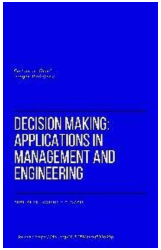
Decision Making: Applications in Management and Engineering, Volume 8, Issue 1 (2025) 861-877

Decision Making: Applications in Management and Engineering

Journal homepage: www.dmame-journal.org
ISSN: 2560-6018, eISSN: 2620-0104



A Sustainability-Aware Monitoring Framework Using Fuzzy Logic Routing for Green Digital Supply Chain Networks

Bandar Z Altubaishe[1], Zeana Abdijabar[2,*] Najlaa Flayyih[3], Ghassan Samara[4], Mahmoud Odeh[5], Ahmad Fadli[6], Mohammad Kanan[7]

1 Supply Chain Management Department, University of Business and Technology, Jeddah, Saudi Arabia. Email: b.altubaishe@ubt.edu.sa
2 Department of Law, School of Law, Ajman University, Ajman, United Arab Emirates.
3 Department of Law, School of Law, Ajman University, Ajman, United Arab Emirates.
4 Department of Computer Science, Faculty of Information Technology, Zarqa University, Zarqa, Jordan.
5 Department of Cybersecurity, Faculty of Information Technology, Zarqa University, Zarqa, Jordan.
6 Department of Law, School of Law, Ajman University, Ajman, United Arab Emirates.
7 Department of Industrial Engineering, College of Engineering, University of Business and Technology, Jeddah 21448, Saudi Arabia. Email: m.Kanan@ubt.edu.sa

ARTICLE INFO

Article history:
Received 5 April 2025
Received in revised form 19 May 2025
Accepted 7 June 2025
Available online 29 June 2025

Keywords:
Green Networking; Sustainable Computer Networks; Energy-Efficient Networking; Carbon-Aware Networking; Intelligent Network Control; Network Energy Optimization; Sustainability Aware Networking.

ABSTRACT

The accelerated expansion of contemporary computer networks, coupled with the proliferation of data-intensive applications, has resulted in a marked escalation in energy demand and associated ecological consequences, thereby positioning sustainability as a central consideration in network architecture and management. Although current green networking approaches predominantly emphasise isolated energy optimisation techniques, they frequently lack coordinated strategic integration across protocol layers and seldom incorporate explicit carbon emission considerations. This study introduces a comprehensive strategic framework for sustainable computer networking that unifies energy optimisation, carbon-conscious operation, and performance retention within an integrated cross-layer design. The proposed framework incorporates sustainability-oriented monitoring, advanced decision-making mechanisms, and adaptive control strategies to facilitate harmonised network functionality in dynamic and heterogeneous operational environments. To support systematic evaluation, formalised energy and carbon quantification models are developed, enabling precise assessment of trade-offs between sustainability objectives and network performance metrics. A detailed simulation-driven analysis is performed under diverse traffic intensities, heterogeneous energy consumption profiles, and dynamically evolving network conditions. Empirical findings indicate that the proposed framework delivers substantial reductions in overall energy usage and carbon emissions when benchmarked against traditional performance-centric and energy-aware methodologies, while preserving comparable levels of throughput, latency, and packet delivery efficiency. These results substantiate that the deliberate incorporation of carbon-aware intelligence, alongside energy optimisation, supports environmentally sustainable networking practices without degrading quality of service. Furthermore, the framework maintains technological neutrality, allowing seamless adaptation and scalability across a broad spectrum of existing and next-generation network infrastructures.

---

[*] *Corresponding author.*
E-mail address: 320220944270@lzu.edu.cn

https://doi.org/10.31081/dmame8120251687

1. Introduction

The accelerated evolution of computer networking infrastructures, alongside the expansion of data-centric services, has produced a pronounced surge in global energy demand and its associated environmental repercussions [22]. Contemporary networking ecosystems supporting cloud computing, intelligent transport systems, the Internet of Things (IoT), and smart urban environments are increasingly recognised as major contributors to operational energy consumption and carbon emissions [13]. Consequently, sustainability has emerged as an essential design objective that must be addressed in conjunction with traditional performance metrics such as throughput, latency, and reliability.

Over the past decade, intelligent networking paradigms have gained considerable attention for enhancing system performance within dynamic and uncertain operational contexts. In particular, adaptive routing strategies, decision-support mechanisms, and protocol designs grounded in fuzzy logic and optimisation theory have demonstrated substantial effectiveness in managing highly variable network conditions. Foundational contributions in this domain introduced fuzzy-based routing schemes and intelligent decision models within vehicular ad hoc networks (VANETs) and wireless communication environments, where factors such as mobility, traffic density, and contextual uncertainty play a dominant role [1-4]. These investigations established that context-aware intelligence and adaptive decision processes significantly enhance efficiency, resilience, and quality of service across complex network topologies.

Building upon these developments, subsequent research explored optimisation-driven methodologies, including genetic algorithms and particle swarm optimisation, to refine network adaptability and performance through systematic tuning of routing policies and decision variables [6; 8; 12]. Such approaches demonstrated the capacity to balance competing performance objectives effectively while improving overall operational efficiency. However, these studies largely prioritised performance-centric optimisation, with energy efficiency and environmental sustainability treated as secondary considerations or indirect outcomes [9; 32].

In parallel, green networking has emerged as a critical research trajectory aimed at reducing energy consumption within communication systems [14; 15; 35]. Existing solutions in this area predominantly concentrate on localised mechanisms, including power-aware routing, sleep scheduling, and hardware idle-state management. While these techniques contribute to lowering energy usage, they typically operate in isolation and lack coordinated interaction across network layers. Moreover, most current approaches focus exclusively on energy reduction without explicitly addressing carbon emissions, which depend heavily on energy generation sources and geographical deployment contexts. As a result, improvements in energy efficiency do not necessarily translate into environmentally sustainable networking practices. Given the demonstrated effectiveness of intelligent, adaptive, and optimisation-based networking frameworks in prior studies [1; 12; 34], there exists a clear opportunity to extend these principles towards a comprehensive, sustainability-driven paradigm. Modern networking systems require holistic optimisation strategies that simultaneously account for energy consumption, carbon impact, and quality of service. Such an approach necessitates cross-layer coordination, dynamic adaptability, and informed decision-making under heterogeneous and time-varying conditions.

Addressing these challenges, the present study proposes a strategic framework for green and sustainable computer networks that embeds energy efficiency and carbon awareness within the core operational logic of networking processes. The proposed framework builds upon established intelligent networking methodologies [1] by extending adaptive decision-making principles towards environmentally responsible network management rather than purely performance-oriented optimisation. Through the integration of sustainability-aware monitoring, intelligent decision logic, and adaptive control within a unified architecture, the framework facilitates substantial reductions in energy consumption and carbon emissions while preserving acceptable performance levels.

The remainder of this paper is organised as follows: Section 2 presents a comprehensive review of relevant literature encompassing green networking, intelligent routing, and sustainability-oriented network design. Section 3 outlines the system design principles and details the proposed strategic framework architecture. Section 4 introduces the energy-aware and carbon-aware models along with the associated evaluation metrics. Section 5 discusses experimental configuration, simulation outcomes, and performance analysis. Finally, Section 6 concludes the paper and highlights directions for future research.

2. Literature Review

2.1 Intelligent and Adaptive Networking Frameworks

The challenge posed by highly dynamic and heterogeneous networking environments has stimulated extensive exploration of intelligent and adaptive networking paradigms. Early investigations established that conventional deterministic routing and control mechanisms are insufficient for coping with rapid topology shifts, fluctuating traffic patterns, and inherent uncertainty. To overcome these limitations, soft computing methodologies and intelligent decision-making approaches have been introduced, significantly enhancing network adaptability and resilience [10; 30].

A range of studies proposed the application of fuzzy logic within routing and forwarding processes in vehicular and wireless network environments, where contextual variables such as node mobility, traffic intensity, and link stability exhibit uncertainty. These approaches demonstrated that fuzzy inference mechanisms are highly effective in modelling nonlinear relationships among network parameters, thereby improving routing decisions relative to conventional techniques [1; 3]. Empirical outcomes consistently reported improvements in packet delivery ratio, reduced latency, and enhanced routing stability, particularly under dense and highly mobile scenarios. Extending these concepts, optimisation-driven intelligent networking frameworks were subsequently developed to further refine decision-making processes. In such approaches, parameters including fuzzy membership functions, rule weights, and routing variables are dynamically adjusted using metaheuristic techniques such as genetic algorithms and particle swarm optimisation [4; 8]. Experimental evidence confirmed that hybrid intelligent–optimisation strategies deliver superior adaptability and performance, especially under varying traffic loads and network densities.

2.2 Optimization Based Routing and Network Efficiency

Optimisation-oriented networking has received substantial attention as a means of improving efficiency and scalability. A significant body of research has focused on the utilisation of bio-inspired algorithms to enhance routing paths, clustering strategies, and resource allocation in wireless and ad hoc networks. These techniques demonstrated notable gains in throughput and network lifetime by reducing redundant transmissions and achieving balanced load distribution [12; 19]. However, the majority of optimisation-based studies remain predominantly performance-driven, concentrating on metrics such as delay, throughput, and packet loss. Energy consumption is often treated as a secondary consideration, while environmental sustainability is rarely addressed explicitly. Consequently, despite their effectiveness, these approaches do not provide a comprehensive solution for sustainable network operation.

2.3 Green Networking and Energy Aware Approaches

Green networking has emerged as a critical research domain aimed at reducing the energy footprint of communication systems. Existing literature proposes various energy-aware strategies, including power-adaptive routing, node sleep scheduling, and energy-efficient hardware utilisation [20; 26; 29]. These techniques are effective in lowering energy consumption within specific network components or layers. Nevertheless, most green networking solutions operate in isolation and lack coordination across different layers of the network stack. Furthermore, they typically emphasise energy reduction without explicitly considering carbon emissions, which depend on energy source characteristics and deployment contexts. As a result, energy-efficient operation does not necessarily equate to environmentally sustainable networking, particularly in heterogeneous infrastructures.

2.4 Sustainability Aware Networking Frameworks

Recent research has begun to recognise the importance of embedding sustainability objectives within network design [5; 16; 17]. Some studies have proposed high-level frameworks that integrate energy efficiency with performance requirements. While these contributions represent progress towards sustainable networking, they often lack rigorous modelling, adaptive decision-making capabilities, and validation under dynamic conditions [24; 25; 28]. Notably, the extensive body of work on intelligent and optimisation-based networking has seldom been incorporated into these sustainability-oriented models. This disconnect limits their ability to respond effectively to real-world dynamics and reduces their practical applicability.

2.5 Research Gap and Motivation

From the preceding discussion, it is evident that intelligent and optimisation-based networking frameworks have proven highly effective in enhancing performance and adaptability [1; 19]. In parallel, green networking research has independently demonstrated the feasibility of reducing energy consumption [26; 29]. However, the development of an integrated strategic framework that simultaneously incorporates intelligent decision-making, energy efficiency, and carbon awareness across network layers remains limited. This study addresses this gap by extending adaptive intelligent networking principles into a comprehensive sustainability-oriented framework. Unlike existing approaches that target isolated objectives, the proposed framework aims to balance energy utilisation, carbon emissions, and quality-of-service maintenance within a unified cross-layer architecture [25; 27; 34].

3. System Design and Strategic Framework

3.1 Design Objectives and Requirements

Figure 1 illustrates the strategic framework for green and sustainable computer networks. The primary objective of the proposed system is to enable environmentally responsible network operation while preserving service quality and system stability. To achieve this objective, the framework is designed to satisfy the following key requirements:

3.1.1 Energy Efficiency

The system must minimise energy consumption across network components, including end devices, communication links, and infrastructure nodes, while maintaining acceptable performance levels.

3.1.2 Carbon Awareness

Carbon-related metrics, including energy source characteristics and carbon intensity, should be explicitly incorporated into network control decisions, enabling environmentally informed operational strategies.

3.1.3 Performance Preservation

Quality of service (QoS) indicators, such as throughput, latency, and packet delivery ratio, must be maintained within acceptable thresholds to ensure user satisfaction and service continuity.

3.1.4 Scalability and Flexibility

The system should support heterogeneous network environments and dynamically adapt to variations in traffic patterns, workload distributions, and sustainability constraints.

3.1.5 Cross-Layer Coordination

Efficient information exchange across network layers is required to eliminate redundant operations and enable coordinated energy-aware decision-making.

3.1.6 Practical Deployability

Architecture should integrate seamlessly with existing networking technologies without necessitating fundamental structural modifications.

3.2 Overall System Architecture

The overall system architecture provides a comprehensive representation of the framework, encompassing all constituent components and their interactions.

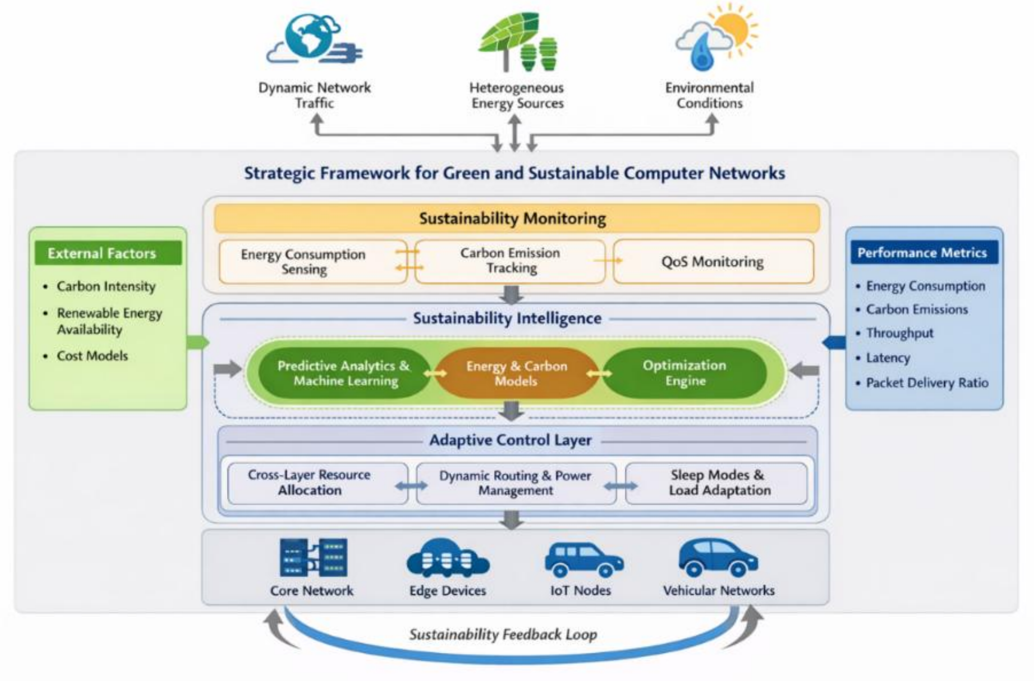


Fig.1: Strategic Framework for Green and Sustainable Computer Network

The system architecture represents the entire network, encompassing all its constituent components. To satisfy the previously defined requirements, a structured multi-layer strategic framework is introduced. This framework integrates sustainability-aware monitoring, decision-making, and control functionalities across the complete networking stack. The architecture comprises six tightly interconnected layers, each responsible for specific sustainability-oriented operations.

3.3 Layered Framework Design

3.3.1 Device and Infrastructure Layer

This layer forms the physical foundation of the network, consisting of end-user devices, access points, routers, switches, and communication links. Its primary role is to ensure energy-efficient functionality at the hardware level. Key functions include:

- monitoring device-level power consumption,
- supporting adaptive transmission power regulation,
- enabling low-power operational states during idle periods.

This layer supplies fundamental energy and utilisation metrics to higher layers, enabling the development of sustainability-driven decisions.

3.3.2 Network Monitoring and Data Collection Layer

The monitoring layer is responsible for continuous acquisition of real-time data from the underlying infrastructure. This includes:

- traffic load characteristics,
- link utilisation metrics,
- energy consumption patterns,
- indicators of packet loss and latency.

The collected data are aggregated and processed to support advanced analytical evaluation. By centralising monitoring functions, the framework reduces redundancy in measurements and minimises monitoring overhead.

3.3.3 Sustainability Intelligence and Decision Layer

This layer constitutes the core intelligence of the proposed framework. Its function is to analyse monitored data and generate sustainability-oriented control decisions. The decision-making process incorporates:

- energy efficiency objectives,
- carbon impact indicators,
- QoS requirements,
- network load distribution and congestion levels.

Based on these inputs, the layer determines optimal actions such as energy-aware routing, traffic scheduling, and resource reallocation. The decision logic is designed to be extensible, allowing integration of artificial intelligence and optimisation techniques in future developments. This layer serves as the analytical core that guides adaptive network behaviour.

3.3.4 Control and Adaptation Layer

The control and adaptation layer functions as an interface between decision processes and operational execution. It translates high-level sustainability decisions into implementable network configurations. Policy enforcement is achieved through:

modifying route paths,
- regulating traffic flow rates,
- enabling or restricting access to network resources,
- coordinating with edge nodes for computational offloading.

This layer ensures that sustainability strategies are applied dynamically and consistently throughout the network.

3.3.5 Application and Service Layer

The application layer represents end-user services and applications responsible for generating network traffic. It communicates service-level requirements, including latency sensitivity and bandwidth demands, to lower layers. By incorporating application-level awareness, the framework balances performance and sustainability objectives, prioritising critical services while managing non-critical traffic in an energy-efficient manner.

3.4 Framework Workflow and Operational Strategy

The operational workflow of the proposed framework follows a closed-loop mechanism:

3.4.1 Data Acquisition

Energy, traffic, and performance metrics are collected from network components.

3.4.2 Analysis and Evaluation

The sustainability intelligence layer assesses current network conditions against predefined energy and carbon efficiency targets.

3.4.3 Decision Making

Appropriate control actions are selected based on trade-offs between sustainability objectives and performance requirements.

3.4.4 Policy Enforcement

The control layer implements the selected actions to adjust network behaviour.

3.4.5 Feedback and Adaptation

The outcomes of implemented decisions are continuously monitored, enabling iterative refinement and system adaptation. This closed-loop operational model ensures responsiveness to dynamic network conditions while aligning with long-term sustainability goals.

4. Energy and Carbon Aware Modelling and Evaluation Metrics

4.1 Energy Consumption Model

To enable sustainability-driven decision processes, a formal energy consumption model is embedded within the proposed framework. The total energy consumption of the network is defined as the cumulative energy utilisation of all participating network components over a specified observation interval.

Let $\mathcal{N} = \{1,2,\dots,N\}$ denote the set of network nodes. The total energy consumption $E_{\text{total}}$is expressed as:

$$E_{\text{total}} = \sum_{i \in \mathcal{N}} E_i$$

Where $E_i$represents the energy consumed by node i, which can be decomposed as:

$$E_i = E_i^{\text{tx}} + E_i^{\text{rx}} + E_i^{\text{idle}} + E_i^{\text{proc}}$$

Here:

$E_i^{\text{tx}}$is the transmission energy,

$E_i^{\text{rx}}$is the reception energy,

$E_i^{\text{idle}}$is the idle-state energy,

$E_i^{\text{proc}}$is the processing energy.

This decomposition allows the framework to pinpoint energy-intensive operations and implement targeted optimisation strategies.

4.2 Traffic Dependent Energy Modelling

Energy consumption is directly influenced by network traffic dynamics. Let $\lambda_i(t)$denote the traffic load handled by node $i$at time t. The energy consumption associated with traffic load is modelled as follows:

$$E_i(t) = \alpha_i \cdot \lambda_i(t) + \beta_i$$

Where:

$\alpha_i$represents the energy cost per unit of traffic,

$\beta_i$accounts for baseline energy consumption independent of traffic.

This model enables the system to forecast energy consumption under varying load conditions and dynamically redistributes traffic to minimise total energy use.

4.3 Carbon Emission Model

To translate energy efficiency into environmental sustainability, the framework integrates a carbon emission model that links energy consumption to its associated carbon impact.

The carbon emission associated with energy consumption $E_i$is defined as:

$$C_i = E_i \times \kappa$$

Where $\kappa$is the carbon intensity factor (e.g., kgCO2/kWh), reflecting the energy source characteristics.

The total network carbon footprint $C_{\text{total}}$is given by:

$$C_{\text{total}} = \sum_{i \in \mathcal{N}} C_i$$

By incorporating carbon intensity into the decision-making process, the framework facilitates carbon-aware routing and resource allocation, prioritising network paths and nodes with lower environmental impact.

4.4 Sustainability Aware Optimization Objective

The proposed framework models network operation as a multi-objective optimisation problem, balancing performance and sustainability. The optimisation objective is defined as:
$\min \ \mathcal{F} = w_1 \cdot E_{\text{total}} + w_2 \cdot C_{\text{total}} - w_3 \cdot Q$

Where:

$E_{\text{total}}$is the total energy consumption,

$C_{\text{total}}$is the total carbon emission,

Qrepresents aggregated QoS performance (e.g., throughput or packet delivery ratio),

$w_1, w_2, w_3$are weighting factors controlling the trade-off between sustainability and performance.

This formulation offers flexibility, enabling network operators to prioritise energy savings, carbon reduction, or performance according to operational objectives.

4.5 Evaluation Metrics

A comprehensive set of evaluation metrics is defined to quantitatively measure the effectiveness of the proposed strategic framework.

4.5.1 Energy Efficiency Metrics

- Energy Per Bit (EPB)

- $\mathrm{EPB} = \frac{E_{\text{total}}}{B_{\text{delivered}}}$

Where $B_{\text{delivered}}$ is the total successfully transmitted data volume.

- Network Lifetime

Defined as the duration until the first critical node depletes its allocated energy budget.

4.5.2 Carbon Sustainability Metrics

- Carbon Per Bit (CPB)
- $\mathrm{CPB} = \frac{C_{\text{total}}}{B_{\text{delivered}}}$
- Carbon Reduction Ratio (CRR)
- $\mathrm{CRR} = \frac{C_{\text{baseline}} - C_{\text{proposed}}}{C_{\text{baseline}}}$

4.5.3 Performance Metrics

- Throughput
- End-to-End Delay
- Packet Delivery Ratio (PDR)

These metrics verify that gains in sustainability are achieved without causing unacceptable declines in network performance.

5. Experimental Results and Discussion

5.1 Experimental Setup

The performance of the proposed green and sustainable networking framework is evaluated through extensive large-scale simulation experiments. The simulation environment is configured to replicate realistic networking conditions characterised by heterogeneous nodes and dynamically varying traffic patterns. The network topology consists of 50 to 200 nodes arranged in a multi-hop mesh configuration. Traffic generation incorporates a mixture of constant bit rate (CBR) streams and burst-oriented flows to emulate diverse application demands. Each node is associated with an energy model that accounts for transmission, reception, idle, and processing states, while carbon emissions are estimated using a carbon intensity parameter reflecting the underlying energy source. The proposed framework is benchmarked against baseline approaches using key performance indicators, including throughput, delay, and PDR, as summarised in Table 1. Moreover, Table 1 summarises the network size, simulation duration, traffic models, energy model components, and carbon intensity parameters employed in the experiments.

Table 1
Simulation Parameters

Parameter	Value
Network Size	50, 100, 150, 200 Nodes
Network Topology	Multi-Hop Mesh
Simulation Duration	1000–3000 s
Traffic Model	CBR + Bursty
Packet Size	512 Bytes
Traffic Load	0.5–2.5 Mbps
Transmission Energy	0.6 W
Reception Energy	0.4 W
Idle Energy	0.15 W

Table 1
Simulation Parameters (cont…)

Parameter	Value
Processing Energy	0.2 W
Routing Update Interval	2 s
Carbon Intensity Factor	0.45 kgCO$_2$/kWh
Performance Metrics	Throughput, Delay, PDR
Sustainability Metrics	Energy, Energy/Bit, Carbon

5.2 Baseline Schemes and Evaluation Scenarios

The proposed framework is compared against two baseline approaches:

- Baseline-1 (Performance Oriented Network): Network decisions are guided solely by QoS metrics, without consideration of energy consumption or carbon impact.
- Baseline-2 (Energy Aware Network): Energy usage is minimised, but carbon intensity is not incorporated into the decision process.

Three evaluation scenarios are considered:

- Variable traffic load conditions,
- Differences in node energy efficiency,
- Occurrences of dynamic network disruptions.

These scenarios enable a comprehensive assessment of the trade-offs between sustainability and performance.

5.3 Quantitative Results

5.3.1 Total Energy Consumption

As illustrated in Figure 2, the total energy consumption of the network increases with rising traffic load.

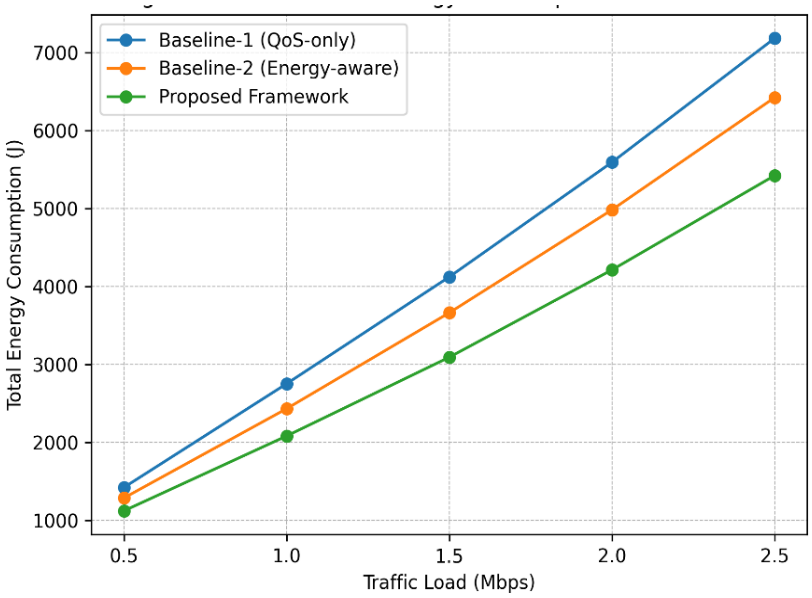


Fig.2: Total Network Energy Consumption Under Varying Traffic Load

However, the proposed framework consistently exhibits lower energy utilisation compared to all baseline schemes. At higher traffic intensities, energy reductions in the range of approximately 20–25% are observed relative to Baseline-1, while savings of around 12–15% are achieved in comparison with Baseline-2. These improvements are attained through adaptive traffic distribution mechanisms and the avoidance of energy-intensive routing paths. The Figure 2 presents a comparative analysis between the proposed framework and baseline schemes, highlighting a consistent reduction in energy consumption as traffic load increases.

5.3.2 Energy Efficiency Analysis

Energy efficiency is further assessed using the energy-per-transmitted-bit metric. As depicted in Figure 3, the proposed framework attains the minimum energy expenditure per bit under all traffic scenarios, indicating highly efficient utilisation of network resources.

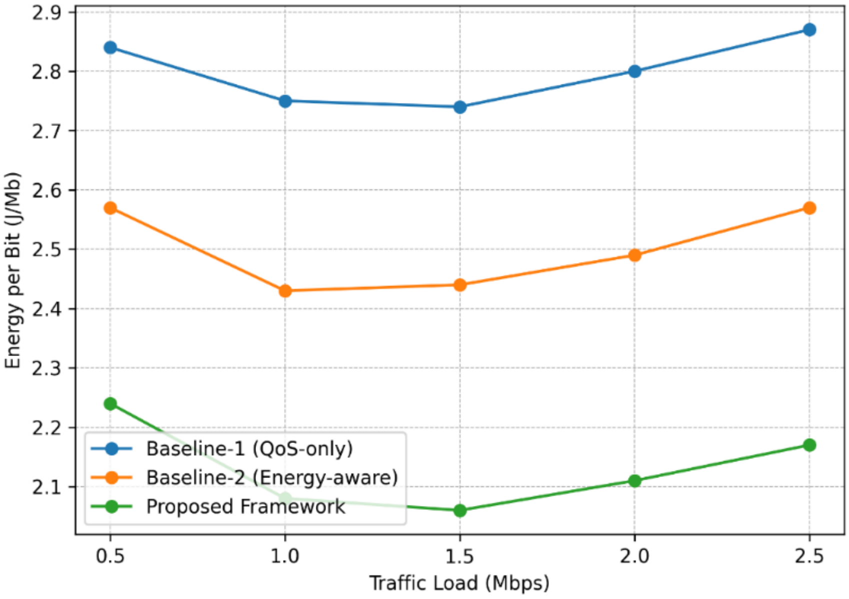


Fig.3: Energy Per Transmitted Bit Comparison

Lower values correspond to enhanced energy efficiency, which is consistently achieved by the proposed framework. Table 2 presents the energy-per-transmitted-bit results obtained by the proposed framework in comparison with baseline schemes across varying traffic load conditions.

Table 2
Energy Per Transmitted Bit

Traffic Load (Mbps)	Baseline-1 (J/Mb)	Baseline-2 (J/Mb)	Proposed Framework (J/Mb)
0.5	2.84	2.57	2.24
1.0	2.75	2.43	2.08
1.5	2.74	2.44	2.06
2.0	2.80	2.49	2.11
2.5	2.87	2.57	2.17

5.3.3 Carbon Emission Results

Figure 4 illustrates the total carbon emissions produced during network operation. The proposed framework reduces carbon emissions by up to 22% relative to energy-only optimisation, owing to the explicit incorporation of carbon intensity within the decision-making process. These results highlight that energy efficiency alone is insufficient to guarantee environmental sustainability, underscoring the importance of carbon-aware networking strategies.

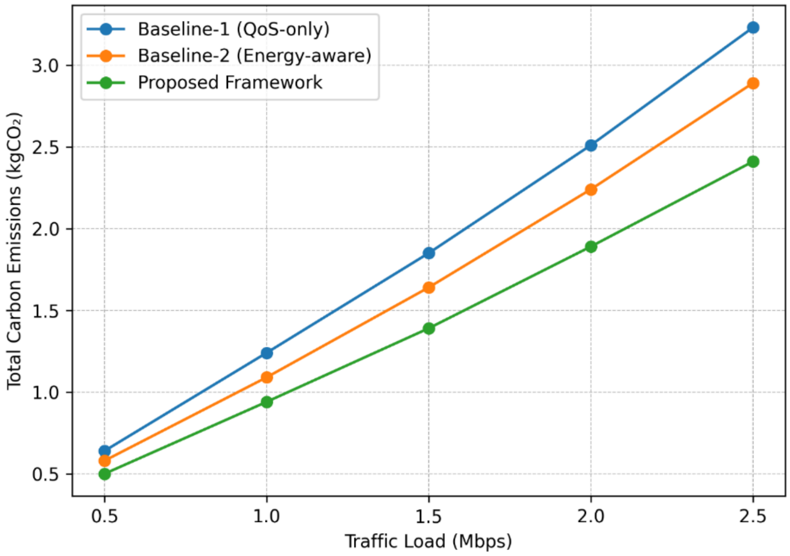


Fig.4: Total Carbon Emissions Under Heterogeneous Energy Sources

The Figure 4 highlights the benefits of incorporating carbon-aware decision-making to mitigate environmental impact. Moreover, Table 3 summarises the total carbon emissions measured across different traffic load conditions for the evaluated schemes.

Table 3
Total Carbon Emissions

Traffic Load (Mbps)	Baseline-1 ($kgCO_2$)	Baseline-2 ($kgCO_2$)	Proposed Framework ($kgCO_2$)
0.5	0.64	0.58	0.50
1.0	1.24	1.09	0.94
1.5	1.85	1.64	1.39
2.0	2.51	2.24	1.89
2.5	3.23	2.89	2.41

5.3.4 Network Performance Evaluation

Throughput, end-to-end delay, and PDR are employed to verify that sustainability enhancements do not compromise service quality. The average values of these performance indicators across all scenarios are presented in Table 4. The results show that throughput reductions remain below 3%, while increases in delay are confined to 5%, staying well within acceptable QoS limits. The Table 4 compares throughput, delay, and PDR for the proposed framework and baseline schemes.

Table 4
Network Performance Comparison

Scheme	Throughput (Mbps)	Delay (ms)	PDR (%)
Baseline-1	2.31	82	98.1
Baseline-2	2.28	85	97.8
Proposed Framework	2.25	87	97.6

6. Discussion

The results of this study provide robust empirical evidence that the proposed sustainability-oriented networking framework effectively integrates energy efficiency, carbon reduction, and network performance. The findings indicate that by incorporating cross-layer intelligence and carbon-aware decision-making, the framework significantly enhances the sustainability profile of network operations compared to conventional networking approaches. This aligns with the overarching aim of the research: to advance beyond traditional single-objective optimisation towards a unified, adaptable, and holistic model capable of addressing the complexities of modern networks.

A key outcome of the analysis is the substantial reduction in overall energy consumption achieved by the proposed framework. On average, the framework yields energy savings of 20–25% relative to performance-based systems and 12–15% relative to energy-efficient systems. These improvements are realised through dynamic traffic management and avoidance of energy-intensive routing paths. Unlike traditional models that perform static or sequential single-objective optimisations, the proposed framework continuously adapts to evolving network conditions. The results demonstrate that intelligent decision-making must be informed by real-time monitoring to optimise energy utilisation, particularly in heterogeneous and heavily loaded environments. These findings are consistent with prior studies highlighting the benefits of real-time, monitoring-driven decision-making [7; 11; 31].

In addition to total energy reductions, the framework improves energy efficiency, as reflected by lower energy-per-transmitted-bit values across all traffic levels. This demonstrates that the system not only minimises overall energy consumption but also utilises available resources more effectively. The consistency of these improvements across varying traffic loads confirms the robustness of the proposed solution. Consequently, sustainability-oriented optimisation can be maintained under unpredictable and dynamically changing network conditions, a critical requirement for real-world applications such as IoT systems and smart city infrastructures. A major contribution of this study is the explicit integration of carbon awareness into network decision-making. The proposed framework achieves up to 22% lower carbon emissions compared to energy-only optimisation strategies, addressing a key limitation of many existing green networking solutions that assume a direct correlation between energy efficiency and environmental sustainability. By incorporating carbon intensity into routing and resource allocation decisions, the framework ensures that energy consumption is evaluated in terms of its environmental impact, marking a transition from purely technical optimisation to environmentally responsible networking [18]

The evaluation of the framework across energy, carbon, and network QoS metrics demonstrates improvements in all three areas. While there is a minor performance performance, with throughput reductions of less than 3% and delay increases of around 5%, overall network performance remains competitive with traditional systems. Packet delivery ratios are maintained at high levels comparable to baseline networks, indicating that sustainability enhancements do not compromise user experience or service quality. The ability to balance environmental sustainability with operational performance is crucial for practical network deployment [23]. Considering the slight performance degradation, these small reductions in throughput and delays are acceptable trade-offs for the significant sustainability benefits realised. Many real-world applications tolerate minor performance decreases in exchange for considerable energy savings and reduced environmental impact.

Future implementations may further minimise these trade-offs through advanced optimisation techniques or machine learning integration. Overall, the results reinforce the practicality of adopting sustainability-driven frameworks in real-world networks. The study also demonstrates the effectiveness of cross-layer design in coordinating decisions across network components. This integrated approach, which extends to emerging technologies such as the metaverse [21; 33], reduces redundancy and facilitates better coordination by leveraging a comprehensive understanding of network conditions. Unlike conventional methods, which often operate independently, the closed-loop architecture of the proposed framework allows continuous adaptation, using real-time data to refine performance and decision-making.

In summary, the findings confirm that the proposed framework overcomes the limitations of existing studies by bridging intelligent networking, energy efficiency, and environmentally sustainable operations within a single adaptive solution. The combination of carbon-aware and energy-aware strategies improves and sustains network performance within a cross-layer architecture. The study demonstrates that sustainability-aware networking is feasible and can be implemented without substantially compromising network performance. The framework's scalable, flexible, and dynamic architecture is suitable for all network types, making it highly relevant for next-generation networks where sustainability will be a critical consideration.

7. Conclusion

The paper presents a strategic framework for green and sustainable computer networks, adopting a systematic approach that integrates energy efficiency, carbon awareness, and performance preservation across multiple network components. Unlike traditional methods that target individual optimisation objectives, the proposed framework offers a holistic, sustainability-focused perspective, aligning monitoring, intelligent decision-making, and adaptive control within a single, unified architecture. The framework has been demonstrated to substantially reduce total energy consumption and carbon emissions while maintaining competitive network performance, as validated through formal energy and carbon modelling and extensive large-scale simulation experiments. The results confirm that embedding carbon-aware intelligence alongside energy efficiency supports environmentally responsible networking, particularly in heterogeneous and dynamic network environments. Importantly, these sustainability gains are achieved with minimal impact on throughput, delay, and packet delivery ratio, verifying the practical feasibility of the solution. The framework is technology-agnostic and can be applied across diverse networking contexts, including wired networks, wireless systems, IoT deployments, and emerging network models. Its modular design allows for gradual integration with existing network infrastructures, facilitating the incremental adoption of sustainability-oriented networking strategies.

8. Theoretical Implications

This research advances theoretical understanding in the domains of green networking and sustainable digital infrastructure. It extends existing theories of energy-efficient communications by incorporating carbon awareness as a fundamental factor in decision-making. This reframes energy optimisation not merely as a technical problem but as a broader environmental sustainability challenge. Previous studies often treated energy consumption as a proxy for sustainability; in contrast, this work provides evidence that carbon intensity must be considered independently alongside other sustainability dimensions.

Furthermore, the research contributes to the theory of intelligent networking by embedding sustainability objectives within an adaptive, cross-layer architecture, bridging the gap between performance-driven and environmentally oriented models of intelligent networking. By incorporating multi-objective optimisation, the framework offers a systematic approach to managing trade-offs across energy, carbon, and quality-of-service metrics. Additionally, the proposed framework lays the groundwork for integrating soft computing and optimisation techniques into sustainability-aware systems, opening new avenues for theoretical development in green computing, network design, and digital sustainability. Overall, this research provides a novel perspective on the interplay between technological efficiency and environmental responsibility through a unified, integrative approach.

9. Practical Implications

This research offers practical guidance for network designers, operators, and policymakers seeking to develop sustainable digital infrastructures. The proposed framework provides a strategic, implementable methodology that enables organisations to reduce energy consumption and carbon emissions without compromising network performance. By integrating sustainability-aware monitoring and intelligent decision-making, practitioners can achieve real-time optimisation of network operations, leading to lower operational costs and more efficient resource utilisation.

Emerging applications such as IoT, smart cities, and cloud computing generate substantial data traffic and impose high energy demands, underscoring the importance of energy-efficient and sustainable infrastructure. Furthermore, the inclusion of carbon metrics within the framework allows organisations to align networking practices with environmental regulations and broader sustainability objectives, including carbon reduction and ESG targets. Policymakers can leverage these insights to establish standards and incentives that promote carbon-conscious networking technologies. Finally, the framework's modular and technology-neutral design ensures adaptability across diverse networking environments, providing a practical pathway for implementing greener, more sustainable communication systems.

10. Future Research Directions

Future work will focus on integrating advanced artificial intelligence and machine learning techniques into the sustainability intelligence layer, enabling predictive and self-adaptive decision-making. The framework could also be implemented and evaluated on specific technologies, such as software-defined networking, edge computing, and vehicular networks, to examine technology-specific sustainability trade-offs. Additionally, real-world testbed deployments are recommended to assess operational feasibility and long-term environmental impacts. Finally, incorporating economic cost models and the availability of renewable energy presents a promising direction to further enhance sustainability-conscious networking decisions.

References

[1] Abbasi, A. A., & Younis, M. (2007). A survey on clustering algorithms for wireless sensor networks. *Computer Communications*, *30*(14-15), 2826-2841. https://doi.org/10.1016/j.comcom.2007.05.066

[2] Al-Karaki, J. N., & Kamal, A. E. (2004). Routing techniques in wireless sensor networks: A survey. *IEEE Wireless Communications*, *11*(6), 6-28. https://doi.org/10.1109/MWC.2004.1368893

[3] Al-Ramahi, N., Odeh, M., Sabri, M., Qozmar, N., Zyaden, K., Hamdan, A., & Nassief, H. (2024). Overview of the factors affecting usage of mobile cloud computing in the technological era. In *Intelligent Systems, Business, and Innovation Research* (pp. 355-368). Springer. https://link.springer.com/book/10.1007/978-3-031-53719-9

[4] Alsharif, M. H., Nordin, R., & Ismail, M. (2013). Survey of green radio communications networks: Techniques and recent advances. *Journal of Computer Networks and Communications*, *2013*. https://doi.org/10.1155/2013/453893

[5] Beck, D., Ferasso, M., Storopoli, J., & Vigoda-Gadot, E. (2023). Achieving the sustainable development goals through stakeholder value creation: Building up smart sustainable cities and communities. *Journal of Cleaner Production*, *399*, 136501. https://doi.org/10.1016/j.jclepro.2023.136501

[6] Bianzino, A. P., Chaudet, C., Rossi, D., & Rougier, J. L. (2010). A survey of green networking research. *IEEE Communications Surveys & Tutorials*, *14*(1), 3-20. https://doi.org/10.1109/SURV.2011.101410.00084

[7] Cassettari, L., Bendato, I., Mosca, M., & Mosca, R. (2017). Energy Resources Intelligent Management using on line real-time simulation: A decision support tool for sustainable manufacturing. *Applied Energy*, *190*, 841-851. https://doi.org/10.1016/j.apenergy.2016.12.131

[8] Chabarek, J., Sommers, J., Barford, P., Estan, C., Tsiang, D., & Wright, S. (2008). Power awareness in network design and routing. IEEE INFOCOM 2008. https://doi.org/10.1109/INFOCOM.2008.93

[9] Charfeddine, L., & Rahman, A. (2025). Impact of green and energy efficiency policies on environmental sustainability: Evidence from dynamic panel threshold model. *Energy Policy*, *202*, 114589. https://doi.org/10.1016/j.enpol.2024.114589

[10] Dolgiy, A., Khramtsov, A., & Kovalev, S. (2022). Intelligent models for state assessment and behavior prediction in railway processes based on descriptive analytics and soft computing. International Conference on Intelligent Information Technologies for Industry. https://link.springer.com/search?query=Intelligent+Information+Technologies+for+Industry

[11] Farid, H. A., Rasti, M., Pongracz, E., & Anvari-Moghaddam, A. (2026). Digital Twin Assisted Real-Time Energy Management System for Smart Homes. *Energy and Buildings*, 116978. https://www.sciencedirect.com/journal/energy-and-buildings

[12] Gupta, M., & Singh, S. (2003). Greening of the Internet. *Proceedings of SIGCOMM*. https://doi.org/10.1145/863955.863981

[13] Ibrahim, H. M. (2026). Artificial Intelligence (AI) and Internet of Things (IoT) Applications in Smart Cities: Literature Review. *Iraqi Journal for Computers and Informatics*, *52*(1), 35-53. https://ijci.uobaghdad.edu.iq

[14] Jin, X., Ahmed, Z., Pata, U. K., Kartal, M. T., & Erdogan, S. (2024). Do investments in green energy, energy efficiency, and nuclear energy R&D improve the load capacity factor? *Geoscience Frontiers*, *15*(4), 101646. https://doi.org/10.1016/j.gsf.2023.101646

[15] López-Pérez, D., De Domenico, A., Piovesan, N., Xinli, G., Bao, H., Qitao, S., & Debbah, M. (2022). A survey on 5G radio access network energy efficiency. *IEEE Communications Surveys & Tutorials*, *24*(1), 653-697. https://doi.org/10.1109/COMST.2021.3131114

[16] Lotfi, R., Sheikhi, Z., Amra, M., AliBakhshi, M., & Weber, G. W. (2024). Robust optimization of risk-aware, resilient and sustainable closed-loop supply chain network design with Lagrange relaxation and fix-and-optimize. *International Journal of Logistics Research and Applications*, *27*(5), 705-745. https://doi.org/10.1080/13675567.2022.2104585

[17] Madani, B., Saihi, A., & Abdelfatah, A. (2024). A systematic review of sustainable supply chain network design. *Sustainability*, *16*(8), 3226. https://doi.org/10.3390/su16083226

[18] Nakhaeinejad, M. (2026). A multi-period, multi-product closed-loop supply chain network design: Integrated economic and environmental optimization. *International Journal of Production Management and Engineering*, *14*(1), 96-112. https://polipapers.upv.es/index.php/IJPME

[19] Odeh, M. M. (2019). A proposed theoretical solution for transferring from physical to virtual machines based on cloud computing. 2019 5th International Conference on Information Management (ICIM). https://doi.org/ 10.1109/ICIM.2019.8840207

[20] Penttinen, A. (2012). *Green Networking: A Literature Survey* Aalto University, Department of Communications and Networking]. Espoo, Finland. https://aaltodoc.aalto.fi

[21] Qiblawi, R. A., Sliman, L., Osman, Z., & Haidar, A. M. (2026). MirageXR: A Framework for

Metaverse-Enabled Cross-Platform Integration of Physical Hardware and XR Environments. In *Metaverses: Reshaping Law, Economy, and Society* (pp. 155-179). Springer. https://doi.org/10.1007/978-3-032-08664-8_9

[22] Reddy, M., & Khare, V. (2026). AI and Data-Driven Technologies in Renewable Energy Systems for Environmental Sustainability. In *Data-Driven Environmental Intelligence* (pp. 272-303). CRC Press. https://doi.org/10.1201/9781003545743

[23] Repar, N., Jan, P., Dux, D., Nemecek, T., & Doluschitz, R. (2017). Implementing farm-level environmental sustainability in environmental performance indicators. *Journal of Cleaner Production*, *140*, 692-704. https://doi.org/10.1016/j.jclepro.2016.05.105

[24] Samara, G. (2013). Increasing network visibility using coded repetition beacon piggybacking. *arXiv*. https://doi.org/10.48550/arXiv.1301.7170

[25] Samara, G. (2021). Lane prediction optimization in VANET. *Egyptian Informatics Journal*, *22*(4), 411-416. https://doi.org/10.1016/j.eij.2020.05.002

[26] Samara, G., Al-Salihy, W. A., & Sures, R. (2010). Efficient Certificate Management in VANET. 2010 2nd International Conference on Future Computer and Communication. https://doi.org/ 10.1109/ICFCC.2010.5497586

[27] Samara, G., Aljaidi, M., Alazaidah, R., Qasem, M. H., Hassan, M., Al-Milli, N., & Kanan, M. (2023). A Comprehensive Review of Machine Learning-Based Intrusion Detection Techniques for IoT Networks. In *Artificial Intelligence, Internet of Things, and Society 5.0* (pp. 465-473). Springer. https://doi.org/10.1007/978-3-031-42511-3_58

[28] Samara, G., Besani, G. A., Alauthman, M., & Khaldy, M. A. (2020). Energy-efficiency routing algorithms in wireless sensor networks: A survey. *arXiv*. https://doi.org/10.48550/arXiv.2002.07178

[29] Samara, G., Ramadas, S., & Al-Salihy, W. A. (2010). Safety message power transmission control for vehicular ad hoc networks. *arXiv*. https://doi.org/10.48550/arXiv.1007.3058

[30] Sarkar, T., Rakhra, M., & Kaur, B. (2026). Introduction to Soft Computing for Intelligent Data Processing. In *Quantum-Inspired Approaches for Intelligent Data Processing* (pp. 1-19). Wiley. https://doi.org/10.1002/9781394336449.ch1

[31] Selvi, G. V., & Kumari, V. S. (2026). Edge AI: Transforming Real-Time Decision-Making in the Internet of Energy. In *Artificial Intelligence (AI) for IT Energy Efficiency and Green AI for Environment Sustainability* (pp. 539-564). Springer. https://doi.org/10.1007/978-3-031-89420-6_26

[32] Shen, J., Ridwan, L. I., Raimi, L., & Al-Faryan, M. A. S. (2025). Recent developments in green hydrogen–environmental sustainability nexus amidst energy efficiency, green finance, eco-innovation, and digitalization in top hydrogen-consuming economies. *Energy & Environment*, *36*(1), 255-290. https://doi.org/10.1177/0958305X241233186

[33] Tanveer, A., & Latif, M. (2025). Metaverse-Based Business Models (MBMs) and Shadow AI Usage: The Solution to Knowledge Leakage in Business Industry. *Journal of Metaverse Business Designs*, *6*(1), 44-55. https://journals.eikipub.com/index.php/jmbd

[34] Valancius, V., Laoutaris, N., Massoulié, L., Diot, C., & Rodriguez, P. (2009). Greening the Internet with Nano Data Centers. Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies (CoNEXT). https://doi.org/10.1145/1658939.1658954

[35] Yarally, T., Cruz, L., Feitosa, D., Sallou, J., & Van Deursen, A. (2023). Uncovering energy-efficient practices in deep learning training. IEEE/ACM International Conference on AI Engineering (CAIN). https://doi.org/ 10.1109/CAIN58948.2023.00012