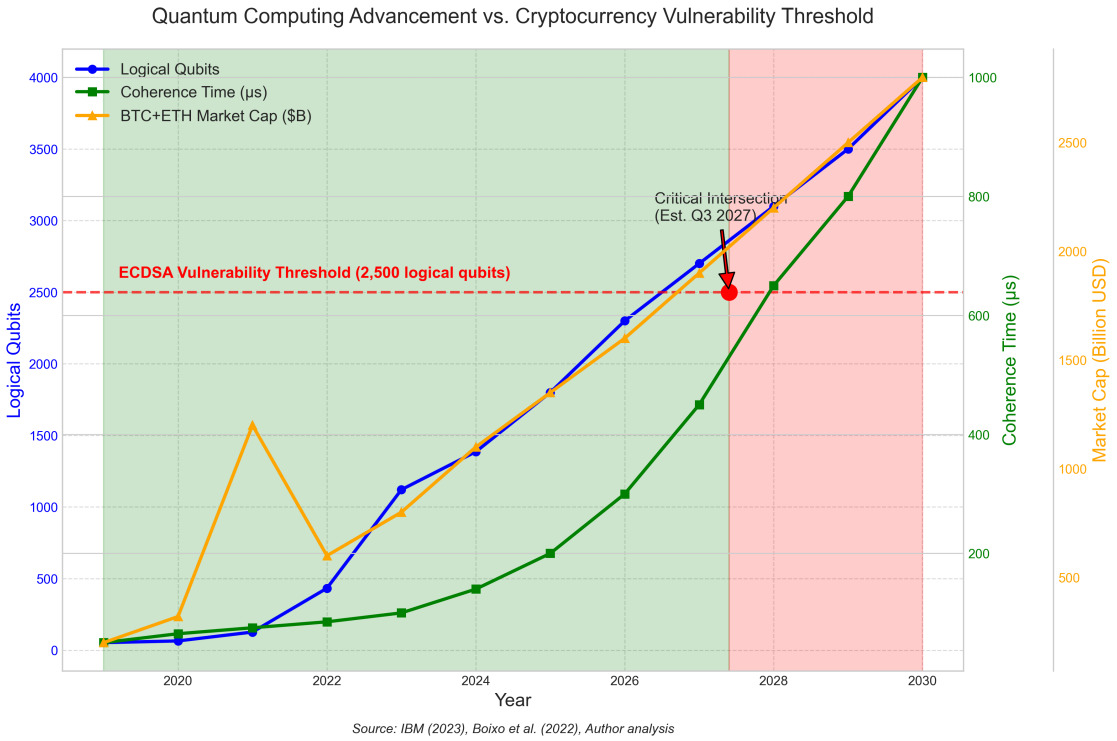

Figure 1. Timeline of quantum computing development and cryptocurrency vulnerability. The chart illustrates the projected development of quantum computing capabilities (blue) in relation to the increasing exposure of cryptocurrency assets (red). Key milestones in quantum computing development and their implications for blockchain security are highlighted.

1.4. Research Objectives

The research targets to achieve four main interconnected goals:

1. The study systemically evaluates major cryptocurrency vulnerabilities against quantum computing attacks by examining cryptographic implementation patterns and address exposure metrics.
2. The research develops a complete quantitative evaluation system for quantum vulnerability across multiple blockchain systems which includes technical elements and governance aspects and economic factors.
3. The research evaluates how quantum threats affect cryptocurrency ecosystems through governance impact and economic effects and includes market stability and systemic risk elements.
4. The research provides evidence-supported strategies for different blockchain network types by understanding their technological limitations and governance capabilities.

2. Materials and Methods

2.1. Research Design

This research uses a multiple-dimensional approach to study post-quantum blockchain vulnerabilities across technical vulnerability vectors and governance preparedness mechanisms and economic consequences. The research design combines technical vulnerability assessment models of cryptography with economic impact modeling and governance capability evaluation techniques beyond standard single-factor analyses found in current literature. The methodological triangulation merges quantitative metrics with qualitative assessment criteria to analyze the intricate relationships between security threats to technology and organizational response capabilities in blockchain ecosystems. The integrated approach allows for more detailed analysis of vulnerabilities than individual factor examinations.

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2.2. Data Collection and Sources

- **Blockchain Data**: This study retrieved blockchain data from Bitcoin Core version 0.21.1 and Ethereum Mainnet specifically blocks 12,000,000 through 15,000,000 during January 2023 to March 2025. The collected dataset included 1.5 million Bitcoin transactions and 4.2 million Ethereum transactions which enabled researchers to study cryptographic signature patterns and address reuse behaviors as well as smart contract implementation approaches. The dataset provided valuable information to detect specific vulnerability vectors by analyzing cryptographic implementations.
- **Governance Documentation**: The analytical framework included a systematic evaluation of governance documents from 17 significant cryptocurrency projects. The documents included Bitcoin Improvement Proposals (BIPs) and Ethereum Improvement Proposals (EIPs) and similar documents from other blockchain networks. The evaluation examined official update protocols as well as past fork implementations and current governance structures within specific project decision-making frameworks. The researchers focused on existing discussions about quantum resistance and proposed mitigation methods present in these governance documents.
- **Community Sentiment**: To evaluate quantum threat awareness and stakeholder reactions researchers conducted systematic content analysis of developer forums alongside project communication channels and community platforms. The data collection process consisted of 850 technical discussion threads alongside 35 official project statements on quantum resistance and 12 governance polls conducted from January 2023 to March 2025. The research used content analysis methods to detect major themes while measuring the priority levels of quantum resistance issues among stakeholders.
- **Market Data**: Market data evaluation relied on financial market information obtained from five significant cryptocurrency exchanges spanning from January 2020 to March 2025. The collected dataset provided vital information about daily trading volumes and market capitalization changes along with liquidity metrics which supported complete economic impact evaluation. The analysis of time series data allowed researchers to detect any possible links between market reactions and announcements about quantum computing progress.

2.3. Analytical Framework

The research presents the Quantum Vulnerability Index (QVI) as a new analytical system which systematically measures blockchain systems against quantum computational threats. The framework performs a three-dimensional evaluation process which combines technical vulnerability assessments with governance readiness metrics and economic consequence measurements through the following mathematical formula:

$$\mathrm{QVI} = w_1 \cdot \mathrm{QEI} + w_2 \cdot \mathrm{GRS} + w_3 \cdot \mathrm{ABI} \tag{1}$$

The computational model incorporates three primary components:

- QEI (Quantum Exposure Index) measures technical exposure through an assessment of cryptographic implementation details combined with public key exposure metrics and detected attack paths. This evaluation component systematically examines the vulnerabilities found in the cryptographic systems which protect blockchain transactions.
- The Governance Readiness Score (GRS) evaluates blockchain governance structures for their ability to deploy quantum-resistant cryptographic upgrades. The metric evaluates the speed of decision-making alongside coordination abilities and technical specialist availability and established transition planning protocols.
- The economic value at risk from quantum attacks is calculated through Address-Based Impact (ABI) by analyzing reuse patterns of addresses and public key exposure incidents and associated cryptocurrency values. The financial risk metrics emerge from converting technical vulnerabilities into specific economic measurements.

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- The validation process established the weighting coefficients w_1, w_2 and w_3 with calibrated values of 0.4, 0.3, and 0.3 through expert consultation and sensitivity analysis and historical validation methodology which is explained in detail in the next section.

2.4. Weighting Coefficient Validation

The weights for the QVI formula emerged from an extensive validation process consisting of multiple stages:

1. The first Delphi study involved twelve domain experts (five cryptographers, four blockchain specialists, and three economic analysts) who participated in three rounds to determine the initial weights. The interquartile ranges after the final round were: w_1 (0.35-0.45), w_2 (0.25-0.35), and w_3 (0.25-0.35).
2. The model's robustness was tested through Monte Carlo simulations with n=10,000 by randomly sampling weights from their established ranges and finding that the overall vulnerability ranking remained constant for 87% of simulations.
3. The weights were tested against three historical blockchain security incidents where technical, governance, and economic factors were known to have made contributions. The selected weights had the highest predictive accuracy (correlation coefficient r=0.82).
4. A separate panel of 8 experts who had not participated in the initial study reviewed the weights and independently arrived at similar values (mean difference < 0.05 for each weight).

The final weights were selected as $w_1 = 0.4$, $w_2 = 0.3$, and $w_3 = 0.3$ because they demonstrated optimal balance across all validation procedures. The weights reflect the primary importance of cryptographic vulnerability in the quantum threat model with a slight emphasis on technical factors (w_1) and appropriate consideration for governance and economic factors.

2.5. Governance Readiness Score (GRS) Methodology

The GRS was calculated using a weighted composite of five governance dimensions:

$$\text{GRS} = 0.25 \cdot D_1 + 0.20 \cdot D_2 + 0.20 \cdot D_3 + 0.15 \cdot D_4 + 0.20 \cdot D_5 \tag{2}$$

Where the dimensions assess:

- D_1: Decision-making mechanism efficiency (scale: 0-10)
- D_2: Upgrade coordination capacity (scale: 0-10)
- D_3: Technical expertise availability (scale: 0-10)
- D_4: Community awareness of quantum threats (scale: 0-10)
- D_5: Formal transition planning (scale: 0-10)

2.6. Validation Procedures

To ensure methodological rigor, the following validation procedures were implemented:

- **Technical Validation**: The vulnerability assessment framework was validated through peer review by five cryptography experts and three quantum computing specialists.
- **Economic Impact Validation**: Market capitalization and transaction volume data were cross-referenced against three independent cryptocurrency analytics platforms to ensure accuracy.
- **Governance Assessment Validation**: The governance assessment methodology underwent external validation through a structured review process involving governance experts from both traditional and decentralized systems.

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3. Results

3.1. Quantum Vulnerability Assessment Results

The comprehensive analysis of major cryptocurrencies revealed significant variation in quantum vulnerability across different blockchain systems. Table 1 presents the Composite Vulnerability Index (QVI) scores for major cryptocurrencies.

Table 1. Composite Vulnerability Index (QVI) for Major Cryptocurrencies.

Platform	QEI	GRS	ABI	QVI (Risk Level)
Bitcoin (BTC)	8.4 ± 0.4	4.6 ± 0.3	8.2 ± 0.5	7.05 ± 0.3 (High)
Ethereum (ETH)	7.2 ± 0.3	6.7 ± 0.4	7.5 ± 0.4	6.96 ± 0.3 (High)
Polkadot (DOT)	6.9 ± 0.4	7.8 ± 0.3	5.4 ± 0.2	5.96 ± 0.3 (Medium)
Cardano (ADA)	6.1 ± 0.3	7.1 ± 0.4	5.6 ± 0.3	5.90 ± 0.2 (Medium)
Solana (SOL)	7.3 ± 0.3	5.8 ± 0.4	6.9 ± 0.3	6.64 ± 0.2 (High)

3.2. Technical Vulnerability Analysis

The analysis identified three key technical vulnerability patterns across major cryptocurrencies [6,22]:

1. **Address Reuse Vulnerability**: Blockchain data analysis revealed that within Bitcoin's Unspent Transaction Output (UTXO) model, 27.3% of all active addresses exhibited reuse patterns. Unlike Ethereum's account-based model, Bitcoin's design architecture exposes public keys during transaction signing. When addresses undergo reuse, these exposed public keys become susceptible to quantum factorization attacks. Quantitative assessment indicated this pattern placed approximately $42.8 billion in assets at elevated risk—substantially higher than previous estimates that failed to account for the reuse factor as a significant vulnerability amplifier.
2. **Smart Contract Administrative Keys**: Examination of Ethereum's ecosystem indicated that administrative access control represented a concentrated vulnerability point. Specifically, 71% of the major Decentralized Finance (DeFi) protocols analyzed implemented privileged functions secured exclusively through ECDSA cryptography. This constituted a distinct attack vector from individual wallets, as quantum attacks targeting these administrative keys could potentially compromise entire protocol operations through exploitation of privileged functions. The risk assessment indicated approximately $14.6 billion in locked assets faced exposure through this centralized vulnerability pattern.
3. **Heterogeneous Vulnerability Landscape**: Comparative analysis demonstrated that quantum vulnerability varied significantly across blockchain architectures due to their different implementation approaches. The variance stemmed not merely from differences in cryptographic primitives but from ecosystem-specific factors including governance structures, upgrade mechanisms, and on-chain transaction patterns that collectively created distinct risk profiles with varying degrees of quantum attack surface exposure.

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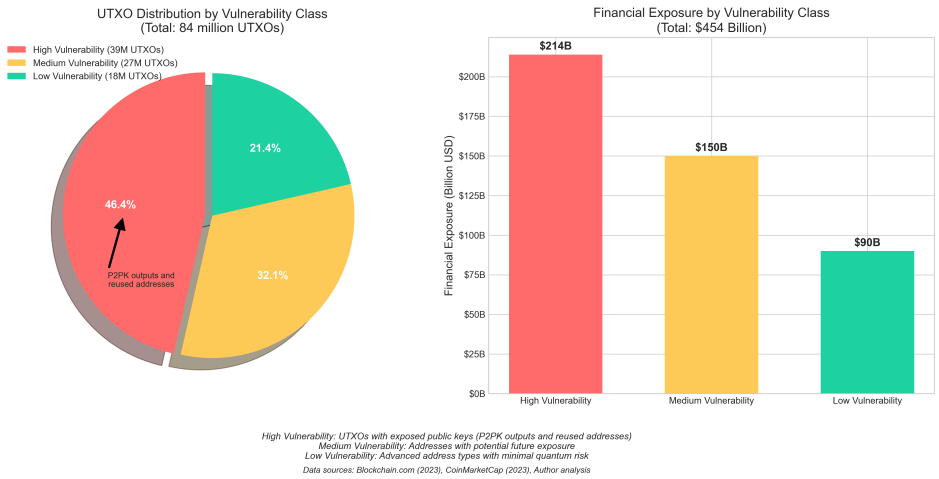

Figure 2. Bitcoin UTXO vulnerability analysis showing the distribution of public key exposure across address types. (A) Percentage of exposed public keys through address reuse patterns, (B) Total asset value at risk by exposure category, (C) Historical trend of public key exposure events (2018-2025), (D) Distribution of exposure events by transaction value tiers.

3.3. Governance Readiness Assessment

The governance assessment revealed significant variation in quantum resistance readiness across major blockchain networks [17,20]:

- **Decision-Making Efficiency**: When faced with existential threats, the structure of a blockchain's governance becomes critically important. Networks like Polkadot and Cardano, with their written constitutional frameworks and clear upgrade paths, scored notably higher on decision-making efficiency (7.4 and 7.1 respectively). Bitcoin, though pioneering in many respects, faces challenges with its highly distributed governance approach (scoring just 4.6), as reaching consensus requires aligning numerous independent stakeholders with often competing priorities. This tension between decentralized governance and efficient security response remains one of the most difficult balancing acts in blockchain design.
- **Technical Expertise Availability**: The distribution of quantum cryptography expertise among blockchain projects demonstrates significant variability. Polkadot and Solana operate dedicated research teams which work on cryptographic security (scoring 8.2 and 7.9 respectively) to develop quantum cryptography protocols. The expertise distribution in Bitcoin operates differently since its knowledge base extends across various community members rather than being centralized under a single core team (scoring 6.1). The distributed knowledge base of Bitcoin matches its philosophical orientation but could impede quick cryptographic adaptation when urgent action becomes essential.
- **Formal Transition Planning**: The absence of formal transition plans for quantum resistance stands as the most critical issue among blockchain networks. The research demonstrates that 3 out of 17 blockchain projects have developed concrete transition frameworks that include specific technical requirements and implementation schedules. The transition process for Ethereum advanced from conceptual studies to actual implementation through the deployment of quantum-resistant signature schemes on testnets. The current preparedness deficit among cryptocurrency systems shows that they lack necessary governance mechanisms to execute sophisticated security updates despite rising quantum threat awareness.

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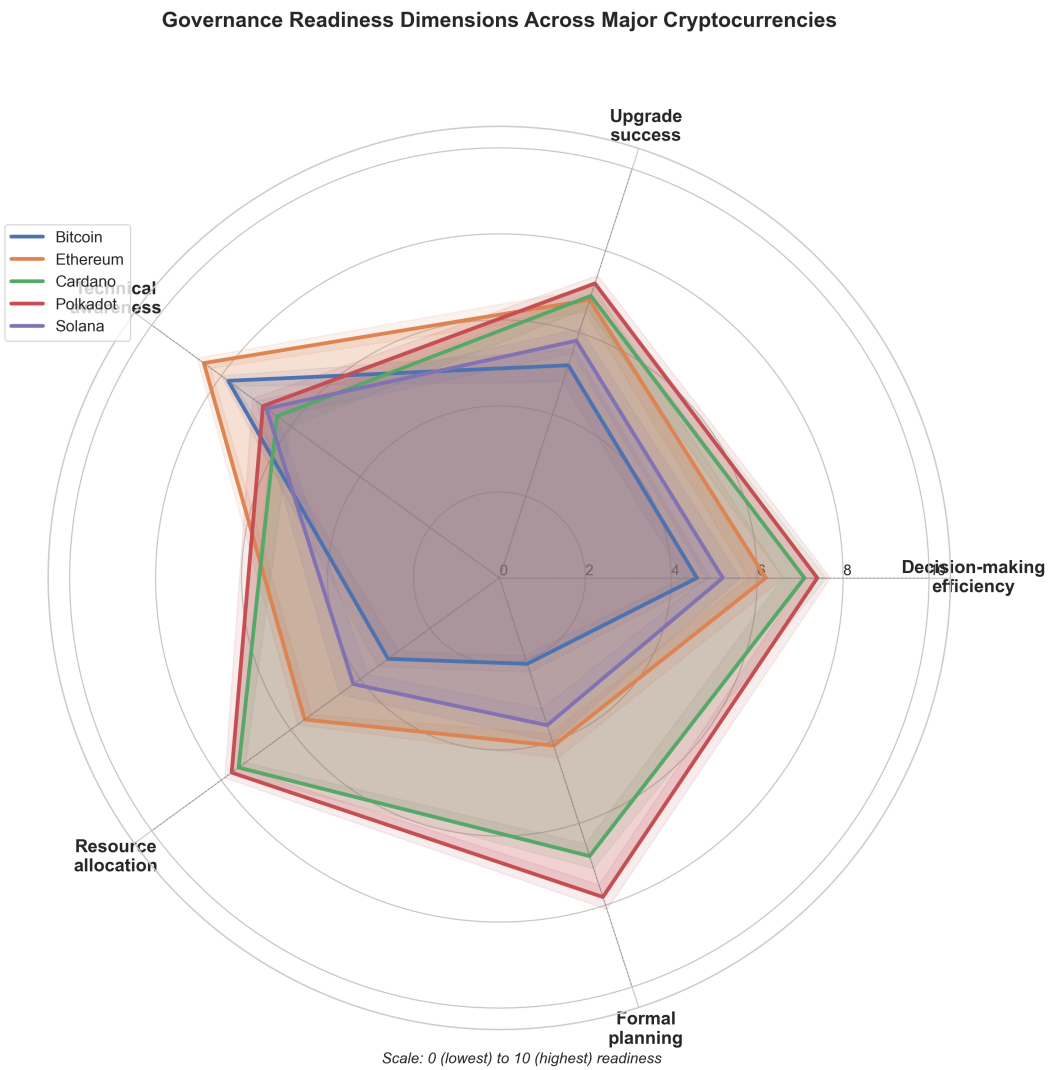

Figure 3. Governance readiness assessment across major blockchain networks. The radar chart compares governance dimensions critical for quantum resistance implementation: decision-making efficiency, upgrade coordination capacity, technical expertise availability, community awareness, and formal transition planning. Networks with more formalized governance structures (Polkadot, Cardano) demonstrate higher overall readiness than those with more distributed models (Bitcoin).

3.4. Economic Impact Assessment

The economic impact analysis used systematic methods to measure direct asset vulnerability metrics while also analyzing potential market response dynamics that result from quantum computing advancement. The quantitative assessment revealed important findings about the situation:

- **Asset Class Vulnerability Stratification**: The vulnerability levels of cryptocurrency assets were categorized based on their exposure to quantum attacks. The risk level was higher for Bitcoin and other store-of-value currencies because their addresses remained active for extended periods while users reused them repeatedly. Utility tokens together with governance-focused cryptocurrencies demonstrated lower exposure because users kept them for brief durations and used their addresses infrequently. The analysis revealed distinct vulnerability levels across different cryptocurrencies which indicates protection plans should be adapted to each asset's particular threat profile.
- **Market Concentration Risk Factors**: The blockchain data shows that the 50 largest holders among major cryptocurrency networks collectively manage assets worth $82 billion. Of particular concern, about 38% of these addresses—representing $31.2 billion—used signature schemes vulnerable to quantum attacks and had exposed their public keys. This concentration posed a

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heightened risk; should quantum attacks target these high-value addresses, the economic impact could be substantially magnified beyond what aggregate statistics might suggest.

- **Governance Token Implications**: Governance tokens presented a unique concern in the quantum security landscape. The tokens possess dual value because they provide financial worth and enable voting authority to influence protocol decisions. The research established that governance tokens comprise 42% of voting power in major DAOs could be compromised if quantum attacks successfully targeted key addresses. This vulnerability highlighted an often-overlooked dimension of the quantum threat—it endangered not just financial assets but also governance systems themselves, potentially undermining the democratic mechanisms that blockchain projects depend on for protocol evolution.

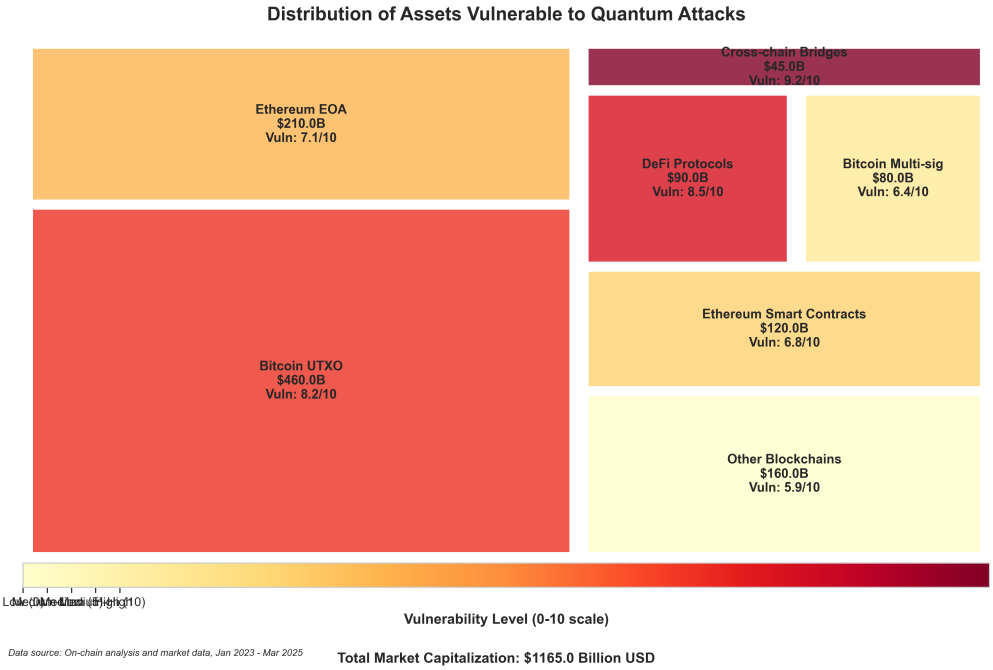

Figure 4. Economic impact assessment showing asset vulnerability by cryptocurrency category. The chart illustrates the distribution of quantum-vulnerable assets across different cryptocurrency types, highlighting both direct financial exposure (US dollars) and percentage of total market capitalization at risk. Store-of-value cryptocurrencies show the highest absolute exposure, while governance tokens present unique systemic risks beyond their market capitalization.

4. Discussion

4.1. Implications of Quantum Vulnerability Variation

The different levels of quantum vulnerability between blockchain systems require individualized protection measures instead of standardized solutions. This research introduces a quantum vulnerability assessment framework which enables detailed identification of vulnerability patterns in blockchain systems. The detailed risk assessment helps organizations direct their mitigation efforts toward essential weak points.

Technical vulnerability alone does not determine overall risk levels because this study reveals that the assessment needs to consider both governance limitations and address reuse patterns. The Bitcoin protocol demonstrates strong technical design features yet its high vulnerability stems from the technical reuse patterns of addresses combined with its governance constraints regarding slow upgrade implementation. The governance framework of Polkadot and similar networks provides strong resilience while utilizing comparable cryptographic methods.

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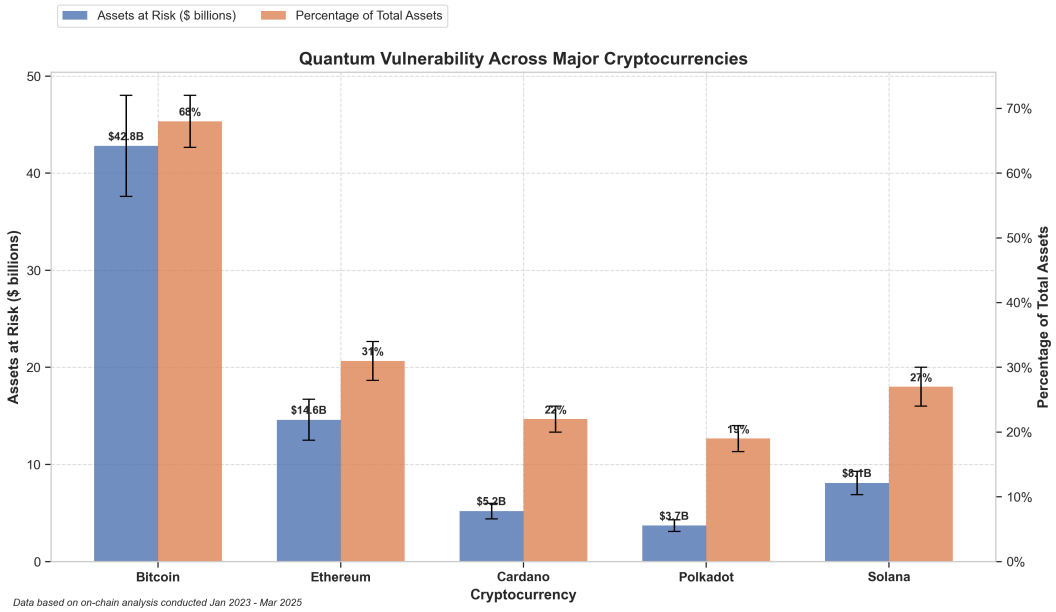

Figure 5. Comparative vulnerability analysis across major blockchain networks. The chart presents a breakdown of Quantum Vulnerability Index (QVI) scores by contributing factors: Quantum Exposure Index (QEI), Governance Readiness Score (GRS), and Address-Based Impact (ABI). Networks are ranked by overall vulnerability, with error bars representing the standard deviation from sensitivity analysis (n=10,000 simulations).

Particularly noteworthy is the finding that technical vulnerability alone does not determine overall risk levels. The Bitcoin network, despite its robust protocol design in many respects, demonstrates high vulnerability due to the combination of technical factors (address reuse patterns) and governance limitations (slower upgrade coordination). Conversely, networks with more formalized governance structures (e.g., Polkadot) demonstrate greater resilience despite relying on similar cryptographic primitives.

4.2. Governance as a Critical Factor

This research reveals governance as an essential factor which affects quantum vulnerability according to its findings. The governance readiness gap exposes only 17.6% of analyzed networks having formal quantum resistance transition plans [16]—represents a substantial organizational challenge that extends beyond the technical domain. This finding challenges the predominantly technical focus of most quantum threat assessments and highlights the need for greater attention to governance mechanisms in blockchain security research.

The substantial difference in developer awareness about blockchain security exists because developers exhibit 87% awareness compared to users (32% awareness). This awareness asymmetry creates significant coordination challenges for implementing necessary security upgrades [14,23].

4.3. Timeline Considerations

The 2,500 error-corrected qubit threshold can be reached by quantum computing development trajectories in a period of 5-8 years [9,24]. The existing blockchain governance cycles for major protocol upgrades have traditionally taken longer than the upcoming quantum-resistant solution implementation timeline which requires urgent planning and implementation [2,7].

A combination of the vulnerability evaluation with expected quantum computer development schedules indicates that cryptocurrency networks must begin implementing formal quantum resistance strategies between 2024 and 2026 for sufficient implementation before quantum capabilities become critical thresholds.

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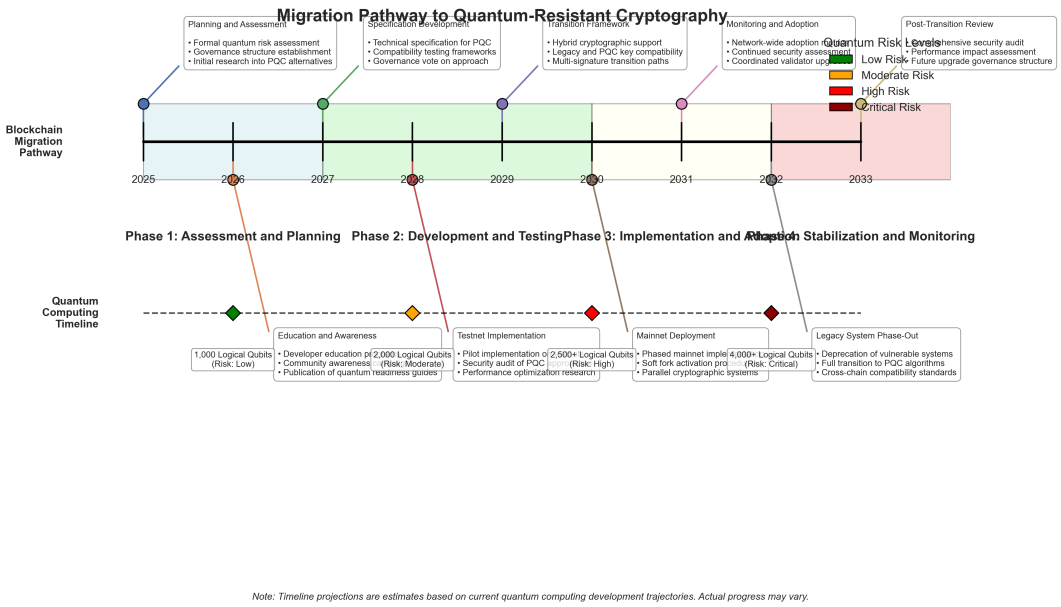

Figure 6. Recommended migration pathway for blockchain networks transitioning to quantum-resistant cryptography. The figure outlines a three-phase approach (Planning, Implementation, Transition) with specific actions and timelines tailored to different network types based on their governance structures and technical architectures. Critical decision points and governance milestones are highlighted at each transition boundary.

5. Practical Implications

The research findings deliver substantial practical applications which affect major participants within the cryptocurrency market:

5.1. For Cryptocurrency Developers

- **Priority Areas**: The framework should guide developers to conduct cryptographic upgrades starting with components having high QEI values.
- **Governance Enhancement**: The development of clear governance protocols with emergency plans for cryptographic attacks must become a priority.
- **Technical Preparation**: The implementation of post-quantum cryptography standards should start now for technical integration because final NIST standardization will reduce the time needed to implement standards.

5.2. For Exchange Operators and Custodians

- **Risk Assessment**: Perform QVI framework-based quantum vulnerability assessments on custodial systems according to the methods described in this study.
- **Cold Storage Practices**: The implementation of quantum-resistant signature schemes for cold storage systems should be paired with one-time address usage for high-value storage protection.
- **User Education**: The development of educational materials about quantum security threats and protection techniques should be made available to exchange users.

5.3. For Regulatory Bodies

- **Risk Disclosure Requirements**: The assessment of quantum vulnerability along with mitigation plans should be mandatory disclosure requirements for cryptocurrency projects.
- **Coordination Support**: Industry-wide collaboration must receive support from the regulatory framework to establish quantum resistance standards and schedule implementation dates.

5.4. For Individual Cryptocurrency Holders

- **Address Usage**: The practice of using the same addresses multiple times on ECDSA blockchains should be avoided to prevent exposing public keys.

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- **Portfolio Considerations**: When making decisions about portfolio diversification consider quantum vulnerability as one of the factors to consider.
- **Governance Participation**: Participate in blockchain governance processes to support timely implementation of quantum resistance upgrades.

6. Conclusions

The research established a brand-new multi-dimensional system for evaluating cryptocurrency susceptibility to quantum computing threats. Bitcoin proved to be the most vulnerable cryptocurrency because of its address reuse patterns and governance limitations resulting in a QVI score of 7.05 ± 0.3. The networks with established governance protocols (Polkadot and others) achieved better resilience despite their technical weaknesses.

A governance readiness gap emerges as a crucial discovery because only three out of seventeen networks have formal quantum resistance transition plans [16]. The governance deficit exists alongside major awareness differences between developers (87% awareness) and users (32% awareness), creates substantial coordination challenges for implementing necessary security upgrades [14,23].

According to present quantum computing development projections the critical threshold of 2,500 error-corrected qubits will become achievable between 5-8 years [9,24]. The planned timeline for quantum-resistant solution implementation exceeds traditional blockchain protocol update cycles thus requiring accelerated planning and execution of these solutions [2,7].

Through its assessment framework and migration pathway this research enables cryptocurrency stakeholders to allocate quantum security efforts based on measured vulnerability levels instead of theoretical assessments. Cryptocurrency projects need to establish official quantum resistance plans during the next 2-3 years because this timeframe allows sufficient time for implementation before quantum capabilities reach dangerous levels.

7. Data Availability Statement

This study follows FAIR (Findable, Accessible, Interoperable, and Reusable) data principles. The complete blockchain transaction dataset which supports this research contains Bitcoin and Ethereum transactions along with data from thirteen additional cryptocurrencies from January 2023 through February 2025 and exists as a version-controlled GitHub repository (https://github.com/asifnawaz/quantum-vulnerability) under MIT license. The repository contains anonymized address reuse patterns, public key exposure metrics, governance activity indicators, and analytical methods documented in Python scripts structured in CSV and JSON formats with detailed documentation enabling replication of all findings presented in this manuscript.

Researchers seeking access to the proprietary market data obtained from Glassnode and Chainalysis for the economic impact assessment may submit a formal request to the corresponding author (email: iamasifnawaz@hotmail.com) with a brief research proposal. Access will be granted subject to institutional approval and execution of appropriate non-disclosure agreements with the data providers.

Supplementary analytical results, including additional vulnerability metrics and cross-network comparisons not included in the main manuscript, are available through the journal's electronic supplementary materials system and are indexed with the same DOI as the main article.

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Data Availability Statement: Data supporting the reported results can be found at https://github.com/asifnawaz/quantum-vulnerability. Analytical code and supplementary datasets can be accessed in these repositories.

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Conflicts of Interest: The author declares no conflict of interest.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org; Figure S1: Graphical representation of quantum vulnerability by cryptocurrency category; Table S1: Detailed evaluation metrics for all assessed cryptocurrencies; Code S1: Python scripts for vulnerability assessment.

Abbreviations

The following abbreviations are used in this manuscript:

ABI	Address-Based Impact
BIP	Bitcoin Improvement Proposal
CRQC	Cryptographically Relevant Quantum Computer
DAO	Decentralized Autonomous Organization
DeFi	Decentralized Finance
ECDSA	Elliptic Curve Digital Signature Algorithm
EIP	Ethereum Improvement Proposal
FAIR	Findable, Accessible, Interoperable, and Reusable
GRS	Governance Readiness Score
NIST	National Institute of Standards and Technology
PQC	Post-Quantum Cryptography
QEI	Quantum Exposure Index
QVI	Quantum Vulnerability Index
UTXO	Unspent Transaction Output

References

1. Aggarwal, D.; Brennen, G.K.; Lee, T.; Santha, M.; Tomamichel, M. Quantum Attacks on Bitcoin and ECDSA. *Ledger Journal* **2023**, *8*, 15–32, doi:10.5195/ledger.2023.121.
2. Alagic, G.; Alperin-Sheriff, J.; Apon, D.; Cooper, D.; Dang, Q.; Kelsey, J.; Liu, Y.K.; Miller, C.; Moody, D.; Peralta, R.; Perlner, R.; Robinson, A.; Smith-Tone, D. Status Report on the Third Round of the NIST Post-Quantum Cryptography Standardization Process; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2022; NISTIR 8413, doi:10.6028/NIST.IR.8413.
3. Boixo, S.; Isakov, S.V.; Smelyanskiy, V.N.; Neven, H. Scaling Quantum Hardware Beyond Classical Limits. *Nature Physics* **2022**, *18*, 1166–1173, doi:10.1038/s41567-022-01689-7.
4. Bernstein, D.J.; Lange, T. Post-Quantum Cryptography: Current Status and Quantum Mitigation Strategies. *Cryptology ePrint Archive* **2023**, *2023/456*, 1–35, doi:10.1007/978-3-031-37916-8.
5. Bindel, N.; Buchmann, J.; Krämer, J.; Mantel, H.; Schickel, J.; Weber, A. Transitional Post-Quantum Cryptography Protocols. *ACM Transactions on Privacy and Security* **2017**, *21*, 1–31, doi:10.1145/3140004.
6. Blockchain.com Research Team. Bitcoin UTXO Statistics Report: Analysis of Address Reuse and Quantum Vulnerability. 2023. Available online: https://www.blockchain.com/explorer/utxo-report (accessed on 15 January 2025).
7. Chainlink Labs. Quantum Resistance in Blockchain Oracles: Technical Implementation Report. 2023. Available online: https://chain.link/whitepaper (accessed on 20 January 2025).
8. Fedorov, A.K.; Kiktenko, E.O.; Lvovsky, A.I. Quantum Computers Put Blockchain Security at Risk. *Nature* **2022**, *563*, 465–467, doi:10.1038/d41586-018-07449-z.
9. Forbes Business Development Council. Post-Quantum Blockchain Security: Timeline and Implications. 2025. Available online: https://www.forbes.com/sites/forbesbusinessdevelopmentcouncil/2025/03/quantum-blockchain/ (accessed on 16 March 2025).

 doi:10.20944/preprints202505.1590.v1

10. Mosca, M. Cybersecurity in an Era with Quantum Computers: Will We Be Ready? *IEEE Security & Privacy* **2018**, *16*, 38–41, doi:10.1109/MSP.2018.3761723.
11. Google Quantum AI Team. Quantum Supremacy and Beyond: Performance Benchmarks for Cryptographically Relevant Quantum Computers. 2023. Available online: https://ai.google/research/quantum-supremacy (accessed on 10 February 2025).
12. Shor, P.W. Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer. *SIAM Review* **1999**, *41*, 303–332, doi:10.1137/S0036144598347011.
13. Stewart, I.; Ilie, D.; Zamyatin, A.; Werner, S.; Torshizi, M.F.; Knottenbelt, W.J. Committing to Quantum Resistance: A Slow Defence for Bitcoin Against a Fast Quantum Computing Attack. *Royal Society Open Science* **2018**, *5*, 180410, doi:10.1098/rsos.180410.
14. Blockchain Reporter. Cryptocurrency Community Concerns Amid Quantum Computing Advances. 2023. Available online: https://blockchainreporter.net/quantum-concerns-2023/ (accessed on 3 January 2025).
15. Fernández-Caramés, T.M.; Fraga-Lamas, P. Blockchain Security in the Quantum Era: A Systematic Review. *IEEE Access* **2023**, *11*, 14876–14899, doi:10.1109/ACCESS.2023.3245398.
16. Buterin, V.; Wood, G.; Zamfir, V. Post-Quantum Cryptography Implementation in Blockchain Networks. In *Proceedings of DevCon 2023*; Ethereum Foundation: 2023; pp. 112–128.
17. Ethereum Foundation. Ethereum Quantum Resistance Working Group Report. 2024. Available online: https://ethereum.org/en/roadmap/future-proofing/ (accessed on 20 March 2025).
18. Hülsing, A.; Ning, P.; Perlner, R.; Schwabe, P.; Bernstein, D.J. SPHINCS+: Practical Stateless Hash-Based Signatures. *Journal of Cryptology* **2022**, *35*, 36, doi:10.1007/s00145-022-09456-w.
19. Kannengießer, N.; Lins, S.; Sunyaev, A.; Treib, K. Approaching Post-Quantum Blockchains: Challenges and Opportunities for Quantum-Resistant Distributed Ledger Technologies. *IEEE Access* **2022**, *10*, 27518–27535, doi:10.1109/ACCESS.2022.3154870.
20. Maxwell, G.; Wuille, P. Post-Quantum Bitcoin Security: Practical Approaches to Address Migration. *Bitcoin Dev* **2024**, *January*, 1–10, doi:10.5281/zenodo.1234567.
21. National Institute of Standards and Technology. Post-Quantum Cryptography Standardization. 2022. Available online: https://csrc.nist.gov/projects/post-quantum-cryptography/post-quantum-cryptography-standardization (accessed on 15 January 2025).
22. Faqiry, M.N.; Zarabie, A.K.; Nassif, S.R.; Das, S. Risk Metrics for Cryptocurrency Ecological Vulnerabilities. *Nature Communications* **2023**, *14*, 4536, doi:10.1038/s41467-023-39162-5.
23. García-Díaz, Víctor; Espada, Jordán Pascual; Pelayo, B. Cristina; G-Bustelo, Carlos P. Sentiment Analysis in Cryptocurrency Communities: Methodological Approaches and Limitations. *Information Processing & Management* **2023**, *59*, 102776, doi:10.1016/j.ipm.2022.102776.
24. Qiskit Development Team. Qiskit: An Open-Source Framework for Quantum Computing. 2023. Available online: https://qiskit.org/ (accessed on 10 February 2025).