

Sustainable and Green Networking: Architectures, Techniques, and Future Directions for Energy-Efficient Communication Infrastructures

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Abstract: *Information and Communication Technology (ICT) infrastructure is rapidly becoming an electrical energy consumer, and an increasingly non-trivial emitter of greenhouse-gases as a result of the growth of global data traffic, cloud computing, artificial-intelligence workloads and always-connected Internet-of-Things (IoT) devices. Sustainable and Green Networking tackles this challenge by building energy-awareness into the design, deployment and operation of communication networks without affecting performance, reliability and quality of service. This paper summarizes the key concepts of green networking derived from literature published from 2022 to 2025, outlines the major classes of energy-saving techniques (standby and sleep modes, rate adaptation, energy-proportional computing, Software-Defined Networking (SDN) and Network Function Virtualization (NFV) based orchestration, and renewable-powered infrastructure) and suggests a cross-layer conceptual framework that brings these techniques together under a single carbon-intensity feedback loop. As examples of application areas, green 5G/6G radio access networks, sustainable data centers, and energy efficient IoT/edge computing are presented. A comparative study of the energy savings potential reported in the recent literature is presented, followed by a discussion of open challenges in the research field: the performance-energy trade-off, the standardization of energy information exposure, and the AI/ML energy-overhead trade-off, as well as interesting future research directions: the standardization of energy information exposure and the AI-native energy orchestration. The results will inform researchers, network operators and policymakers in their quest for more sustainable digital infrastructures.*

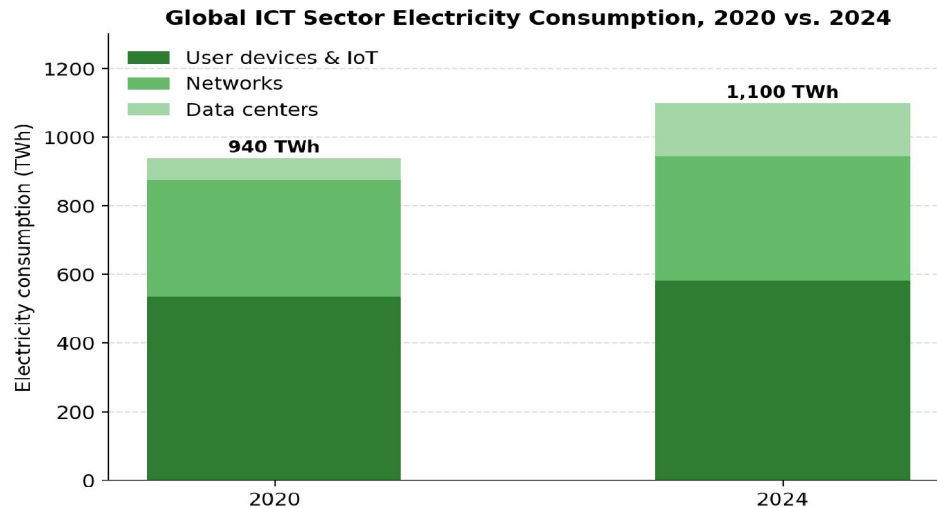
Keywords: Green networking, energy efficiency, sustainability, Software-Defined Networking, Network Function Virtualization, data centers, carbon footprint, renewable energy, 5G/6G, Internet of Things.

I. INTRODUCTION

The Internet has transformed from a service that makes data available “best effort” to a network that powers virtually the entire global economy for cloud computing, streaming media, artificial intelligence (AI) and billions of connected devices over the last several years. This expansion has occurred at a high price in terms of energy. The global electricity consumption of networking equipment, data centers and end-user devices now accounts for a significant and



increasing share of the world's electricity consumption and the sector's greenhouse-gas emissions estimated at between about 1.5% to 4% of global emissions, when manufacturing, operation and end-of-life stages are included [1] [2]. Industry estimates from recent reporting suggest that global electricity consumption in the ICT sector has risen from nearly 940 TWh in 2020 to nearly 1,100 TWh in 2024, with electricity demand for data centres rising at the fastest rate, approximately 9% per year, largely due to the growth of AI workloads [3].



Source: illustrative figures synthesized from Ericsson Mobility Report ICT carbon-footprint data (2024).

Fig. 1. Global electricity consumption of the ICT sector in 2020 and 2024 by user devices/IoT, networks and data centers.

This trend has led to increased research on the study and practice of Green Networking, also known as Sustainable or Energy-aware Networking, which aims to design communication networks with hardware, protocol, traffic, and infrastructure that lead to a decrease in the energy consumption and environmental impact of these networks, whilst maintaining acceptable performance and reliability [4, 5]. Green networking is primarily for the switches, routers, base stations, links, and control plane software that transport data over the network, unlike green computing, which is primarily concerned with the servers and end user devices. This paper makes three contributions. First, it unifies an existing green networking technique taxonomy based on the surveys of 6G energy-awareness, network-softwareization and data-center sustainability in the range 2022-2025 [4]-[7]. Second, it suggests a conceptual framework, which is cross-layer, and which connects application-level sustainability policies with the physical infrastructure decisions via a common energy-and-carbon feedback loop, inspired by the energy-information exposure concepts standardised in 3GPP and ITU [4]. Third, it brings together recent quantitative data on the energy-savings potential of the individual techniques and speaks about the outstanding challenges that are yet to be addressed to make green networking a reality at scale. The rest of the paper is structured as follows. Based on literature review, the related work is discussed in Section II. The taxonomy of green networking technique is presented in section III. Energy and carbon-footprint information is used in Section IV to further motivate the problem. The proposed framework is introduced in Section V. In Section VI, the application domains and case studies are discussed. Section VII is a direct comparison of techniques quantitatively. Section VIII presents open challenges, Section IX future directions and Section X concludes the paper.

II. RELATED WORK

The field of green networking research has seen a significant increase in its pace since 2022 as a result of the combination of 5G densification, growth in traffic volume powered by AI and shrinking corporate and regulatory sustainability goals. Setiawan et al. [5] reviewed the energy efficiency in three energy paradigms for network-

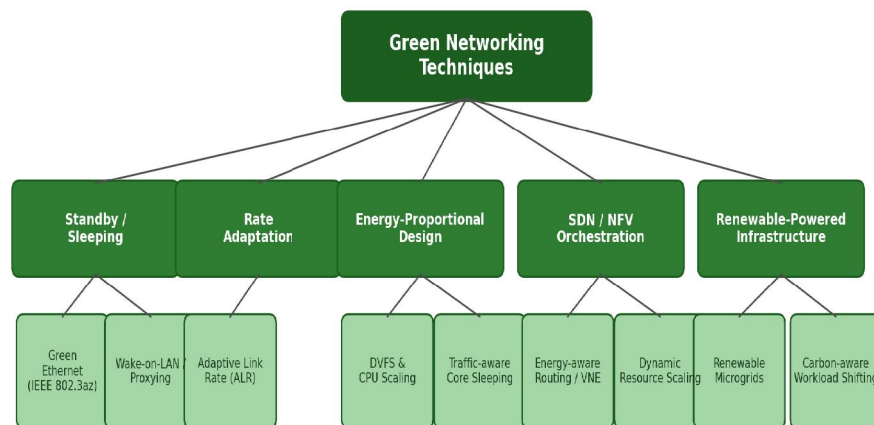


softwarization: Software-Defined Networking (SDN), Network Function Virtualization (NFV), and network slicing (NS) and introduced a taxonomy of energy efficiency strategies by looking at the control and management- and orchestration (MANO) layers. GreenNFV [12] is a deep-reinforcement-learning framework that simultaneously optimizes CPU scaling, cache allocation and packet-batching parameters for virtualized network functions while meeting SLA requirements, with energy-efficiencies up to 50% for evaluated scenarios. Singh et al. [9] studied the role of SDN, NFV and Cloud-RAN in achieving greener cellular networks, and suggested an integrated framework for operators. From the radio-access side, Larsen et al. [8] gave an overview of energy-saving methods for 5th generation and beyond (5G and beyond) RANs, such as sleep modes, load-adaptive hardware, and renewable-power integration, while Lorincz et al. [13] specifically addressed the tuning of network slicing for energy efficiency in the 5th generation networks. Bolla et al. studied the enablers of zero-carbon network slices and vertical edge services for 6G [10] and Ahmadi et al. gave an overview of the 6G Open RAN challenges and opportunities for sustainability [11]. Most comprehensively, Kamran et al. [4] reviewed energy-aware design principles for 6G networks, documenting the standardization efforts in 3GPP, ITU, and IEEE, and introducing an energy information function which presents detailed energy and carbon-source information to the network decision-making process, which is similar to the cross-layer feedback loop proposed in Section V of this paper. Infrastructure related, Cao et al. [7] gave a systematic survey towards carbon-neutral data centers, which classifies the related literature into three groups: workload scheduling, cooling, and integration of renewable energy; and Radovanović et al. [22] described a production carbon-aware computing system that can reorder and relocate flexible compute workloads to peak the periods of grid carbon intensity. Alsharif et al. [6] and Upadhye et al. [14] provided an overview of energy-efficient computing and Green IoT, respectively, listing edge/fog/cloud energy-saving methods for massive IoT deployments. This paper is an extension and synthesis of this rapid development of literature on energy techniques in the RAN, data-center, and IoT layers, explicitly linking the different energy techniques at RAN level, data-center level, and IoT level under a unified carbon-intensity feedback mechanism which was not simultaneously presented in previous surveys.

III. TAXONOMY OF GREEN NETWORKING TECHNIQUES

To sum up the aforementioned surveys, today's green networking approaches fall into five main categories, as shown in Fig. 2: (i) standby and sleeping techniques, (ii) rate and capacity adaptation, (iii) energy-proportional design, (iv) SDN/NFV-based orchestration, and (v) renewable-based infrastructure. They are explained below.

Taxonomy of Green Networking Techniques



Synthesized from recent green-networking, SDN/NFV, and 6G energy-efficiency surveys published 2022-2025.

Fig. 2. Synthesizing recent (2022-2025) green-networking work, SDN/NFV work, and 6G energy-efficiency work to taxonomy green networking techniques.



A Standby and Sleep Based Techniques These methods take advantage of the fact that most networks are not fully utilized; links, ports and even whole radio cells are often idle or lightly loaded. The 6G surveys recently have classified base-station sleep states based on the turn-on time, where micro-sleep, light sleep, and deep sleep have the lowest, medium, and highest power draw, respectively, but the highest turn-on latency in the deepest state. Larsen et al. [8] also list the discontinuous transmission/reception (DTX/DRX) schemes and the advanced multi-domain sleep adaptation of 5G-and-beyond RANs over time, frequency, antenna, and power domains. The most important design challenge is transition latency: a too aggressive sleep policy may adversely affect responsiveness or go against service level agreements if not properly bounded. B. Rate Adaptation Rate- and capacity-adaptation techniques adjust the speeds of links, or the power with which they transmit data, or the processing frequency of the data at one link to another to match demand at that particular moment. Azzino et al. [15] consider design choices to reduce latency and power usage in 6G networks, such as lowering the transmit power for the base station when the latency requirement is low, and intelligently switching between a macro layer and a pico layer by changing the traffic. C. Energy-Proportional Design Energy-proportional design is the belief that the power used by a device should correlate to the energy being consumed, with the power consumption being near 0 when the load is near 0. Cao et al. [7] talk about this as one of its fundamental levers to achieve carbon neutral data centers by consolidating servers and switches according to the workload and turning off the capacity that is not being used, or rather powering it down or turning it into a different use. This course covers the concepts and tools of D. SDN/NFV-Enabled Green Networking. SDN decouples the control plane from the data plane to provide the logically centralized controller with a global view of the topology and traffic. This visibility can then be used in energy-aware routing algorithms to use only a small number of active links and devices to route traffic [5]. Alongside this, NFV removes the dependency on dedicated network appliances, so that Virtual Network Functions (VNFs) can be scaled up dynamically to accommodate network demand and be concentrated onto fewer physical servers, as shown by reinforcement-learning-based resource scheduling techniques that can reduce the energy consumption of NFV by up to 50% compared to traditional dedicated appliances [12] (Nine et al. 2017). Singh et al. [9] demonstrate the advantages of SDN, NFV and Cloud-RAN by providing the orchestration layer to coordinate energy-aware decisions at a network scale, instead of a device scale. E. Renewable-Powered Infrastructure The last one is not about how much energy is used, but the source of energy. The cost of renewables is declining [16] and, as a result, it is now becoming more economically feasible to power base stations, data centers, and network points-of-presence with solar, wind, or other renewables, to help lower carbon intensity of network operations directly. Renewable integration is also growing as a lever, as noted in GSMA's mobile network energy-efficiency benchmark [17] and the closely related technique, carbon-aware workload shifting as detailed by Bolla et al. [10] in a new paper, which shifts delay-tolerant traffic or compute jobs to data centers or times when the grid's carbon intensity is lowest.

IV. MOTIVATION

project aims to determine the energy and carbon footprints associated with ICT.

The scale of the problem determines the priorities for green networking research. Table I presents representative estimates of the global electricity consumption and GHG emissions of the ICT sector from industry and academic sources, published in recent papers and reports (2023-2024). Although methodologies and systems boundaries vary with the reported ranges accordingly, all sources note two common trends: the absolute energy demand is growing, with data centers and AI workloads contributing significantly to this growth, and the percentage of the demand supplied by electricity from sources with lower carbon or renewable energy is a significant factor in emissions reduction [1]-[3], [18], [19].

Metric	Estimate	Source
Global ICT electricity use (2024)	~1,100 TWh (~4% of global total)	Ericsson Mobility Report [3]



Metric	Estimate	Source
Global ICT electricity use (2020)	~940 TWh	Ericsson Mobility Report [3]
Data-center electricity growth	~9% per year since 2020 (AI-driven)	Ericsson Mobility Report [3]
Network-segment electricity growth	~2% per year since 2020	Ericsson Mobility Report [3]
ICT share of global GHG emissions	1.5% - 4% (lifecycle-inclusive)	World Bank/ITU [1]; Bieser et al. [2]
Required ICT emissions cut by 2030	45% (to align with 1.5 °C pathway)	ITU Green Digital Action [18]
Global electricity demand growth (data centers & AI)	Sharp acceleration through 2026	IEA Electricity 2024 [19]

TABLE I. Representative Estimates of ICT Energy and Carbon Footprint

V. PROPOSED CROSS-LAYER SUSTAINABLE NETWORKING FRAMEWORK

The techniques used in Section III all lower the necessary amount of energy in their respective areas of the network, but when coordinated among the various layers, the benefit of these techniques is maximized. This section puts forth a four-layer cross-layer architecture, as illustrated in Fig. 3, with a common telemetry and carbon-intensity feedback loop, following the Energy Information Function concept standardized in 3GPP and ITU forums for 6G.

Proposed Cross-Layer Sustainable Networking Framework

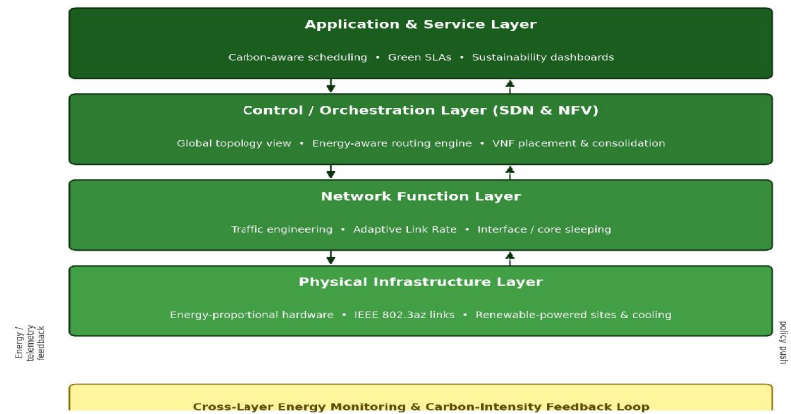


Fig. 3. Proposed cross-layer sustainable networking framework linking application intent to physical infrastructure through a shared energy and carbon-intensity feedback loop.

The Application and Service Layer represents the sustainability intention – for instance, a carbon-aware Service Level Agreement (SLA) that permits extra latency, but routes the network traffic through sustainably powered infrastructure, as recently practiced with energy-aware service classes for 6G [4]. This intent is turned into specific decisions on routing, placement and scaling, with the help of a global topology and telemetry view, realized via SDN controllers and NFV orchestrators [5], [9]. The decisions are made by the Network Function Layer, which performs traffic engineering, adaptive link rate and interface or core sleeping [8, 15]. The third and final piece of the Physical Infrastructure Layer is the energy-proportional hardware and renewable energy-powered facilities that end up making up the network's energy consumption and carbon intensity [7], [16]. Operating like carbon-aware computing systems currently in use in data-centers, a bidirectional feedback loop carries the energy usage and utilization of the system upward, and policy and



control decisions downward, allowing the system to adapt in near real-time to changes in traffic demand, hardware availability, and the carbon intensity of the grid.

VI. APPLICATIONS AND CASE STUDIES

A. Green 5G/6G Radio Access Networks

Radio Access Networks (RANs) are the most energy consuming component of mobile networks, and recent estimates have shown that over 70% of an operator's energy is used in the RAN, with power amplifiers accounting for approximately 80% of a base station's energy usage [4]. Some of the green 5G/6G technologies discussed by Larsen et al. [8] involve enhanced sleep modes, load-adaptive hardware configurations, and renewable-power integration; green energy network slicing is discussed by Lorincz et al. [13] as a technique that right-sizes radio resources based on the traffic class served. Bolla et al. [10] talk about enablers for zero-carbon network slices in 6G and Ahmadi et al. [11] write about the new sustainability opportunities and new energy-orchestration challenges posed by the disaggregated architecture of Open RAN. Predictive traffic analysis is now beginning to be adopted by AI technology to turn off cells in advance when there is not much demand, like during the night in an area with mostly residential coverage [4].

B. Sustainable Data Centers

Data centres include compute, storage, an internal network, and the energy consumption of the IT equipment, power delivery, and cooling. Cao et al. [7] categorize sustainable data-center operation into three areas: workload consolidation, advanced cooling, and renewable-energy integration; Alkrush et al. [20] critically review the technologies that are typical in data centers, including air cooling, free cooling, and liquid cooling; and Sun et al. [21] survey emerging coolants for high-density AI server racks, such as nanofluids. On the operational level, Radovanović et al. [22] introduce a production carbon-aware computing system to move flexible compute workloads in time and space to reduce carbon emissions while avoiding additional hardware investment. Data-center and AI-related electricity consumption is projected to continue to grow in the future, and this is expected to be a crucial component of any sustainable energy strategy [19].

C. Green iot and edge computing

Duty-cycled radios, low power wide-area network protocols, and energy-harvesting sensor nodes are encouraged by the growing number of battery-powered IoT devices. Alsharif et al. [6] give an extensive overview of energy-efficient edge, fog, and cloud computing techniques that facilitate sustainable massive IoT deployments, such as energy-aware scheduling, task offloading, and selective resource activation, whereas Upadhye et al. [14] give an overview of Green IoT more widely and suggest the use of renewable-powered edge nodes, and AI-assisted resource management for future directions. Edge computing extends these device-level approaches at the network level: processing information at the edge lowers the amount of energy- and latency-consuming traffic flowing over backhaul and core-network links, but also spreads out (and potentially replicates) compute resources which also need to be managed energy-efficiently.

D. SDN/Cloud-Based Green Orchestration

In cloud and multi-tenant network settings, SDN controllers can be used to engineer energy-aware traffic, saving on the amount of active substrate required for the traffic of multiple tenants, while still maintaining guarantees of network isolation and performance. In both the works presented by Nine et al. [12] and Singh et al. [9] it is shown that decisions made by the orchestration layer can significantly reduce energy usage without breaking the SLA for the services. This, together with the ability to place workloads according to the carbon footprint of clouds around the globe [22], enables operators to move compute and traffic toward regions and windows of reduced grid carbon intensity, thus demonstrating the connection between network level orchestration and actual emissions reductions.

VII. COMPARATIVE ANALYSIS

Fig. 4 summarizes the ranges of energy-savings reported in the literature reviewed in Sections III and VI for 2022-2025. The upper bound reported for renewable-powered infrastructure is the greatest, as it has the potential to achieve operational carbon emissions close to zero at favorable renewable generation location [16], [17] however this can only



be achieved if capital investment is possible and renewable generation can be provided locally. Direct reduction of energy consumption techniques include VNF consolidation [12] and AI/ML optimization [4, 22] with the largest reported energy savings, and sleep/standby modes [4, 8] and SDN traffic engineering [5, 9] provide substantial, widely applicable energy gains. These numbers are more representative than absolute: realized savings will vary greatly based on traffic patterns, hardware generation and the degree of aggressiveness used to tune a technique given the latency and reliability requirements.

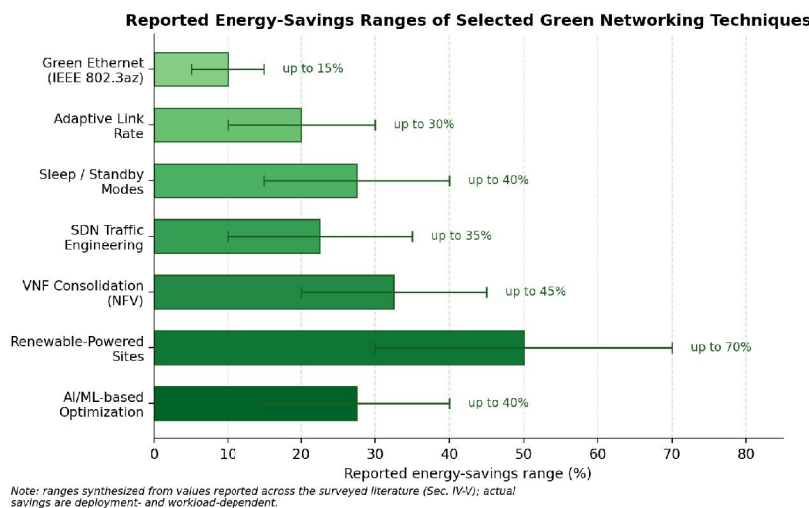


Fig. 4. Reported energy-savings ranges for selected green networking techniques, synthesized from the surveyed 2022-2025 literature

Table II summarizes the qualitative trade-offs of each technique category along three practical dimensions: implementation complexity, latency impact, and maturity/deployment readiness.

Technique Category	Implementation Complexity	Latency Impact	Deployment Maturity
Standby / Sleep Modes	Low	Moderate (wake-up delay)	High - actively standardized [4]
Rate Adaptation	Low-Medium	Low	Medium [15]
Energy-Proportional Design	Medium	Low-Moderate	Medium [7]
SDN/NFV Orchestration	High	Low (if well-engineered)	Medium-High [5], [9], [12]
Renewable-Powered Infrastructure	High (capital-intensive)	None (siting only)	Growing rapidly [16], [17]

TABLE II. Qualitative Comparison of Green Networking Technique Categories

VIII. CHALLENGES AND OPEN ISSUES

- Performance-energy trade-off: If the energy saving policies are too aggressive (deep sleep, low clock rate), the latency or jitter may increase which may violate the strict requirements for 5G/6G and real-time applications [4] [8].
- Inconsistent measurement: Energy-efficiency metrics differ between vendors and studies; GSMA's benchmarking initiative shows how methodological differences make it difficult when doing a fair comparison of techniques, and verifying claimed savings [17].



The energy overhead of training and running the AI/ML for energy-aware optimization can be a significant burden, as highlighted by recent 6G surveys as an open research challenge [4].

- Rebound effect from the growth of AI and data: Efficiency can be balanced by the exponential growth of the traffic associated with the proliferation of IoT devices, video streaming and the training and inference of AI [2], [3], [19].
- Stranded assets: Relatively high initial costs needed to retrofit existing infrastructure with energy-proportional hardware or renewable energy solutions and long payback periods [16].
- While Open RAN can provide new sustainable opportunities, the disaggregation of RAN functions to different vendors and/or sites can create challenges for coordinated energy management.

IX. FUTURE RESEARCH DIRECTIONS

- AI-native energy orchestration: Reinforcement-learning-based controllers for jointly optimizing routing, VNF placement, and sleep scheduling, utilizing real-time carbon-intensity signals, e.g., via production systems like carbon-aware computing for datacenters [22].
- Standardized energy-information exposure: Proposal to extend the Energy Information Function concept and the subsequent 3GPP/ITU work items to cover the exposure of energy usage and its source type across the network domains [4].
- 6G-native sustainability: Incorporating energy and carbon awareness into the 6G design from the beginning, such as the zero-carbon network slicing [10] and sustainable 6G Open RAN design [11] rather than adding sustainability features to the existing 5G design.
- Advanced data-center cooling and materials: Further development of liquid-cooling, immersion cooling, and the development of nanofluid cooling technologies to lower the auxiliary energy consumption of high-density AI server rack cooling systems [20] and [21].
- Energy harvesting, renewable energy-powered edge nodes, and resource management using AI for large-scale deployment of Green IoT nodes [6], [14].
- Cross-sector renewable integration: Increased network operator and renewable-energy market coupling due to cost of generation reductions [16] and sector benchmarking efforts [17].

X. CONCLUSION

As well, networking has become a strategic priority for network operators, cloud providers and policy makers, and has grown from a field of specialized research to a key element of the sustainability agenda. This paper surveyed the key classes of green networking techniques that were identified in the literature during 2022-2025, ranging from standby and rate-adaptation methods at the device level, energy-proportional design principles, SDN/NFV-enabled orchestration, to renewable-powered infrastructure, and proposed a cross-layer framework to coordinate these techniques by their shared use of an energy and carbon-intensity feedback loop. The comparative literature evidence shows that a single technique alone is not enough: the greatest and most permanent benefits come from using a combination of device efficiencies and intelligent, carbon-aware orchestration—and a real move towards renewable resources. With AI workloads and global connectivity continuing to increase, the rest of the gaps will be closed – standardized energy-information exposure, AI-native orchestration, and management of the AI/ML energy-overhead trade-off – and it will be these latest hurdles that will determine whether the networking industry can expand sustainably or simply efficiently. The next step would be to validate the proposed framework in the field in various operator networks as well as conditions of renewable energy availability.

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