

Government Policy Frameworks for Quantum-Enabled Educational Infrastructure: Bridging the Digital Divide in Rural Communities

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Abstract

The emergence of quantum technologies presents both opportunities and challenges for educational equity, particularly in rural communities that face persistent digital infrastructure gaps. This article examines the role of government policy in facilitating the diffusion of quantum-informed educational innovations to underserved areas. While acknowledging the current limitations and high costs of quantum technologies, we analyze how strategic public investment in foundational infrastructure, workforce development, and research partnerships can prepare rural regions for future technological transitions. Drawing on innovation diffusion theory and empirical evidence from technology adoption patterns, we propose a multi-tiered policy framework that balances immediate practical needs with long-term technological readiness. Our analysis reveals that successful integration of advanced technologies in rural education requires coordinated interventions addressing infrastructure deficits, human capital development, and institutional capacity building. The findings suggest that government-led initiatives must prioritize incremental technological adoption while maintaining realistic expectations about quantum technology timelines and costs.

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1 Introduction

The rapid advancement of quantum technologies has generated considerable attention among policymakers seeking to harness their potential for economic development and social progress (European Commission. Joint Research Centre, 2016). However, the debate surrounding quantum technologies often overlooks a fundamental challenge: how can societies ensure equitable access to these emerging innovations, particularly for rural communities that already struggle with basic digital infrastructure? This question becomes especially pressing in the context of education, where technological disparities between urban and rural areas continue to widen despite decades of policy interventions (Fan et al., 2000).

The educational sector represents a critical domain for technological innovation, as it shapes human capital formation and determines long-term economic competitiveness. Yet rural communities face persistent barriers to accessing advanced educational technologies, including inadequate infrastructure, limited financial resources, insufficient technical expertise, and institutional constraints that impede innovation adoption (Middleton, 1993). These challenges are compounded when considering quantum technologies, which require substantial capital investment, specialized knowledge, and supporting infrastructure that far exceeds the requirements of conventional digital technologies.

Current discourse on quantum technologies tends to emphasize their revolutionary potential while underestimating the practical challenges of implementation, particularly in resource-constrained settings. de Jong (2022) highlights the need for demystification of unrealistic perceptions and contextualization through enabling socio-technical environments. Similarly, Wolbring (2022) demonstrates that social considerations remain largely absent from quantum technology research, with only 0.24% of technical abstracts mentioning social terms. This analytical gap is particularly problematic for education policy, as it fails to address how quantum innovations might be adapted for diverse socioeconomic contexts.

The central question animating this article is: what role can government policy play in bridging the gap between quantum technological advancement and rural educational needs? Rather than assuming direct implementation of quantum computing or quantum communication systems in rural schools, we examine how governments

can strategically position these communities to benefit from quantum-related innovations through intermediary technologies, workforce preparation, and infrastructure development. This approach recognizes that the pathway from quantum research to practical educational applications involves multiple stages of technological translation and adaptation.

Our analysis contributes to the literature on innovation diffusion by examining how government interventions can modify adoption patterns for advanced technologies in contexts characterized by significant resource constraints. We build on innovation diffusion frameworks while incorporating insights from recent research on quantum technology implications (Kop, 2023; Possati, 2024). Additionally, we draw on empirical evidence regarding the effectiveness of government spending on rural development and education infrastructure (Fan et al., 2000; Schiff and Wang, 2010).

The article proceeds as follows. Section 2 establishes the theoretical framework connecting innovation diffusion theory with digital infrastructure development. Section 3 examines the current state of quantum technologies in educational contexts, emphasizing realistic assessments of costs and capabilities. Section 4 analyzes government-led technology adoption models in rural areas, identifying successful intervention patterns. Section 5 proposes policy frameworks for equitable access to advanced technologies. Section 6 discusses economic and social implications. Section 7 concludes with policy recommendations and directions for future research.

2 Theoretical Framework: Innovation Diffusion and Digital Infrastructure

The adoption of technological innovations in educational settings follows patterns that are well-documented in the innovation diffusion literature. Key attributes that influence adoption rates include relative advantage, compatibility, complexity, trialability, and observability. For quantum technologies in rural education, each attribute presents distinct challenges. The relative advantage remains uncertain given the nascent stage of practical applications, compatibility with existing infrastructure is limited, complexity is extraordinarily high, opportunities for trial are minimal due to costs, and observability of benefits is constrained by the abstract nature of quantum phenomena.

López-Claros (2011) demonstrates that innovation capacity varies significantly across development contexts, with institutional frameworks, human capital, and infrastructure playing crucial enabling roles. Rural communities typically score lower on these dimensions, creating a systematic disadvantage in technology adoption.

This disadvantage is compounded for quantum technologies, which require more sophisticated supporting infrastructure than conventional digital innovations.

The concept of digital divide has evolved from simple access metrics to encompass usage patterns, skill development, and meaningful participation in digital economies (Ebua, 2023). Kuban State Agrarian University et al. (2025) highlights how automation and artificial intelligence exacerbate inequality through unequal access to technologies and digital skills, particularly in remote regions. The quantum technological transition risks deepening these divides unless proactive policy interventions address structural barriers.

Government intervention in technology diffusion can be conceptualized through multiple theoretical lenses. Public goods theory suggests that government provision is justified when markets fail to supply socially optimal levels of infrastructure. Network externalities theory indicates that early public investment can catalyze broader adoption by reducing coordination problems. Human capital theory emphasizes government's role in funding education and training that private actors may underprovide due to appropriability challenges.

Empirical research on government spending effectiveness provides important insights. Fan et al. (2000) found that in rural India, investments in roads and agricultural research had greater impact on growth and poverty reduction than direct poverty-targeted programs. This suggests that infrastructure and knowledge development may be more effective than targeted technology deployment. Similarly, Schiff and Wang (2010) demonstrated that technology diffusion from developed to developing countries is mediated by education and governance quality, indicating that absorptive capacity is critical.

For quantum technologies specifically, Peterssen (2020) emphasizes the need for specialized workforce development, while Arrow et al. (2023) advocates for comprehensive quantum ethics education. These insights suggest that successful integration of quantum innovations in education requires substantial preparatory investments in human capital and institutional capacity.

The theoretical framework guiding our analysis rests on three pillars. First, innovation adoption in resource-constrained environments requires government intervention to overcome market failures and coordination problems. Second, effective intervention must address both immediate infrastructure needs and long-term capability development. Third, successful technology diffusion depends critically on local absorptive capacity, requiring coordinated investments in education, training, and institutional development.

3 Quantum Technologies in Educational Contexts: Current State and Limitations

Understanding the realistic potential and limitations of quantum technologies for education is essential for grounding policy discussions in empirical reality. Current quantum technologies can be categorized into four domains: quantum computing, quantum communication, quantum sensing, and quantum simulation ([European Commission. Joint Research Centre, 2016](#)). Each domain presents different maturity levels, cost structures, and potential educational applications.

Quantum computing remains in early development stages, with current systems requiring extreme cooling, specialized facilities, and expert operation. The notion that quantum computers might be deployed directly in rural schools is unrealistic for the foreseeable future. However, cloud-based access to quantum computing resources could potentially support advanced STEM education, allowing students to experiment with quantum algorithms remotely. This model parallels current cloud computing services but requires robust internet connectivity, which many rural areas lack.

Quantum communication technologies, particularly quantum key distribution, are more mature but still prohibitively expensive for most educational institutions. [Young et al. \(2024\)](#) notes that functional quantum networks may be achieved by 2030, but deployment will likely prioritize high-security applications rather than educational settings. The relevance for rural education lies primarily in workforce preparation, ensuring that future generations possess the foundational knowledge to participate in quantum-enabled economies.

Quantum sensing offers potentially nearer-term applications, with quantum sensors demonstrating superior precision in measuring magnetic fields, gravity, and time ([Mauranyapin et al., 2022](#)). These technologies could enhance science education through advanced instrumentation, but current costs remain prohibitive for widespread educational deployment. More realistically, quantum sensing principles might inform educational curricula, helping students understand measurement precision and quantum phenomena.

[Krelina \(2021\)](#) provides a sobering assessment of quantum technology timelines, noting that military applications drive much current development. This reality suggests that civilian educational applications will lag behind defense and commercial deployments, potentially widening disparities if rural communities are left behind in subsequent adoption waves.

The cost structure of quantum technologies presents a fundamental barrier. Ini-

tial capital requirements far exceed conventional educational technology budgets. A single dilution refrigerator for quantum computing costs several hundred thousand dollars, while quantum communication systems require specialized photon detectors and fiber infrastructure. Maintenance demands specialized expertise that is scarce even in urban centers, much less in rural areas.

Moreover, the pedagogical value of direct quantum technology access in primary and secondary education is questionable. Meyer (2023) argues for quantum ethics education rather than technical quantum training at undergraduate levels, suggesting that understanding implications may be more important than operational skills for most learners. This perspective supports a policy approach emphasizing foundational STEM education and quantum literacy rather than direct technology deployment.

Despite these limitations, quantum technologies may indirectly benefit rural education through several pathways. First, quantum-enhanced drug discovery and materials science could improve educational outcomes through better health and nutrition. Second, quantum-inspired classical algorithms may enhance educational software without requiring quantum hardware. Third, workforce preparation for quantum industries could create economic opportunities for rural communities, reducing incentives for talent migration to urban centers.

Realistic policy must acknowledge that quantum technologies' direct educational applications remain distant for most rural communities. However, this does not diminish the importance of preparing these communities for eventual technological transitions through infrastructure development, digital literacy programs, and STEM education enhancement.

4 Government-Led Technology Adoption in Rural Areas

Historical patterns of technology diffusion in rural areas reveal both successful and unsuccessful government intervention models. Fan et al. (2000) demonstrates that in rural India, government investments in roads and agricultural research significantly impacted productivity and poverty reduction, while targeted poverty programs showed modest effects. This finding suggests that enabling infrastructure and knowledge generation may be more effective than direct technology provision.

The experience with information and communication technologies in rural areas offers instructive lessons. Many governments implemented programs to bridge digital divides through subsidized internet access, computer labs in schools, and digital

literacy training. Successful initiatives combined infrastructure provision with human capital development and institutional support. Technology adoption impacts on inclusive growth varied substantially across countries, depending on complementary factors including education, market access, and labor mobility.

Government-led technology adoption programs can be categorized into several models. The direct provision model involves government purchasing and distributing technology to rural institutions. This approach often fails when maintenance, training, and operational support are inadequate. The subsidy model reduces technology costs for rural adopters but may create dependency and distort markets. The infrastructure model focuses on enabling conditions such as electricity, internet connectivity, and transportation, allowing markets to drive technology adoption. The capacity-building model emphasizes training, education, and institutional development to enhance absorptive capacity.

For quantum technologies specifically, the infrastructure and capacity-building models appear most promising. Direct provision is impractical given costs and complexity, while subsidies alone cannot overcome fundamental infrastructure and knowledge barriers. Instead, governments should focus on creating conditions that allow rural communities to participate in quantum-enabled economies when technologies mature.

[Schiff and Wang \(2010\)](#) identifies education and governance as critical mediators of technology diffusion from developed to developing contexts. This insight suggests that improving educational quality and institutional capacity in rural areas should be priority interventions, even if quantum technology deployment is distant. By building strong foundational capabilities, rural communities position themselves to adopt innovations as they become available and economically viable.

Public capital's role in economic development has been extensively studied. [Bom and Ligthart \(2008\)](#) finds through meta-analysis that public capital contributes positively to private output, with an average elasticity of 0.08. However, effectiveness varies by context, infrastructure type, and governance quality. For rural education, this suggests that strategic public investment in digital infrastructure, STEM facilities, and teacher training can generate significant returns, even without direct quantum technology deployment.

International comparisons reveal diverse approaches to rural technology adoption. Some countries prioritize universal connectivity, ensuring that all communities have high-speed internet access. Others focus on centers of excellence, concentrating resources in selected locations to achieve technological leadership. A hybrid approach may be most appropriate for quantum technologies, combining broad foun-

dational infrastructure with targeted investments in quantum research and education hubs that can serve wider regions.

The challenge of maintaining technological infrastructure in rural areas is often underestimated. [Middleton \(1993\)](#) emphasizes that vocational training systems in developing countries frequently suffer from inadequate maintenance and operational support. For complex quantum-related technologies, this problem is magnified. Government policy must address not only initial deployment but also long-term sustainability through local capacity development and regional support networks.

Adaptive governance structures that allow policy experimentation and learning are essential for emerging technologies. [de Jong \(2022\)](#) proposes flexible regulatory frameworks and anticipatory governance for quantum technologies. Rural technology adoption policies should similarly embrace experimentation, allowing local variations and learning from implementation experiences.

5 Policy Models for Equitable Access to Advanced Technologies

Developing effective policy frameworks for quantum technology diffusion in rural education requires balancing multiple objectives: equity, efficiency, sustainability, and technological readiness. We propose a multi-tiered approach that addresses immediate educational needs while preparing for long-term technological transitions.

The first tier focuses on foundational digital infrastructure. Without reliable electricity, internet connectivity, and basic computing resources, discussions of quantum technologies remain academic. Government policy should prioritize universal broadband access, stable power supplies, and basic digital literacy. These investments create enabling conditions for all subsequent technological adoption. The adoption rate A_t at time t can be expressed as a function of infrastructure quality I_t , human capital H_t , economic resources E_t , and governance effectiveness G_t . For rural areas, improvements in infrastructure and human capital through public investment can partially compensate for lower economic resources.

The second tier emphasizes STEM education enhancement. Rather than focusing narrowly on quantum technologies, policy should strengthen mathematics, physics, and computer science education broadly. This approach builds foundational knowledge that enables future quantum literacy while providing immediate benefits through improved general education. Teacher training is particularly critical, as rural schools often face challenges in recruiting and retaining qualified STEM educators.

The third tier involves targeted quantum literacy programs. As quantum technologies approach practical deployment, educational curricula should introduce quantum concepts at appropriate levels. Meyer (2023) advocates for quantum ethics education that examines social implications rather than technical details. This approach is particularly suitable for rural contexts, where emphasis on responsible technology use and societal impacts may be more valuable than operational training.

The fourth tier addresses workforce development for quantum industries. While quantum research and production may concentrate in urban centers, ancillary services, applications development, and technology translation could occur in rural areas if appropriate skills exist. Government policy should support vocational training programs that prepare rural workers for quantum-related employment, potentially through partnerships with industry and universities.

Partnership models between government, universities, and private sector can leverage resources and expertise. Vermaas (2017) emphasizes the need for multidisciplinary collaboration in understanding quantum technology impacts. Similar collaboration is essential for implementation, with universities contributing research and training, government providing funding and coordination, and private sector offering practical applications and employment pathways.

Regional coordination can achieve economies of scale in technology deployment and maintenance. Rather than attempting to provide advanced technologies to every rural school independently, governments might establish regional quantum education centers that serve multiple communities. This hub-and-spoke model allows concentrated investment in facilities and expertise while extending access through outreach programs, remote learning, and visiting faculty arrangements.

Equity metrics are essential for evaluating policy effectiveness. Traditional measures like student enrollment or graduation rates should be supplemented with technology access indicators, digital literacy assessments, and participation rates in advanced STEM courses. Policy effectiveness should be measured by reductions in disparities between rural and urban educational outcomes.

Financing mechanisms require careful design. Direct budget allocations provide certainty but may be politically vulnerable. Dedicated funds or trusts can ensure continuity across political cycles. Public-private partnerships can leverage private capital but require strong regulatory oversight to prevent profit-seeking behavior that undermines equity goals. Development banks and international organizations may provide concessional financing for infrastructure projects with strong social returns.

Temporal sequencing of investments is critical. Infrastructure development must

precede advanced technology deployment. Human capital formation requires sustained effort over years or decades. Attempting to deploy quantum technologies before foundational conditions are met wastes resources and generates disappointment. Policy should establish clear milestones and prerequisites for advancing from one tier to the next.

6 Economic and Social Implications

The diffusion of quantum technologies in rural education carries profound economic and social implications that extend beyond immediate educational outcomes. Understanding these broader effects is essential for designing comprehensive policy interventions and managing potential risks.

From an economic perspective, enhanced educational infrastructure and technological capacity can reduce rural-urban migration by creating local opportunities. [Kuban State Agrarian University et al. \(2025\)](#) demonstrates how automation increases productivity but also deepens inequalities when access is uneven. By ensuring rural communities participate in technological transitions, government policy can mitigate these disparities and promote more balanced regional development.

Human capital formation represents a key channel through which education influences long-term economic growth. [Schiff and Wang \(2010\)](#) shows that education mediates technology diffusion from developed to developing contexts, suggesting that investments in rural education generate multiplier effects through enhanced absorptive capacity. For quantum technologies, early education establishes foundational knowledge that enables future participation in quantum-enabled industries and services.

The labor market implications of quantum technology advancement are complex. [Yolusever \(2025\)](#) examines how AI and automation reshape employment, noting that while some jobs are displaced, new opportunities emerge requiring different skill sets. Quantum technologies may follow similar patterns, with traditional technical roles evolving toward quantum-specific competencies. Rural workers without access to quantum education risk exclusion from emerging employment opportunities, exacerbating existing economic divides.

Income inequality may be affected through multiple channels. If quantum technologies primarily benefit educated urban populations, existing inequalities will deepen. Conversely, if policy interventions successfully extend quantum education opportunities to rural areas, inequality could be reduced through expanded access to high-skill, high-wage employment. The distributional impact depends critically

on policy design and implementation effectiveness.

Social capital and community cohesion are often overlooked in technology policy discussions. [Wolbring \(2022\)](#) notes the absence of marginalized groups from quantum technology discourse, suggesting risk of social exclusion. Educational programs that engage rural communities in quantum technology discussions can build awareness, reduce alienation, and foster inclusive participation in technological futures.

Cultural considerations are important but frequently neglected. Technology adoption is not merely a technical process but involves cultural adaptation and meaning-making. [Possati \(2024\)](#) advocates for hermeneutic technology assessment that examines how technologies are socially constructed and communicated. Rural communities may have different values, priorities, and concerns regarding quantum technologies than urban populations, requiring culturally sensitive policy approaches.

Gender disparities in STEM education and technology access require explicit policy attention. Rural areas often exhibit more pronounced gender gaps in educational attainment and technology use. Quantum education initiatives should incorporate strategies to encourage female participation, ensuring that benefits are broadly distributed and talent pools are maximized.

Environmental sustainability represents both a challenge and an opportunity. Quantum technologies require significant energy for operation, particularly quantum computing systems that need extensive cooling. However, quantum sensing might improve environmental monitoring, and quantum optimization could enhance resource efficiency. Policy should consider environmental implications when designing rural technology initiatives, potentially prioritizing applications with sustainability benefits.

The psychological and cultural impacts of rapid technological change merit consideration. [Vermaas \(2017\)](#) highlights the need to make quantum theory understandable to diverse audiences, moving beyond enigmatic framings that may alienate non-specialists. Education programs should demystify quantum technologies while acknowledging their complexity, helping rural communities engage critically rather than viewing quantum innovations as incomprehensible or threatening.

International competitiveness is sometimes invoked as a rationale for quantum technology investment. However, for rural communities, national competitiveness arguments may seem remote from daily concerns. Policy communication should emphasize local benefits such as employment opportunities, improved services, and community development rather than abstract national goals.

7 Conclusion

This article has examined the role of government policy in facilitating quantum technology diffusion in rural education, addressing a critical gap in both quantum technology literature and rural development research. Our analysis reveals several key findings with important policy implications.

First, direct deployment of quantum technologies in rural educational settings is neither economically feasible nor pedagogically justified in the near to medium term. Current quantum technologies require capital investments, technical expertise, and supporting infrastructure that far exceed rural educational budgets and capabilities. However, this reality does not diminish the importance of policy interventions. Rather, it redirects attention toward foundational investments that prepare rural communities for eventual technological transitions while delivering immediate educational benefits.

Second, effective government intervention must adopt a multi-tiered approach that prioritizes foundational digital infrastructure, enhances STEM education broadly, introduces quantum literacy at appropriate levels, and develops workforce capabilities for quantum-related industries. This sequencing recognizes that technological adoption requires enabling conditions that cannot be bypassed through direct technology provision. Infrastructure, human capital, and institutional capacity must be developed systematically over time.

Third, equity considerations must be central to policy design rather than afterthoughts. Rural communities face systematic disadvantages in technology adoption due to resource constraints, geographic isolation, and institutional weaknesses. Without deliberate policy interventions that provide higher investment rates and targeted support, quantum technological advancement will exacerbate existing educational and economic inequalities. The social costs of widening divides include foregone human capital development, regional economic stagnation, and social fragmentation.

Fourth, successful policy requires sustained commitment over extended timeframes. Technology diffusion, particularly for complex innovations like quantum technologies, is a multi-decade process. Educational infrastructure development, teacher training, curriculum reform, and cultural adaptation cannot be accomplished through short-term projects. Government policy must establish stable funding mechanisms, institutional structures, and evaluation frameworks that ensure continuity across political cycles.

Fifth, partnerships between government, universities, and private sector are essential for leveraging expertise and resources. No single actor possesses all necessary

capabilities for successful quantum technology diffusion. Universities contribute research knowledge and training capacity, government provides coordination and funding, and private sector offers practical applications and employment pathways. Effective partnership models require clear role definitions, shared objectives, and governance structures that balance different stakeholder interests.

Several policy recommendations emerge from our analysis. Governments should prioritize universal broadband access in rural areas, as this represents the foundational infrastructure enabling all subsequent technological adoption. Teacher training programs should be expanded and strengthened, particularly in STEM fields, recognizing that human capital development is the most critical bottleneck for educational technology diffusion. Quantum literacy should be integrated into secondary and tertiary curricula, emphasizing social implications and ethical considerations alongside technical concepts. Regional quantum education centers could serve multiple rural communities, achieving economies of scale while extending access through outreach and remote learning programs.

Our analysis has several limitations that suggest directions for future research. We have not conducted empirical assessments of specific policy interventions, relying instead on theoretical frameworks and comparative evidence. Detailed cost-benefit analyses of different investment strategies would strengthen policy guidance. Our focus on education has limited attention to other potential applications of quantum technologies in rural development, such as agricultural optimization or healthcare improvement. The political economy of technology policy deserves deeper examination, particularly regarding how rural interests can be effectively represented in policy processes dominated by urban and commercial concerns.

The emerging quantum technology revolution presents both challenges and opportunities for rural communities. With thoughtful, sustained policy interventions that prioritize equity alongside efficiency, governments can ensure that these communities participate in and benefit from technological progress rather than being left behind. The stakes are high, as the choices made today will shape educational opportunities, economic prospects, and social cohesion for generations to come.

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