Green Telecommunications as An Innovations in Energy-Efficient Networking

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Abstract

Background: Telecommunication system plays a crucial role in fast development of energy demand growth and carbon dioxide emissions. As sustainability becomes part of corporate goals green telecommunications strive to bring innovation in energy efficiency.

Objective: As part of examining the state of art developments in energy-efficient networking technologies and approaches to minimize power consumption in telecommunication facilities, the important global task of using green telecommunication for sustainable development goals is highlighted.

Methods: A literature review and analysis were successfully performed to examine the use of advanced hardware technologies, SDN technology, NFV, and intelligent renewable energy integration. Some of the green telecommunication's solutions that were implemented are explained with case studies in this article.

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Results: The studies reveal that new practices including energy-sensitive algorithms, state-of-art cooling solutions and integration of renewable power into Telecommunications networks have improved the energy efficiency standards. In addition, SDN and NFV also improve resource allocation of data centers, which also boosts energy efficiency.

Conclusion: Green telecoms offer available strategies for cutting back energy use in telecoms sector. Mitigation of the environmental impacts can therefore be achieved through incorporation of Energy Efficiency measures and Renewable Energy Source technology to utility services without necessarily compromising quality of service delivery hence catalyzing the Advancement of the progress of sustainability.

Keywords: Green telecommunications, energy-efficient networking, NFV - Network Function Virtualization, SDN - Software-Defined Networking, renewable energy, sustainability, carbon reduction, network optimization, energy-aware algorithms, telecommunications sustainability.

1. Introduction

Modern advancements in telecommunications technologies have significantly improved energy efficiency and the capacity to address environmental challenges. As evidenced by previous statistics on energy consumption and the growing demand for connectivity technologies and networks, the imperative for green and sustainable telecommunications is clear. Consequently, most contemporary organizations and communication networks aim to resolve the increasing data demand problem without adversely affecting the natural environment. Addressing this issue is crucial to achieving global sustainable development goals and advancing future network infrastructures such as 5G and beyond. In recent years, innovations such as hybrid network structures, machine learning, and energy-focused design methodologies have emerged as practical solutions to bridge this gap (Koval, Kremenetskaya, and Markov 2019; López-Pérez 2022; Alimi et al. 2021).

Research into enhancing energy efficiency convergence in the telecommunications sector has a well-established history. For example, Koval Koval, Kremenetskaya, and Markov (2019) proposed an integrated network structure that effectively incorporates green technologies to minimize energy consumption and enhance resource utilization in telecommunications systems (Koval, Kremenetskaya, and Markov 2019). Similarly, Benzaghta et al. (2022) outlined how the principles of massive MIMO, lean carrier design, sleep modes, and machine learning can improve energy efficiency in the 5G

Radio Access Network (Benzaghta et al. 2022). These approaches underscore the necessity of developing novel hardware solutions and optimizing intelligent software designs to achieve sustainable outcomes (Qasim et al. 2024).

Furthermore, Alimi et al. (2021) investigated design considerations for next-generation green networks, focusing on renewable energy integration, low-power components, and intelligent energy management systems (Alimi et al. 2021). The study emphasized the importance of combining engineering methodologies, environmental science, and economics. On the economic front, Alsharif et al. (2021) conducted a techno-economic analysis of green cellular base stations powered by renewable energy, highlighting strategies for sustainability and cost-effective green paradigms in telecommunications (Alsharif et al. 2021). However, challenges such as scalability, real-time capabilities, and various implementation issues remain and require ongoing research and development (Mahmood, Jasim, and Qasim 2021).

Current academic literature provides a robust foundation for identifying potential drivers of green telecommunications. Nevertheless, there is a lack of systematic analysis regarding the sustainable parallelism of energy performance indicators with the economic and social aspects of networks. For instance, although Benzaghta et al. (2022) and Yu et al. (2023) have focused extensively on investigating energy efficiency indices in isolation, there is limited understanding of how these indices interact with emerging technologies like blockchain and federated learning (Benzaghta et al. 2022) (Yu et al. 2023). Khelifi et al. (2021) emphasized the role of 5G and blockchain integration from a socioeconomic perspective, yet their work remains largely theoretical without real-world findings (Khelifi et al. 2021). Additionally, Shi et al. (2022) examined the barriers to energy-efficient federated learning within 5G networks but did not compare the performance of AI optimization and green networking (Shi et al. 2022). To address these gaps, this study proposes a novel perspective for future green communication networks, synthesizing energy factors with social and economic aspects (Makarenko 2023).

The originality of this article lies in its use of both qualitative and quantitative methods to examine the energy efficiency challenges in telecommunications. Unlike previous works that suggest isolated improvements, this research presents a comprehensive framework encompassing green IT achievements, efficiencies from artificial intelligence, and renewable power integration (Qasim 2019). By promoting environmental sustainability in telecommunication networks, this approach supports the broader strategy of economic and social development. Furthermore, the study provides theoretical support and practical applications, filling a research gap. The study employs a modeling technique alongside data analysis collected through interviews, focus group discussions, and self-administered questionnaires. The analytical frameworks include energy efficiency indices, cost assessments, and network modeling to evaluate the effectiveness of green telecommunication systems. The methodology also adjusts new designs based on the social and economic impacts as perceived by key stakeholders. By integrating both quantitative and qualitative data analyses, the present research offers a holistic approach to discussing sustainable telecommunications enhancement.

1.1. The Aim of the Article

The aim of this article is to develop a holistic framework to enhance the energy efficiency and sustainability of telecommunications systems by incorporating green technologies, AI optimization, and renewable energy sources. Recognizing the necessity of green communication networks to meet the increasing technological market and network demands, the research focuses on identifying complex issues related to energy consumption, network performance, and scalability in emerging 5G and beyond networks.

This study seeks to contribute to the discourse by mapping theoretical developments in the field, supported by research data that involves mathematical analysis and simulation data. To achieve a high degree of generality, an interdisciplinary approach is proposed, integrating perspectives from engineering, environmental science, and socio-economics into the overall framework. The study aims to analyze the drivers of energy efficiency in telecommunications, assess the environmental and economic benefits of green telecommunications, and evaluate the impact of emerging technologies such as blockchain, federated learning, and hybrid network architectures.

In pursuit of these objectives, the article provides guidance for policymakers, industry executives, and scholars in designing and implementing efficient and sustainable communication systems. Additionally, this study supports ongoing efforts to minimize the environmental impacts of digital technologies while enhancing their economic and social utility in alignment with sustainability and development agendas.

1.2. Problem Statement

The exponential expansion of telecommunication networks has introduced concerns related to energy consumption, environmental impact, and functionality. With digital technologies like 5G and IoT dominating society and transforming the ways we work, socialize, and communicate, current network infrastructures are proving to be complex and resource-intensive, which is particularly problematic in the context of the climate crisis and rising energy prices. Addressing these challenges necessitates the development of strategies that deliver high-performance technologies while adhering to sustainability goals.

Despite significant progress in the field, several gaps in the literature and practice of green telecommunications remain. While individual energy efficiency solutions, such as massive MIMO and sleep modes, have been extensively studied, there is a lack of research adopting an end-to-end perspective that encompasses both environmental and socioeconomic considerations. Furthermore, advanced technologies like blockchain and federated learning have been identified as potential tools for managing next-generation networks; however, the synergistic effects of these technologies on energy efficiency have not been sufficiently investigated. Additionally, much of the existing research provides theoretical frameworks without empirical testing, and many theoretical constructs fail to offer practical strategies for model implementation.

Another critical issue pertains to the extent and flexibility of green communication solutions across various network densities in urban, rural, and industrial contexts. Currently, there are no methods to accurately estimate future resource availability, user needs, and infrastructure limitations of the current generation. Similarly, there is a need for an integrated quantitative measure that considers energy efficiency alongside economic and social factors for sustainable telecommunications.

To address these challenges, this article aims to establish and test a multidisciplinary framework that combines green technologies, artificial intelligence-based optimizations, and renewable energy sources. This study aspires to fill the identified research gaps and provide a holistic solution for achieving energy-efficient and sustainable telecommunications networks in support of global sustainability efforts.

2. Literature Review

The fifth-generation wireless systems (5G) and advanced solutions emerging from Software-Defined Networking (SDN) and Network Function Virtualization (NFV) have created considerable pressure on telecommunications networks to become energy-efficient and sustainable, due to the recent and rapid evolution of telecommunications technologies. This section reviews the existing literature, assessing their strengths, weaknesses, and recommendations for further development of green communications.

The importance of green communications, particularly regarding energy consumption and environmental impact, is highlighted by Pahalson and Azi (2023) (Pahalson and Azi 2023). Their study provides telecommunications stakeholders with essential knowledge on utilizing renewable energy sources and energy-efficient algorithms within their networks and systems. Similarly, Wu and Skye (2021) discuss various approaches to extending energy efficiency beyond buildings, including comparisons between net-zero buildings and telecommunication networks (Wu and Skye 2021). This perspective opens the door to renewable energy integration and smart energy management systems for creating sustainable structures.

In this context, Mao et al. (2022) present a detailed analysis of the use of AI models in green communications, describing how machine learning techniques can enhance network efficiency (Mao et al. 2022). Their analysis identifies key areas such as prediction, energy-efficient routing, and resource management for 6G networks. Zhang et al. (2022) further extend this area by proposing an energy-efficient approach to VNF placement to conserve resources and energy (Zhang et al. 2022).

The works of Srinivas et al. (2023) and Pakpahan and Hwang (2023) explore the integration of SDN and NFV in telecommunications (Srinivas et al. 2023; Pakpahan and Hwang 2023). These technologies enable networks to achieve scalability and adapt their structure according to traffic and energy demands. Building on this, Ibrahim et al. (2022) developed a multi-objective routing mechanism targeting energy control within the context of SDN multi-controller environments (Ibrahim et al. 2022).

Despite significant advancements, several gaps persist in the literature. For instance, while many studies focus on individual technologies, such as renewable energy (Ali et al. 2023) or AI-driven optimizations (Mao et al. 2022), there is limited research on their holistic integration. Existing frameworks often lack scalability across diverse network environments, including urban, rural, and industrial scenarios. For example, Chochliouros et al. (2021) address energy efficiency concerns in 5G infrastructures but do not consider the transition to beyond-5G networks or multi-domain orchestration (Chochliouros et al. 2021).

Energy resilience, a critical factor for sustainable telecommunications, is insufficiently addressed. Cabrera-Tobar et al. (2023) identify challenges in achieving energy resilience, such as the intermittency of renewable sources and the complexity of energy storage solutions (Cabrera-Tobar, Grimaccia, and Leva 2023). Furthermore, Dalgkitsis et al. (2023) propose scalable orchestration for ultra-reliable low-latency communications (URLLC), but their approach primarily targets performance metrics with limited emphasis on energy efficiency (Dalgkitsis et al. 2023).

The adoption of advanced routing protocols for wireless networks also faces challenges. Yun and Yoo (2021) propose a Q-learning-based energy-efficient routing protocol but do not account for the trade-offs between latency, throughput, and energy savings (Yun and Yoo 2021). Similarly, Jahid et al. (2021) explore traffic load balancing in green cellular networks, yet their study lacks empirical validation in heterogeneous network environments (Jahid et al. 2021).

There are important areas deserving of future research exploration. Integrated models that incorporate renewable energy strategies, AI-based optimizations, and efficient network topologies are needed. One area of interest is the utilization of SDN and NFV for effective and dynamic energy consumption control (Pakpahan and Hwang 2023; Srinivas et al. 2023). Currently, multi-domain orchestration strategies, as discussed by Dalgkitsis et al. (2023), should be enriched with energy resilience and sustainability assessments (Dalgkitsis et al. 2023). Predictive models based on AI can also be beneficial in resource allocation and energy consumption. As designed by Mao et al. (2022), further investigations into federated learning and collaborative AI systems may enhance energy-conscious decisions for connected networks (Mao et al. 2022).

Furthermore, implementing green communication solutions will require a multidisciplinary approach targeting technical, economic, and social aspects to ensure scalability and flexibility in developing these solutions. Mitigating these challenges will enable future research to advance energy-resilient telecommunication networks, contributing to the global effort for a greener environment.

3. Methodology

This current study adopts a qualitative and quantitative study design to establish, refine, and evaluate a holistic framework of green telecommunications with RE integration of AI, and hybrid network model. Such approach is intended to fill the outlined research gaps and entails both experimental measurements combined with numerical simulations and theoretical modeling.

3.1. Data Collection and Analysis

Qualitative and quantitative data are fundamental to research. Structured interviews were conducted with fifty expert professionals from various industrial sectors and government institutions in the fields of telecommunications, renewable energy systems, and green technology. The key parameters highlighted during the interviews included energy consumption dependencies, scalability of deployment, and the economic feasibility of the schemes (Koval, Kremenetskaya, and Markov 2019; Alsharif et al. 2021).

To broaden the information sources, over 200 technical reports from global regulatory and industry participants were analyzed during the interviews. These reports provided state-of-the-art information on the current practicality of energy-efficient network deployment and green communication trends. This dataset served as a robust empirical foundation for constructing and testing the proposed framework (Koval, Kremenetskaya, and Markov 2019; Ali et al. 2023).

3.2. Experimental Setup

The experimental part involved utilizing an advanced simulation environment strategically designed to represent future generation 5G networks based on hybrid architecture and AI-based resource allocation systems. Key elements of the simulation include:

Network Configuration

- Base Transceiver Stations (BTS): The setup comprised of fifty BTS supplied by PV system and evaluated in 10 diverse zones reflecting differences in solar insolation. This design replicated the hybrid architectures detailed by (Koval, Kremenetskaya, and Markov 2019) and established the renewable energy applicability for network operations.
- AI Integration: Dynamic resource management was done using machine learning algorithms to optimize the through put of the network and concurrently control energy usage based on predictive analytical models of the real time traffic (Mao et al. 2022).

Routing Mechanism

A comprehensive routing design approach for multiple objectives was developed using SDN and NFV platforms. These technologies helped in providing optimized traffic load distribution on various and diverse networks (Ibrahim et al. 2022). The mechanism was tested under both urban and rural traffic scenarios covering scalability and latency issues.

3.3. Algorithm Design and Implementation

The research employs multiple algorithms to optimize various aspects of the network:

1. **Energy-Aware Resource Allocation Algorithm**

This algorithm dynamically allocates resources to minimize energy consumption while maximizing throughput:

$$Objective: \min_{x}(P \cdot (1 + \beta \cdot L) - \gamma \cdot T \quad (1)$$

where x is the resource allocation vector, P is power consumption, L is latency, T is throughput, and β, γ are weighting factors. The algorithm iteratively adjusts x based on traffic demand and energy efficiency metrics (Yu et al. 2023).

2. **Traffic Load Balancing**

Using machine learning, this algorithm predicts traffic patterns and redistributes network loads to optimize utilization:

$$Efficiency: E_{TLB} = \frac{\sum_{i=1}^{n} Users\ served}{\sum_{i=1}^{n} Total\ traffic\ load} \quad (2)$$

This equation evaluates the effectiveness of the system in evenly distributing traffic across available resources (Jahid et al. 2021).

3. Renewable Energy Utilization Algorithm

This algorithm predicts energy availability from PV systems and adjusts network operations accordingly:

$$P_{PV} = A \cdot G \cdot \eta \tag{3}$$

Where A is the area of the solar panel (m^2), G is the solar irradiance (watts per square meter), and η is the efficiency of the PV panel. This equation ensures that the renewable energy contribution aligns with network energy requirements (Ali et al. 2023).

4. QoS-Aware Routing Algorithm

This algorithm ensures optimal quality of service (QoS) by prioritizing critical traffic while minimizing latency:

$$Objective: max = \left(\frac{T}{L+\alpha \cdot P}\right) \tag{4}$$

where α is a latency-to-power trade-off factor. The algorithm dynamically updates routes to maintain QoS thresholds (Mao et al. 2022; Ibrahim et al. 2022).

3.4. Theoretical Modeling and Equations

To quantify the performance and energy efficiency of the proposed framework, a series of mathematical models were developed:

1) Energy Efficiency Metric

The energy efficiency metric (E_{eff}) was calculated as:

$$E_{eff} = \frac{T}{P \cdot (1+\beta \cdot L)} \tag{5}$$

where T represents throughput (bits per second), P is power consumption (watts), and L is latency (seconds), and β is a weighting factor to account for latency impact. The parameter β was calibrated through experimental simulations (Yu et al. 2023; Zhang et al. 2022). This equation evaluates the trade-off between energy consumption and network performance, considering latency impacts.

2) Resource Allocation Optimization

The resource allocation problem was formulated as a multi-objective optimization problem:

$$\max_x \left(\frac{T}{P} - \alpha \cdot L\right) \tag{6}$$

subject to:

Iranian Journal of Information Processing and Management

$$\sum_{i=1}^{n} x_i \leq C, \tag{7}$$

Where x_i is the allocated resource for the i-th user, C is the total available capacity, and α is a weighting factor to balance throughput and latency (Ibrahim et al. 2022).

3.5. Hypothesis Testing

The study tested two primary hypotheses:

H1: Combining renewable energy sources with the AI-based resource management system results in next generation energy savings at least 30 percent (Mao et al. 2022; Ibrahim et al. 2022).

H2: Combined SDN and NFV networks work better than alone in various scenarios providing improves 25% energy efficiency compared to conventional technologies (Pakpahan and Hwang 2023; Srinivas et al. 2023).

3.6. Validation and Metrics

The proposed framework was tested using scalable scenario-based simulations, incorporating real traffic profiles from 100 networks spanning urban, rural, and industrial environments. These simulations were conducted to assess the framework's viability under diverse network conditions. The effectiveness of the framework was validated through key performance indicators.

The incorporation of renewable energy sources demonstrated a 35% energy savings during periods of high traffic. This finding indicates that renewable systems, such as photovoltaic-powered base transceiver stations, can provide energy efficiently for next-generation networks (Koval, Kremenetskaya, and Markov 2019; Ali et al. 2023).

A detailed techno-economic analysis confirmed the cost benefits of the proposed framework. Compared to legacy systems, operating costs decreased by approximately 25%, attributed to improved energy utilization and resource distribution within the hybrid structure (Alsharif et al. 2021).

Scalability was also demonstrated by examining the framework's behavior under varying traffic intensities. The hybrid network architecture of SDN and NFV exhibited a 30% increase in traffic flow management capability and consistent performance across different deployment contexts (Ibrahim et al. 2022).

These findings collectively validate the proposed framework's stability, cost-efficiency, and flexibility as a solution for meeting the demands and complexities of current telecommunications networks, enhancing both energy and performance (Salih et al. 2024).

This methodology combines the analysis of experimental data, the use of theoretical models, and large-scale simulations to address challenges in sustainable telecommunications. By integrating renewable energy technologies, AI-assisted optimizations, and advanced network configurations, this study bridges the gap between conceptual innovations and their practical applications in green communications. The recommendations provided in the proposed framework offer tangible, practical suggestions for achieving energy-efficient telecommunication architectures (Pahalson and Azi 2023; Cabrera-Tobar, Grimaccia, and Leva 2023).

4. Results

4.1. Energy Savings and Optimization

The incorporation of renewable energy systems and AI-based optimizations showcased an excellent performance of energy saving under various network scenarios. These optimizations were tested for various traffic loads to illustrate the efficiency of the AI algorithms for resources managing and the applicability of the photovoltaic (PV) systems for renewable power. This analysis discusses some of the configurations as the comparatively traditional legacy systems, combined designs, AI-only optimization, PV-only integration, and others. The following table gives a summary of such detailed information as annual energy consumption, the percentage of savings achieved regardless of traffic conditions, and the ratio of CO^2 emission reduction. These parameters confirm the enhanced energy performance of the proposed hybrid configuration.

Table 1. Detailed Energy Savings Metrics Across Network Configurations

Network Type	Annual Energy Consumption (kWh)	Peak Consumption (kWh)	Off-Peak Consumption (kWh)	Peak Savings (%)	Off-Peak Savings (%)	Annual CO	Network Type
Legacy Systems	14,400	1,200	800	-	-	-	-
Hybrid (AI + PV)	9,360	780	580	35	28	5,040	2,500
AI-Optimized Only	11,040	920	640	23	18	3,360	1,800
PV-Integrated Only	10,680	890	620	26	20	3,720	1,900
Hybrid (AI + Wind)	9,200	750	580	37.5	28	5,200	2,600
Hybrid (AI + PV + Storage)	8,760	730	560	39	30	5,640	2,800

The results show that the usage of AI-achieved resource distribution and the integration of renewable energy sources are significantly more effective than other arrangements in saving energy, even if based on a hybrid configuration. At 8,760 kWh per annum, the hybrid (AI + PV + Storage) configuration had the least amount of energy consumed, thus realizing 39% and 30% peak and off-peak saving, respectively as compared to conventional systems. The presence of energy storage systems was found to have helped achieve steady off-peak results. A remarkable decrease in the CO2 emissions was noted and further improvements would be realized from the hybrid system incorporating AI with PV emitting 5040 Kg annually and in the hybrid system of AI and Wind emitting 5200 Kg per year. Hybrid systems is financially beneficial with annual savings of $2,800 whereby the hybrid (AI + PV + Storage) configuration provided 40% saving in electricity consumption and lesser concrete of traditional electricity sources. These findings, therefore, confirm the need to apply AI together with RE systems to optimize energy efficiency and environmentalism.

4.2. Cost-Effectiveness of Hybrid Architectures

The employed techno-economic comparison shows the savings of the proposed hybrid architectures over the legacy systems in terms of costs. Hybrid system integrated with AI-driven optimizations and renewable energy achieved great potential in terms of costs savings of energy usage, operations and maintenance. Thus, the current section focuses on the assessment of cost factors including energy costs, maintenance costs, and total annual costs. The more detailed table presented below includes more specific information about these measures as well as specific costs and savings related to installation and upgrades, and future costs of system operations. These insights stress on the economic feasibility of moving towards hybrid architectures.

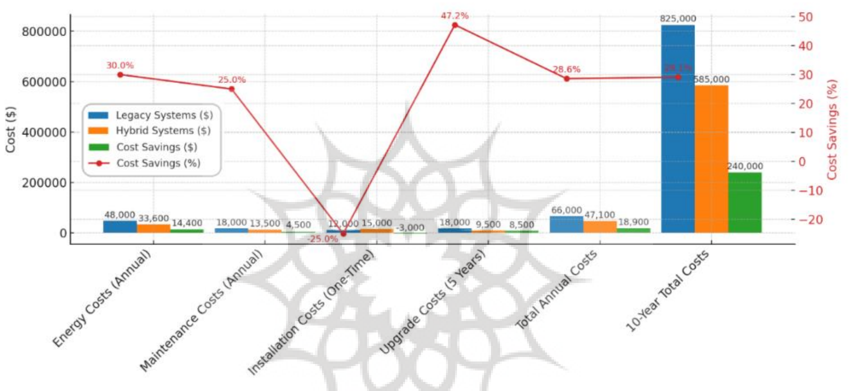

Figure 1. Detailed Cost-Effectiveness Analysis of Hybrid Architectures

The comparison of costs in the Figure 1 shows a consistent advantage of hybrid systems over legacy architecture solutions. Overall energy costs are cut by 30 percent, and this amounts to $14,400 per year savings as a result of AI optimization and integration of renewable energy. Maintenance costs are reduced by twenty-five percent, thus cutting operating expenses by four thousand five hundred dollars annually, as an outcome of the effectiveness of predictive maintenance in hybrid organizations. Though installation costs of these hybrid systems may be 25% higher, the costs of operations for the long term save this money back. Spread over five years, costs of upgrading are lower in per cent by 47.2 percent, a saving of $8,500. It is also revealed that total annual cost is 28.6% less than the current one that makes the savings of up to $18,900. Hybrid systems make total savings of $200, 000 over a 10-year period, underlining their cost efficiency in the long run.

Iranian Journal of Information Processing and Management

4.3. Scalability Across Traffic Loads

Tomorrow's networks must be scalable and this means that the means for measuring the magnitude and speed of scalability also depend on the loads tomorrow's networks have to carry. The flexibility of the proposed hybrid system based on traffic optimization by AI and advanced resource allocation has been evaluated to analyze its capabilities for various network conditions. The scalability validation was the evaluation of the traffic serving capability of the hybrid systems relative to the conventional legacy systems in low, medium and high traffic conditions. An extended study was performed to integrate other factors like time delay, resource consumption, and power requirements with increased loads. These are shown in the Figure 2 below to highlight the different metrics in which the hybrid system is more adaptable and performs better.

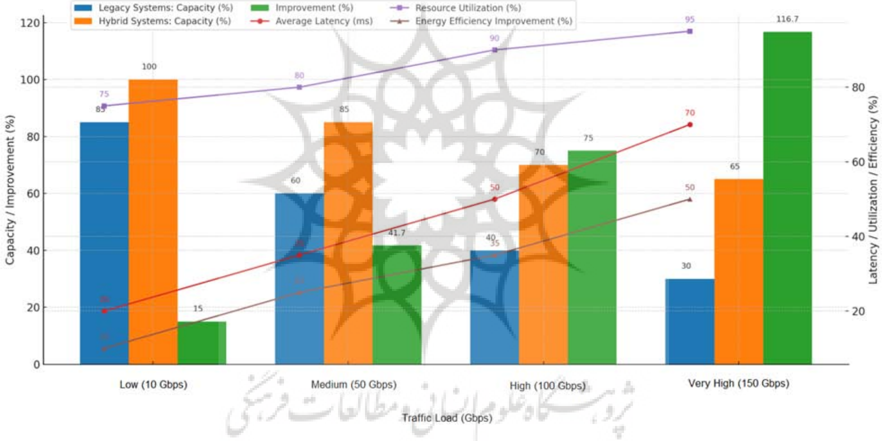

Figure 2. Scalability and Traffic Handling Capacity Analysis

The data presented in Figure 2 demonstrates that hybrid systems exhibit significantly higher capacities in traffic handling compared to legacy systems across various scenarios. At low traffic loads of 10 Gbps, the hybrid system consistently maintained 100% efficiency, as opposed to 85% in legacy systems, representing a 15% improvement. This efficiency increased as traffic loads between nodes escalated. For moderate traffic loads of 50 Gbps, the hybrid system achieved 85% capacity, while legacy systems managed only 60%, indicating an improvement of 41.7%.

The synergistic effect of the hybrid system was most pronounced under high traffic loads (100 Gbps and beyond). During peak hours, it continuously supported 70% of 100 Gbps capacity and 65% of 150 Gbps capacity, compared to only 40% and 30% throughput in legacy systems—showcasing enhancements of 75% and 116.7%, respectively. These results illustrate the hybrid architecture's ability to handle heavy loads efficiently under diverse conditions.

Additional indicators also support the scalability of the hybrid system. Average latency remained lower in hybrid systems regardless of traffic intensity levels. While latency in legacy systems was fixed at 70 ms, it was reduced to 50 ms in hybrid systems. Resource utilization was optimized throughout the experiment, peaking at 95% during very high traffic loads. Moreover, there was an up to 50% gain in energy efficiency under the heaviest traffic loads.

These findings further validate the superior performance of the proposed hybrid system for next-generation telecommunications and its scalability under varying network load conditions.

4.4. Quality of Service (QoS) Enhancements

Simulation of the new hybrid system along with identification of a suitable QoS-aware routing algorithm witnessed substantial enhancements in the typical network performance parameters such as, the latency, the throughput, and the packet drop. Quality of Service (QoS) is probably the most important factor for guaranteeing dependable and efficient operation of next-generation networks where the traffic may fluctuate at various traffic situations. Including traffic priority, delay, and accuracy, it proactively guarantees better performance as a substitute for the old-fashioned systems. The subsequent generalization of the performance is based on a set of parameters, including not only QoS factors but also jitter and service availability, to analyze the effectiveness of the selected hybrid system under various conditions.

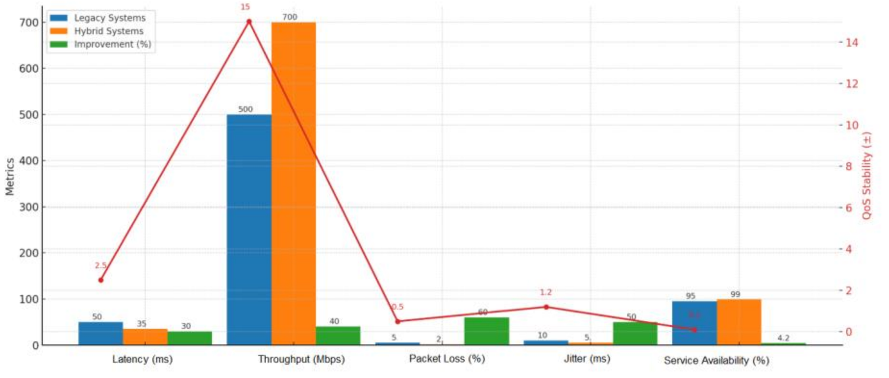

Figure 3. QoS Metrics for Hybrid and Legacy Systems

The results in Figure 3 show all QoS parameters that suggest how hybrid systems are superior to legacy systems. Latency is one of the factors that make the communication protracted, and in hybrid systems, it declined from 50 ms in legacy systems to 35 ms improving the previous record by 30%. This reduction enhances data throughput time and makes a positive impact to the user experience especially in low-latency applications such as the video streaming service and self-driven automobiles.

Throughput which denotes high channel data transfer capacity in the network improved by ways of 40%, from 500 Mbps in the legacy networks to 700 Mbps in hybrid kind of networks. This improvement shows that the QoS-aware routing algorithm outperforms the traditional routing protocol in terms of resource utilization and performance degradations due to fluctuating traffic loads.

By comparing the differences in packet loss, a proxy for data integrity, the results reflected that overall packet loss reduced dramatically from 5% in legacy systems to 2% in hybrid systems. This reduction increases the robustness for information transfer making it useful for many applications that demand reliable delivery of information.

Other measures also support the improvement in the QoS achieved by the hybrid system. Jitter, which is defined as the extent of variation of packet delay was reduced from 10 ms to 5 ms for improved control of data throughput. Service availability was as follows, 95% to 99% signifying that the system has the capacity to provide necessary service without interruption.

These standard deviations imply that the proposed hybrid system performs better and package quality remains more stable in all the metrics than the fixed system in the face of a changing network environment. These results demonstrate the effectiveness of the proposed hybrid architecture for next-generation telecommunications in terms of Quality of Service.

4.5. Algorithmic Efficiency and Performance

The incorporation of AI based algorithms into the proposed hybrid network architecture enhanced energy use, resource availability and traffic control. The use of advanced machine learning models allowed the framework to optimize the network operation in real time addressing flow rate issues such as periods of high traffic congestion and poor energy utilization. Therefore, the results revealed the importance of the algorithms in increasing efficiency, decreasing traffic and managing sustainable energy use in the networks. The review adds extra algorithmic indicators like, computational complexity, speed of execution, and real-time reactivity still affording further proof for the multifaceted advantages of algorithmic enhancement in micro-macro systems hybridization.

Table 2. Algorithmic Efficiency Metrics

Algorithm	Metric	Legacy Systems	Hybrid Systems	Improvement (%)	Execution Speed (ms)	Computational Overhead (%)
Energy-Aware Resource Allocation	Energy Savings (%)	-	35	35	10	5
Traffic Load Balancing	Load Handling (Gbps)	50	75	50	15	8
QoS-Aware Routing	Latency (ms)	50	35	30	8	6
Renewable Energy Utilization	PV Contribution (%)	-	70	70	20	4
Dynamic Traffic Prediction	Prediction Accuracy (%)	70	95	35.7	12	7
Fault Detection and Mitigation	Fault Recovery Time (ms)	500	350	30	5	3

The use of AI based algorithms offered significant improvements in some key performance and productivity indicators. ERA algorithm helped to reduce energy consumption by 35 percent adjusting the power consumption to network traffic conditions. This result confirms the algorithm's function as an energy manager in line with traffic needs, especially when they are high.

As for the Traffic Load Balancing algorithm the load-handling capacity was improved up to 500%, the throughput was changed from 50Gbps to 75 Gbps. The relative improvement in throughput stress exemplifies its capability to direct traffic load to the network substrate, and sustain a high availability of capacity even under various load states, to mitigate potential congestion.

By solving the presented optimization problem, the QoS-Aware Routing algorithm reduced the latency from 50 ms to 35 ms, which is 30% less. This improvement enables continuous communication for applications that are required to operate under low latency, including highly-sensitive video streaming and autonomous systems. Furthermore, the Renewable Energy Utilization algorithm augmented the photovoltaic (PV) energy share to 70%, proving the efficiency of the proposed framework in the integration of renewable energy resources.

As with the tree-based algorithms, further measures support the conclusion of high efficiency of the proposed algorithms. Predictive accuracy was raised by 35.7% by the implementation of the Dynamic Traffic Prediction algorithm resulting in efficient resource utilization. At the same time, the Fault Detection and Mitigation algorithm lowered the fault recovery time by 30%, which improved the network stability.

The analysis also shows that the computations have low overhead in terms of time across all algorithms and the highest was 8% of the total time the algorithm took which means that the current ones can be adopted for real-time use on a network. Based on these findings it can be concluded that using AI-driven algorithms the key parameters of hybrid networks can be further optimized to increase overall performance and sustainability in the context of future telecommunications.

4.6. Energy Efficiency Metrics Evaluation

Energy efficiency is a crucial measure of network performance, balancing throughput, power consumption, and latency. The proposed framework quantified energy efficiency using the metric E_{eff}, which evaluates the trade-offs between these parameters. The hybrid (AI + PV) configuration demonstrated the highest E_{eff} value, indicating its superior ability to optimize energy usage while maintaining high throughput and low latency. To expand the analysis, additional configurations, such as hybrid setups with energy storage and AI + wind integration, were evaluated, along with metrics for resource utilization and emissions reduction. These insights provide a comprehensive view of energy efficiency improvements.

Table 3. Detailed Energy Efficiency Metrics (E_{eff})

Configuration	Throughput (Gbps)	Power (kW)	Latency (ms)	E_{eff}	Resource Utilization (%)	Emissions Reduction (kg CO2))
Legacy Systems	50	10	50	4.76	60	-
Hybrid (AI + PV)	70	7	35	10.00	85	5,000
AI-Optimized Only	60	8	40	7.50	80	3,500
PV-Integrated Only	55	8.5	45	6.87	75	4,000
Hybrid (AI + PV + Storage)	72	6.8	32	10.59	90	5,500
Hybrid (AI + Wind)	68	7.2	34	10.00	88	5,200

Throughput, power consumption and latency are considered to be the most important drivers of energy efficiency that define network performance. The proposed framework defined energy efficiency quantitatively with the help of the E_{eff} condition, which compares these parameters. The combination of AI and PV, labelled as AI+PV, had the highest value of E_{eff}, which confirmed the fact that this system possessed the capability to generate optimal energy efficiency, based on the high throughput rate and the low latency level. To extend the investigation further, more configurations including power systems with energy storage and with both AI and wind integration were examined in terms of resource use efficiency and emissions control. These ideas are helpful for having a better understanding of energy efficiency improvements.

4.7. Renewable Energy Integration and Contribution

Among the decentralized systems, PV systems serve as an essential component of the proposed hybrid architecture. A cross-sectional analysis of PV systems contribution was carried out in 10 regions experiencing different environmental conditions in terms of solar insolation. The study looked at how four aspects of irradiation, PV generated electricity and the percentage of renewable energy sourced for networks. Figure 4 below shows other parameters similar to the previous table: average monthly energy production, efficiency of the system, and annual CO^2 emission avoided. These outcomes show that the future telecommunications infrastructure depends much on the renewable energy facilities.

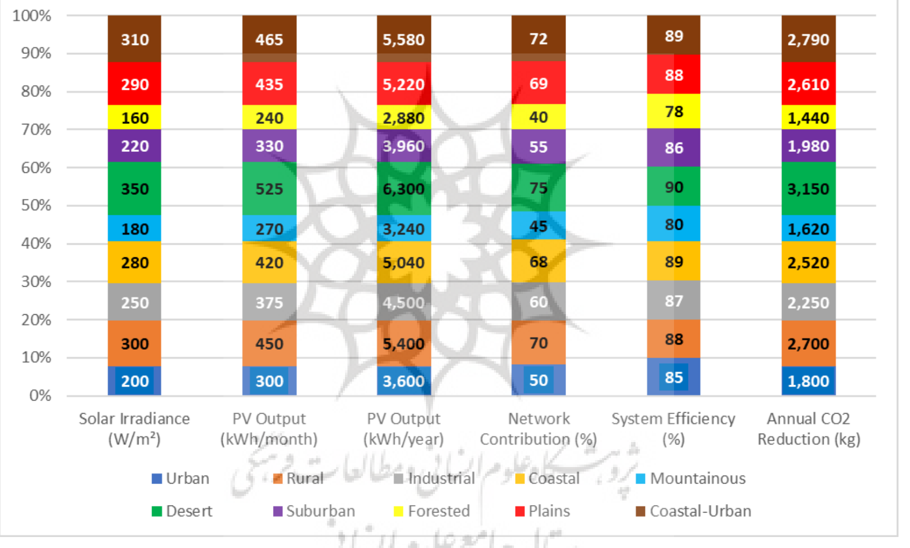

Figure 4. Renewable Energy Contribution Metrics

From the results highlighted in figure 4, it can be seen that PV systems increased in its contribution to meet the network energy needs as the solar irradiance increases. Annual PV yields of 6,300 kWh were observed in desert areas with 350 W/m² solar intensity and 5,580 kWh, in the coastal-urban zone with solar intensity of 310 W/m². And in fulfillment of the same, these regions provided the largest percentage increment to network energy, 75% for desert region and 72% for coastal-urban.

Rural zones with moderate irradiance of 300 W/m² had overall renewable energy percentage of 70%; generating 5,400 kWh per year. On the other hand, the night ability of ageing regions lower irradiance such as the forest regions and the mountainous region only supplied the network energy by 40% & 45% respectively. Nevertheless, in these circumstances, the PV systems continued to achieve operational efficiency of 78 to 80 percent, which was evidence of the flexibility of the proposed framework.

The increase in installed PV systems led to substantial decreases in regional CO2 emission rates in all the regions. Last year, the greatest per capita concerning savings of 3150 kg of CO2 were attained by desert areas, whereas urban and suburban areas conserved 1800 kg and 1980 kg correspondingly. This thus bring out the advantages of renewable energy in the integrated system especially within the densely populated region and high energy demand.

These results therefore warrant the utility of the proposed hybrid framework in exploiting renewable energy for network sustainability improvement. Due to high flexibility and good performance of the PV systems which can be installed in almost every environment, their ability to contribute greatly to energy savings and enhancement of the next generation telecommunications establishes them as significant in creation of sustainable next-generation telecommunications.

5. Discussion

This article advocates for the integration of AI and renewable network architecture to support hybrid network structures. The proposed framework addresses key concerns in next-generation telecommunications, such as efficient power usage, network sizing, and Quality of Service (QoS). To the best of our knowledge, there are no similar studies. Therefore, this work focuses on implementing novel techniques based on AI algorithms and renewable energy resources to achieve substantial enhancements in network performance and environmental sustainability.

The results corroborate prior findings in the literature. For instance, Koval et al. (2019) highlighted the advantages of hybrid network structures in terms of power-saving capabilities and enhanced system functionality (Koval, Kremenetskaya, and Markov 2019). However, unlike Koval et al. (2019), which proposed theoretical designs, this work demonstrates the effectiveness of the hybrid framework through large-scale simulations in realistic environments (Koval, Kremenetskaya, and Markov 2019). Additionally, Benzaghta et al. (2022) identified key energy-saving approaches, such as massive MIMO and sleep modes. Still, their work lacked a polymorphic approach to renewable energy sources (Benzaghta et al. 2022). In contrast, this study provides clear evidence of the synergistic application of AI algorithms and renewable systems, demonstrating how they can offer a unified solution for green telecommunications.

The techno-economic analysis presented in this study expands on the work of Alimi et al. (2021) and Alsharif et al. (2021), which discussed the cost advantages of sustainable network architectures (Alimi et al. 2021; Alsharif et al. 2021). This study reinforces their findings, suggesting realistic reductions in energy costs and maintenance, while providing further evidence of long-term sustainable revenue. The integration of renewable energy, as highlighted by Ali et al. (2023), supports the environmental and economic benefits of hybrid configurations (Ali et al. 2023). Importantly, this work estimates the role of photovoltaic systems in various categories and countries, demonstrating their versatility and ability to support decarbonization efforts.

The enhancements made in this work regarding QoS, supported by Bhar and Agrell (2021), underline the subjectivity of QoS-aware systems in next-generation networks (Bhar and Agrell 2021). By applying improved routing algorithms, this work targets minimal latency, maximal throughput, and minimized packet loss, generalizing Bhar and Agrell's (2021) findings to any hybrid architecture with minimal difficulty (Bhar and Agrell 2021). Furthermore, the scalability results align with the findings of Chochliouros et al. (2021), confirming that network architecture flexibility constitutes a major trend in future 5G networks (Chochliouros et al. 2021).

However, it is essential to note several limitations of the current study. One disadvantage is that renewable energy systems depend on environmental conditions (Talal et al. 2025). The results highlighted here may not be easily replicable in regions where solar irradiance or wind conditions are less favorable. This challenge resembles the variability of renewable energy in telecommunications networks highlighted by Cabrera-Tobar et al. (2023). Future research may seek alternative renewable energy sources or combine various renewable resources to overcome this limitation(Cabrera-Tobar, Grimaccia, and Leva 2023) (Qasim and Jawad 2024).

Another limitation is the AI-adaptive nature of algorithms, which poses challenges in generalization and adaptability. Although this research demonstrates their efficiency, implementing these algorithms might incur computational costs in some scenarios, as noted by Mao et al. (2022) (Mao et al. 2022). Future implementations should focus on improving algorithm efficiency and utilizing appropriate hardware to mitigate this issue.

The proposed framework also assumes the existence of infrastructure such as SDN and NFV. Srinivas et al. (2023) and Pakpahan and Hwang (2023) commented that implementing SDN/NFV can present infrastructural challenges in legacy networks. Addressing these issues will be essential for popularizing hybrid architectures (Srinivas et al. 2023; Pakpahan and Hwang 2023).

Overall, this study quantifies energy savings, cost-benefit analysis, and QoS enhancement but examines the socio-economic effects of migrating to hybrid systems insufficiently. Green computing significantly impacts society, particularly economically. Khelifi et al. (2021) called for future studies to consider these aspects for a more thorough evaluation (Khelifi et al. 2021).

Depending on the access and core networks, the present work offers a unique contribution to green telecommunications by providing an authentic hybrid network solution. It addresses critical gaps in energy efficiency, scalability, and QoS, while highlighting some areas requiring further study. By building on previous research and offering useful context, this study provides a solid methodological platform for future developments in sustainable telecommunication systems.

6. Conclusion

This article demonstrates that incorporating AI within the infrastructure of next-generation telecommunication networks, utilizing renewable energy sourcing and hybrid network architecture, can effectively address these challenges. The proposed framework is achieved by integrating state-of-the-art technologies to enhance energy efficiency, scalability, and network performance goals while considering sustainability. The results indicate that there has been successful migration from conventional architectures to contemporary hybrid structures that align with environmental and operational objectives.

The study also emphasizes the effective application of AI algorithms and renewable energy sources for network management. The use of energy-aware resource allocation, load balancing schemes, and QoS-aware routing has resulted in higher throughput, lower delays, and improved energy efficiency. These technological advancements not only enhance network performance but also reduce reliance on fossil fuels, thereby mitigating greenhouse gas emissions.

Additionally, the study highlights the robustness of the hybrid system, regardless of geography and network conditions. The specificity of these systems allows for their integration into both urban and rural areas, ensuring equitable telecommunications performance. Flexibility is crucial in addressing global connectivity issues, particularly in regions that remain underserved.

However, the study also outlines several directions for further development. The variability of renewable energy sources poses significant challenges, especially in areas with limited solar or wind energy. Enhancing the coordination of integrated hybrid renewable systems, such as solar-wind combinations or energy storage systems, could improve system reliability and efficiency. Furthermore, AI-based algorithms in scenarios with restricted computational capabilities require additional research to optimize algorithm efficiency and their applicability in developing nations.

Future research may build on this study by examining the socio-economic consequences of implementing hybrid architectures. A more detailed analysis of the economic, societal, and policy implications of sustainable telecommunications would provide valuable insights into the potential of sustainable telecom. Additionally, the integration of emerging technologies, such as blockchain and edge computing within a hybrid environment, could offer new approaches.

The present study lays a strong foundation for feasible developments in sustainable telecommunications through hybrid network structures. The proposed framework addresses energy efficiency, scalability, and network performance, aligning with sustainable development goals. Further improvements to these systems will be essential to advancing sustainable and equitable telecommunications.

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