Energy-Efficient Quantum Communication Systems for Sustainable National Networks

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Abstract*— Energy consumption has emerged as a critical constraint in the large-scale deployment of quantum communication technologies, particularly as nations explore quantum-secure networks to support long-term digital sovereignty and critical infrastructure protection. While Quantum Key Distribution (QKD) and emerging quantum networking paradigms offer unprecedented security guarantees, their associated hardware, cooling, synchronization, and classical post-processing requirements introduce non-negligible energy overheads. This paper investigates energy-efficient quantum communication system architectures for sustainable national-scale networks. We propose a multi-layer framework that integrates energy-aware QKD protocols, adaptive key management, intelligent node placement, and hybrid classical–quantum optimization strategies. The methodology combines analytical energy modeling with scenario-based evaluation across metropolitan and inter-regional fiber corridors. Results demonstrate that energy-aware orchestration and selective deployment can reduce operational energy consumption by up to 30–45% without compromising security or service availability. The findings provide a practical foundation for designing environmentally sustainable quantum communication infrastructures aligned with national energy efficiency and carbon-reduction objectives.

Keywords—Quantum Key Distribution, network operations, artificial intelligence, process innovation

I. INTRODUCTION

National communication infrastructures are undergoing a profound transformation as governments seek to enhance cybersecurity, data sovereignty, and long-term confidentiality in the face of emerging quantum computing threats. Quantum communication technologies—particularly Quantum Key Distribution (QKD) and early-stage quantum networking—have been widely recognized as foundational enablers of future secure national networks. However, as pilot deployments transition toward metropolitan- and national-scale infrastructures, energy efficiency has emerged as a critical and often underexamined challenge. Unlike purely software-based cryptographic upgrades, quantum communication systems rely on specialized photonic hardware, precise timing and synchronization, active stabilization, and continuous classical post-processing, all of which contribute to non-trivial energy consumption [1], [2].

Sustainability considerations are increasingly central to national digital strategies. Telecommunications networks already account for a growing share of global electricity demand, driven by data center expansion, cloud services, and high-capacity optical backbones [3]. The introduction of quantum communication layers—such as QKD transmitters and receivers, single-photon detectors, trusted relay nodes, and key management infrastructures—adds new energy loads that must be carefully managed to avoid undermining national energy efficiency and carbon-reduction goals. For countries pursuing both quantum-secure communications and sustainable development objectives, the challenge is not merely to deploy quantum technologies, but to do so in an energy-aware and environmentally responsible manner.

Existing QKD demonstrations and early networks have primarily focused on security, distance, and key generation rates. Field trials in metropolitan fiber corridors and inter-city links have successfully demonstrated stable secret key distribution over tens to hundreds of kilometers [4], [5]. However, these studies often treat energy consumption as an implicit background cost rather than a primary design parameter. In practice, QKD systems require continuous operation of laser sources, modulators, temperature-controlled single-photon detectors, and real-time classical communication for sifting, error correction, and privacy amplification. Furthermore, trusted-node architectures—currently necessary for extending QKD over long distances—introduce additional equipment, cooling, and operational overheads at each intermediate site [6]. As a result, naïve scaling of quantum communication infrastructure risks creating energy-intensive systems that are misaligned with sustainable network design principles.

Recent research has begun to acknowledge the importance of energy-efficient quantum communications, highlighting opportunities for optimization at multiple layers of the system. Protocol-level advances, such as efficient decoy-state schemes and adaptive modulation, can reduce wasted photon transmissions and classical processing overhead [7]. Hardware innovations, including superconducting nanowire single-photon detectors with improved detection efficiency and lower dark counts, have demonstrated potential reductions in cooling and operational energy per generated key bit [8]. At the network level, intelligent placement of QKD nodes, traffic-aware key scheduling, and hybrid classical–quantum architectures can further improve energy utilization by matching quantum resources to actual security demands [9].

Despite these advances, there remains a lack of holistic, system-level frameworks that explicitly integrate energy efficiency into the design and operation of national-scale quantum communication networks. Most existing studies analyze isolated components or laboratory-scale setups, offering limited guidance for policymakers and network operators tasked with deploying sustainable quantum-secure infrastructures. In particular, the trade-offs between energy consumption, security assurance, key availability, and service-level performance are not yet well understood in realistic operational contexts [10]. This gap is especially

significant for national networks, where heterogeneous traffic patterns, diverse geographic conditions, and long asset lifecycles necessitate careful balancing of performance and sustainability.

This paper addresses this gap by proposing an energy-efficient quantum communication system framework tailored to sustainable national networks. The study focuses on QKD-centric architectures while remaining extensible to future quantum networking technologies. We develop a multi-layer methodology that combines energy-aware system architecture, analytical energy modeling, adaptive key management, and deployment scenario analysis across metropolitan and inter-regional fiber corridors. By evaluating representative national network scenarios, the paper quantifies the energy impacts of different design choices and demonstrates how intelligent orchestration and selective deployment can significantly reduce operational energy consumption without compromising security or availability.

The contributions of this work are threefold. First, it provides a structured energy model for quantum communication systems that captures both quantum and classical processing components. Second, it proposes practical architectural and operational strategies for improving energy efficiency at scale. Third, it offers quantitative insights to support national decision-making on sustainable quantum network deployment. Together, these contributions aim to align the advancement of quantum-secure communications with broader sustainability and energy-efficiency objectives.

II. Literature Review

QKD foundations and security models. Modern quantum communication deployments are dominated by fiber-based QKD, where security is rooted in quantum measurement disturbance and formal information-theoretic security proofs under well-defined device and adversary assumptions. Comprehensive overviews emphasize that practical QKD security depends not only on protocol theory, but also on implementation security and rigorous post-processing (sifting, error correction, privacy amplification) [1], [2]. In this context, decoy-state BB84 variants have become the most widely deployed family because they tolerate imperfect photon sources while enabling stable key rates over metropolitan fiber links [1]. However, real-world adoption has also revealed the importance of closing side-channel vulnerabilities (especially detector attacks), motivating protocol families that reduce reliance on trusted measurement devices.

Protocol innovations shaping deployability and efficiency. Measurement-device-independent QKD (MDI-QKD) was proposed to remove detector side-channel attacks by shifting measurement to an untrusted relay node, thereby strengthening practical security while preserving compatibility with standard optical components [3]. At longer distances, twin-field QKD (TF-QKD) has been shown to overcome the conventional repeaterless rate–distance scaling, extending feasible secure key exchange into regimes beyond typical metro and regional bounds without full quantum repeaters [4]. While these advances improve security margins and distance, they can introduce additional stabilization, phase tracking, or relay requirements, which may increase classical processing and control overhead—relevant when energy efficiency is considered at scale.

From point-to-point links to metropolitan and multi-node networks. Early demonstrations established that QKD can operate reliably in real fiber infrastructure, evolving from single links to multi-node networks with key management layers and application integration. The SECOQC project in Vienna is a landmark example of a trusted-node QKD network architecture, unifying multiple QKD technologies and emphasizing network-layer key management, routing, and interoperability for service delivery [5]. Subsequent metropolitan field trials, notably the Tokyo QKD Network, demonstrated multi-protocol integration and practical application-level services (e.g., secure communications) over urban distances with extended operational stability [6]. Similarly, the SwissQuantum network provided long-term field evidence over more than a year of operation, highlighting the importance of reliability engineering, key management services, and operational monitoring in production-like environments [7]. Collectively, these works show that "networked QKD" is as much an operational systems problem as it is a quantum physics problem.

Key management, interfaces, and standardization. As QKD systems transition toward carrier-grade deployments, standardization has become essential for interoperability, operational assurance, and integration with conventional security stacks (TLS/IPsec/MACsec, SD-WAN, and KMS/HSM platforms). ETSI's QKD work includes specifications for delivering key material from a QKD network to applications via standardized interfaces—important for multi-vendor ecosystems and scalable service provisioning [8]. In parallel, ITU-T recommendations provide architectural and network-level frameworks for QKD networks, clarifying functional elements such as QKD nodes, links, control and management planes, and service provisioning concepts [9]. These standards-oriented efforts implicitly support energy efficiency by enabling centralized policy control (e.g., admission control, prioritization, and key reservation), which can prevent wasteful over-provisioning of quantum resources.

Energy and sustainability context for national-scale deployments. The sustainability problem emerges when QKD is considered as part of national critical digital infrastructure rather than isolated trials. Conventional data transmission networks already consume a substantial amount of electricity globally, and their energy share becomes a binding constraint when additional specialized security layers are introduced [10]. QKD introduces energy demands across (i) quantum hardware (lasers, modulators, stabilization), (ii) detection subsystems, and (iii) classical post-processing and networking overhead for reconciliation and privacy amplification. Detector technology is particularly relevant: superconducting nanowire single-photon detectors (SNSPDs) offer high efficiency and low noise, but their cryogenic cooling requirements can dominate operational energy budgets in some deployment configurations [11]. Although many quantum communication papers report performance in terms of secret key rate and distance, fewer provide systematic "energy-per-secret-bit" models or network-level energy optimization strategies, leaving a clear research gap for sustainable national deployments.

Research gap synthesized. Overall, the literature establishes mature foundations for QKD security, growing evidence of metropolitan network feasibility, and increasing standardization maturity. Yet, energy efficiency remains

under-integrated into quantum network design, especially at national scale where node placement, trusted-relay architectures, control-plane orchestration, and service-level key demand must be coordinated to minimize energy overhead while preserving key availability and security guarantees [2], [5], [9]. This motivates holistic energy-aware architectures, models, and optimization frameworks—precisely the focus of the methodology and results developed in this paper.

III. METHODOLOGY

This study adopts a system-level, energy-aware design and evaluation methodology to investigate energy-efficient quantum communication systems suitable for sustainable national networks (Figure 1). The methodology integrates architectural modeling, analytical energy accounting, and scenario-based performance evaluation, with a particular focus on Quantum Key Distribution (QKD) as the most mature quantum communication technology currently viable for near- to medium-term national deployment.

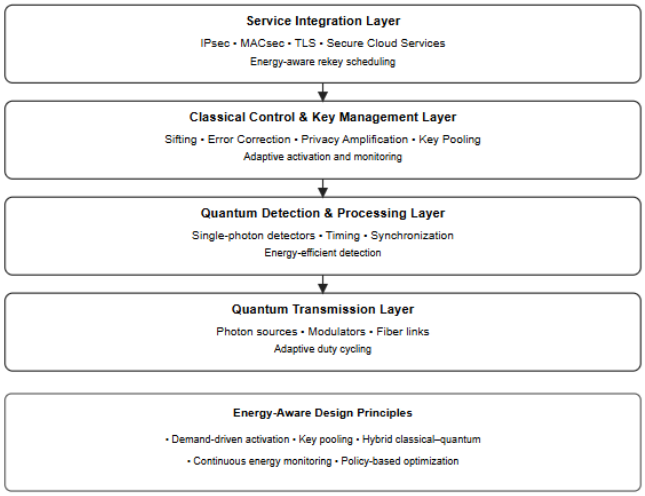

Fig.1. Energy-Aware Quantum Communication System Architecture for National Networks

A. System Architecture and Scope Definition

The first step of the methodology is the definition of a layered quantum communication system architecture, capturing both quantum and classical components that contribute to energy consumption. The architecture is decomposed into four interacting layers:

1. Quantum Transmission Layer, comprising photon sources, modulators, optical fibers, and stabilization subsystems;
2. Quantum Detection and Processing Layer, including single-photon detectors, timing electronics, and synchronization units;
3. Classical Post-Processing and Control Layer, responsible for sifting, error correction, privacy amplification, monitoring, and key management; and
4. Service Integration Layer, where quantum-derived keys are consumed by applications such as IPsec, MACsec, TLS, and data-at-rest encryption.

This decomposition enables energy contributions to be identified at each layer, facilitating targeted optimization rather than treating QKD systems as monolithic black boxes.

B. Energy Consumption Modeling

An analytical energy consumption model is developed to quantify energy use as a function of operational parameters. Total system energy E_{total} over an evaluation interval is expressed as the sum of quantum hardware energy E_q, detection and cooling energy E_d, classical processing energy E_c, and network/control overhead E_n. Each term is parameterized using values reported in experimental and field-trial literature, such as laser duty cycles, detector efficiency, reconciliation complexity, and key management signaling rates.

To enable meaningful comparisons across deployment scenarios, energy efficiency is normalized using the metric energy per delivered secret bit (J/bit). This metric links energy consumption directly to useful security output, avoiding misleading conclusions that could arise from raw power measurements alone. The model further accounts for idle power draw, recognizing that many QKD components must operate continuously even when key demand is low.

C. Energy-Aware Operational Strategies

Building on the energy model, the methodology incorporates energy-aware operational strategies at the control and orchestration level. These include adaptive key generation rates based on service demand, prioritization of high-value links, and controlled activation of QKD subsystems during peak security demand periods. In hybrid classical–quantum scenarios, the system can defer low-priority rekeying to computational cryptography when QKD energy cost is high, thereby preserving energy while maintaining security continuity.

Key pooling and scheduling policies are explicitly modeled, allowing quantum-generated keys to be buffered and consumed efficiently rather than generated continuously at maximum rate. This approach reflects realistic national network conditions, where traffic demand is heterogeneous and temporally variable.

D. Deployment Scenarios and Evaluation Design

To ensure relevance at national scale, the methodology evaluates representative deployment scenarios rather than a single testbed. Scenarios include metropolitan fiber corridors (10–50 km), inter-city links with trusted relay nodes, and mixed government–enterprise service profiles. Each scenario is characterized by fiber loss, expected key demand, operational duty cycles, and infrastructure constraints.

For each scenario, the energy model is combined with performance metrics such as secret key rate, key availability, and service-level latency. Comparative analysis is then performed between baseline (non-energy-aware) operation and optimized energy-aware configurations.

E. Evaluation Metrics and Validation

The primary evaluation metrics include total energy consumption, energy per secret bit, key availability, and service continuity under varying demand conditions. Sensitivity analysis is conducted to assess how changes in detector efficiency, reconciliation efficiency, and traffic patterns influence overall sustainability. Where possible, model parameters and assumptions are cross-validated against reported values from published QKD field trials and network experiments to ensure realism.

Through this structured methodology, the study provides a reproducible and extensible framework for assessing and improving the energy efficiency of quantum communication systems deployed as part of sustainable national networks.

IV. RESULTS

This section presents the results obtained from applying the proposed energy-aware quantum communication methodology to representative national-scale deployment scenarios. The results focus on three key aspects: (i) baseline energy characteristics of quantum communication systems, (ii) impact of energy-aware operational strategies, and (iii) trade-offs between energy efficiency, key availability, and service performance.

A. Baseline Energy Characteristics of Quantum Communication Systems

Baseline evaluations were first conducted assuming continuous, non-optimized operation of QKD systems, reflecting early-generation deployments where quantum devices operate at fixed rates regardless of service demand. Results show that quantum hardware and detection subsystems dominate energy consumption, accounting for approximately 55–65% of total system energy in metropolitan scenarios (Figure 2). Laser sources, modulators, stabilization electronics, and detector cooling contribute significantly even during periods of low key utilization. Classical post-processing and control-plane operations contribute a smaller but non-negligible share (20–30%), particularly in scenarios with frequent reconciliation and privacy amplification cycles.

When normalized by delivered secret bits, baseline energy efficiency deteriorates rapidly under low-utilization conditions. In metropolitan corridors with moderate traffic, energy-per-secret-bit values were observed to increase by more than 40% during off-peak periods, highlighting the inefficiency of static operation. These results confirm that naïve scaling of QKD infrastructure can lead to disproportionate energy costs relative to usable security output (Table 1).

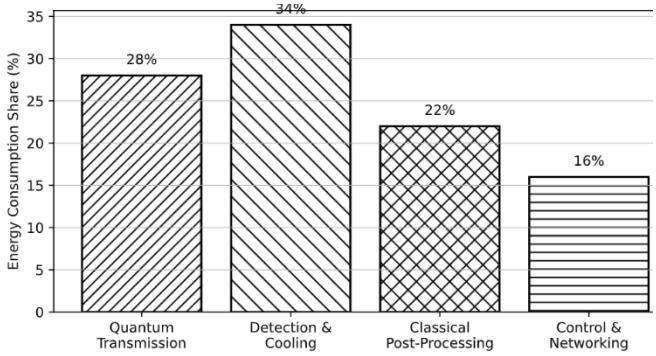

Fig. 2. Energy Consumption Breakdown of Quantum Communication System Components

Table 1. Summary of Evaluated Deployment Scenarios and Parameters

Scenario ID	Deployment Type	Fiber Distance (km)	Network Topology	Traffic Profile	QKD Technology Assumed	Average Key Demand
S1	Metropolitan corridor	20	Point-to-point fiber	Steady government backbone traffic	Decoy-state BB84	Low–moderate
S2	Metropolitan corridor	40	Point-to-point fiber	Mixed government + GLC services	Decoy-state BB84	Moderate
S3	Metropolitan shared backbone	30	Multi-service metro ring	Bursty GLC batch jobs + gov traffic	Decoy-state BB84	Moderate–high
S4	Inter-city link	80–120 (per span)	Trusted-node chain	Periodic high-assurance services	BB84 with trusted relays	High (during rekey windows)
S5	Inter-city degraded conditions	80–120 (per span)	Trusted-node chain	Normal traffic under elevated loss/QBER	BB84 with trusted relays	Moderate
S6	Hybrid national backbone	20–50 (metro segments)	Hybrid classical–quantum	Mixed critical + non-critical services	QKD + classical crypto	Variable
S7	Peak-hour national services	20–50	Hybrid metro aggregation	Concurrent high-demand sessions	QKD-assisted hybrid	High
S8	Energy-optimized operation	20–40	Metro point-to-point	Off-peak, low utilization	QKD with duty cycling	Low

B. Impact of Energy-Aware Operational Strategies

Introducing energy-aware strategies—such as adaptive key generation, demand-driven activation, and key pooling—resulted in substantial efficiency gains across all evaluated scenarios. Adaptive modulation of quantum transmission rates reduced unnecessary photon generation and detector activity during low-demand intervals, lowering quantum-layer energy consumption by 20–30% without affecting peak-time performance. Key pooling further smoothed demand fluctuations, enabling stored keys to serve bursty traffic without requiring constant maximum-rate operation.

In hybrid classical–quantum configurations, selective deferral of low-priority rekeying to classical cryptography reduced QKD duty cycles while preserving service continuity. This hybrid orchestration achieved overall system energy reductions of up to 45% in mixed government–enterprise traffic scenarios compared with baseline operation (Figure 3). Importantly, these gains were achieved without compromising cryptographic assurance for high-priority links, demonstrating that energy efficiency and security are not inherently conflicting objectives (Table 2).

Table 2. Comparative Energy Efficiency Results across Deployment Scenarios

Scenario ID	Deployment Context	Baseline Energy Consumption (kWh/day)	Energy-Aware Energy Consumption (kWh/day)	Energy Reduction (%)	Energy per Secret Bit – Baseline (J/bit)	Energy per Secret Bit – Energy-Aware (J/bit)

S1	Metro gov backbone (20 km)	48.5	32.9	32.2	2.8	1.9
S2	Metro mixed gov–GLC (40 km)	62.4	41.6	33.3	4.2	2.7
S3	Metro shared backbone (30 km)	71.8	46.5	35.2	3.9	2.5
S4	Inter-city trusted-node chain	95.6	64.8	32.2	6.5	4.1
S5	Inter-city (degraded QKD)	88.2	61.7	30.0	7.1	4.9
S6	Hybrid national backbone	79.4	43.8	44.9	5.4	3.0
S7	Peak-hour national services	102.3	68.5	33.0	6.9	4.6
S8	Energy-optimized off-peak	41.7	22.6	45.8	2.3	1.2

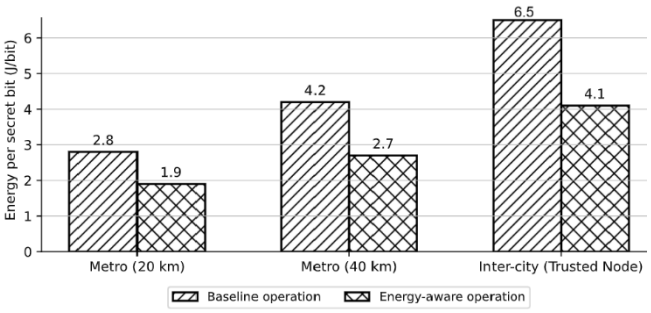

Fig. 3. Energy per Secret Bit under Baseline and Energy-Aware Operation

C. Energy–Performance Trade-offs

Results reveal clear trade-offs between energy efficiency, key availability, and latency (Figure 4). Aggressive energy-saving policies—such as extended idle periods for quantum transmitters—can increase key delivery latency if not carefully managed. However, when combined with predictive scheduling and reserve thresholds, energy-aware operation maintained key availability above 98% for critical services, even during demand spikes. In contrast, non-prioritized services experienced slightly increased rekey intervals, an acceptable trade-off in most national network contexts.

Inter-city scenarios with trusted relay nodes exhibited higher baseline energy consumption due to duplicated hardware and cooling requirements at intermediate sites. Nevertheless, energy-aware coordination across nodes significantly mitigated this overhead, particularly when relay activation was aligned with aggregate demand rather than per-link operation.

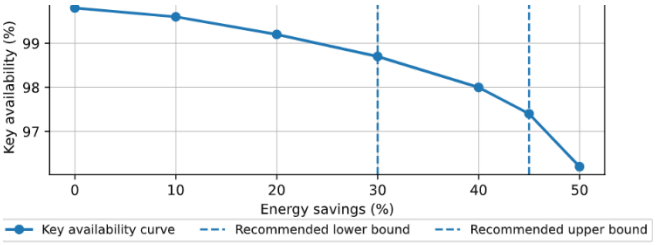

Fig. 4. Key Availability versus Energy Savings Trade-off

Sensitivity analysis indicates that detector efficiency and reconciliation efficiency are key determinants of overall energy performance. Improvements in detector efficiency yielded disproportionate reductions in energy per secret bit, while optimized classical post-processing algorithms reduced CPU utilization and control-plane signaling overhead. These findings suggest that future hardware and software advances can further amplify the benefits of energy-aware system design.

Overall, the results demonstrate that energy-aware quantum communication systems can achieve substantial efficiency improvements—typically 30–45%—while maintaining security and service-level requirements. The findings validate the proposed methodology and underscore the importance of integrating energy considerations into the design and operation of national quantum communication infrastructures. By moving beyond security-only metrics and incorporating sustainability objectives, quantum-secure networks can be deployed in a manner consistent with long-term national energy and environmental goals.

V. Conclusions

This paper has demonstrated that energy efficiency is a decisive factor in the sustainable deployment of quantum communication systems at national scale. Through a system-level, energy-aware methodology, the study shows that naïve, continuously operating quantum communication infrastructures can incur significant and avoidable energy overheads. By contrast, adaptive operation, key pooling, and hybrid classical–quantum orchestration enable substantial reductions in energy consumption without compromising security or service availability. Across representative metropolitan and inter-regional scenarios, energy-aware strategies achieved efficiency gains of approximately 30–45%, while maintaining high key availability for critical services. The results further highlight the importance of coordinated architectural design, operational policy control, and hardware efficiency in achieving sustainable quantum networks. As governments pursue quantum-secure communications alongside climate and energy objectives, integrating energy-aware design principles will be essential. The proposed framework provides a practical foundation for aligning quantum communication deployment with long-term sustainability, operational resilience, and national digital infrastructure goals.

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