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Energy- and Sustainability-Aware Network Performance Evaluation: A Systematic Review of Metrics, Techniques, and Future Trends

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تقييم أداء الشبكات المُدرِك للطاقة والاستدامة: مراجعة منهجية للمقاييس والتقنيات والاتجاهات المستقبلية

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Abstract:
As communication networks continue to expand, energy consumption and environmental impact have emerged as critical dimensions of network performance that traditional evaluation approaches often overlook. This paper presents a systematic review of energy- and sustainability-aware network performance evaluation, integrating classical performance indicators such as throughput, latency, jitter, and packet loss with energy and environmental metrics including energy efficiency (bit/Joule), power consumption, carbon footprint, and water footprint. The study reviews how benchmarking, monitoring, simulation, and modeling techniques incorporate energy and sustainability considerations, and provides a comparative analysis of the trade-offs between conventional performance and energy efficiency. A decision-oriented framework is proposed to map network scenarios to the most suitable sustainability-aware evaluation metrics and techniques. The paper further examines emerging enablers Artificial Intelligence, Software-Defined Networking, Network Function Virtualization, Digital Twins, and energy-aware 6G design and their role in sustainable performance evaluation. Finally, the study highlights the relevance of these approaches to the Arab region and Libya in particular, where energy scarcity and reliance on fossil fuels make energy-aware networking especially significant. The findings show that the environmental impact of networks depends not only on the underlying technology, but also on how performance is measured, governed, and optimized.

Keywords: Network Performance Evaluation, Energy Efficiency, Green Networking, Sustainability, Carbon Footprint, Digital Twin, 6G.

الملخص
مع التوسع المستمر في شبكات الاتصالات، برز استهلاك الطاقة والأثر البيئي كبُعدين حاسمين من أبعاد أداء الشبكات كثيراً ما تُغفلهما طرق التقييم التقليدية. تقدّم هذه الورقة مراجعة منهجية لتقييم أداء الشبكات المُدرِك للطاقة والاستدامة، بحيث تدمج مؤشرات الأداء الكلاسيكية كالإنتاجية والكمون والاضطراب وفقد الحزم مع مقاييس الطاقة والاستدامة مثل كفاءة الطاقة (بت/جول) واستهلاك القدرة والبصمة الكربونية وبصمة المياه. وتستعرض الدراسة كيف تدمج تقنيات القياس المرجعي والمراقبة والمحاكاة والنمذجة اعتبارات الطاقة والاستدامة، مع تحليل مقارن للمفاضلات بين الأداء التقليدي وكفاءة الطاقة.

كما تقترح الورقة إطاراً إرشادياً يربط سيناريوهات الشبكة بأنسب المقاييس والتقنيات المُدرِكة للاستدامة. وتتناول الدراسة كذلك التقنيات الناشئة الذكاء الاصطناعي، والشبكات المُعرَّفة برمجياً، وافتراضية وظائف الشبكة، والتوأم الرقمي، وتصميم شبكات الجيل السادس المُدرِك للطاقة ودورها في التقييم المستدام للأداء. وأخيراً تُبرز الورقة أهمية هذه المقاربات في المنطقة العربية وليبيا خصوصاً، حيث تجعل ندرة الطاقة والاعتماد على الوقود الأحفوري من الشبكات المُدرِكة للطاقة أمراً بالغ الأهمية. وتُظهر النتائج أن الأثر البيئي للشبكات لا يعتمد على طبيعة التقنية وحدها، بل أيضاً على كيفية قياس الأداء وحوكمته وتحسينه.

الكلمات المفتاحية: تقييم أداء الشبكات، كفاءة الطاقة، الشبكات الخضراء، الاستدامة، البصمة الكربونية، التوأم الرقمي، الجيل السادس.

Introduction

Communication networks have become the backbone of nearly every economic and social activity, and their scale continues to grow with the proliferation of mobile devices, cloud services, and the Internet of Things. This growth has a cost that was, for a long time, largely invisible in performance evaluation: the energy consumed by networks and the environmental impact of that consumption. Studies of the electricity used by the information and communication technology (ICT) sector indicate that, without sustained efficiency improvements, networks and data centres could account for a substantial and rising share of global electricity demand and greenhouse-gas emissions in the coming years [1, 3, 19]. Energy and sustainability have therefore moved from peripheral concerns to central design and operational objectives for modern networks [7, 23].

Network performance, however, is still most often evaluated through a traditional set of key performance indicators (KPIs) bandwidth, throughput, latency, jitter, packet loss, and reliability that describe the quality of service delivered to users but say nothing about the energy expended in delivering it [14, 6]. In parallel, a large body of work on green networking and energy-efficient communications has developed metrics and techniques for reducing energy consumption, but this work has largely evolved separately from the mainstream literature on performance evaluation [4, 12, 13]. The result is a gap: performance is measured without reference to energy, and energy is studied without a unified connection to the established practice of performance evaluation. Consequently, there is no consolidated view that treats energy and sustainability as first-class dimensions of network performance, integrated with the traditional indicators and with the techniques benchmarking, monitoring, and simulation used to measure them.

This paper addresses that gap through a systematic review of energy- and sustainability-aware network performance evaluation. Rather than proposing a new protocol or algorithm, it synthesizes existing knowledge to answer how energy efficiency and environmental sustainability can be integrated, systematically, into the evaluation of network performance. Four research questions structure the review: (RQ1) which metrics capture the energy and sustainability dimensions, and how do they relate to the traditional indicators; (RQ2) how do the main evaluation techniques — benchmarking, monitoring, simulation, and modelling incorporate energy and sustainability; (RQ3) what are the trade-offs between conventional performance and energy or sustainability, and how can they be assessed; and (RQ4) which emerging enablers support sustainable evaluation, and what challenges remain open.

The main contributions of this paper are: (i) a consolidated classification of traditional, energy, and sustainability metrics that treats energy and environmental impact as integral dimensions of network performance; (ii) a review of how benchmarking, monitoring, and simulation incorporate energy and sustainability, with a comparison along that dimension; (iii) an explicit trade-off analysis and a decision-oriented framework mapping network scenarios to the most suitable evaluation metric and technique; (iv) an examination of emerging enablers artificial intelligence, software-defined networking, digital twins, and energy-aware 6G design; and (v) a discussion of the relevance of energy-aware networking to the Arab region and to Libya in particular.

Material and methods

This study follows the Systematic Literature Review (SLR) methodology, applying a structured and reproducible procedure to identify, select, and synthesize the relevant literature. The process comprised four stages: defining a search strategy, applying inclusion and exclusion criteria, and carrying out a staged study-selection procedure, each described below.

Search strategy

The literature was gathered from major peer-reviewed digital libraries and indexing services, namely IEEE Xplore, the ACM Digital Library, SpringerLink, ScienceDirect (Elsevier), and Google Scholar, supplemented by reputable scientific journals in communications and sustainability. The search combined performance-evaluation terms with energy and sustainability terms, using queries such as "network performance evaluation", "energy efficiency", "green networking", "energy-aware", and "sustainability metrics", joined with Boolean operators. The search covered publications from 2011 to 2026.

Inclusion and exclusion criteria

Studies were included when they were peer-reviewed journal articles, surveys, or conference papers, written in English, published within the 2011–2026 window, and relevant to at least one research question; priority was given to survey and review articles and to highly cited works in reputable international venues. Studies were excluded when they fell outside the scope of the review, were not peer-reviewed, were inaccessible in full text, were duplicates, or were superseded by a more complete or more recent version by the same authors.

Study selection process

The selection proceeded in stages consistent with the PRISMA approach: identification of records, duplicate removal, title-and-abstract screening against the criteria, and full-text eligibility assessment. Table 1 summarizes the stages and the progressive narrowing of the study set.

Table 1 Study selection process summary.

Stage	Action	Outcome
1. Identification	Retrieve records from digital libraries using the search terms	Initial pool of candidate studies
2. Duplicate removal	Remove records appearing in more than one source	Deduplicated set
3. Screening	Screen titles and abstracts against inclusion/exclusion criteria	Reduced set of relevant studies
4. Eligibility	Assess remaining studies in full text for relevance and quality	Set of eligible studies
5. Inclusion	Retain studies that pass full-text assessment	Final evidence base for synthesis

Note: insert the record counts at each stage once the final search is executed; a PRISMA flow diagram may be added.

Results and discussion

Network performance and sustainability fundamentals

Network performance refers to the effectiveness and efficiency with which a network delivers data between communicating endpoints. Traditionally, it has been characterized through a set of KPIs — bandwidth, throughput, latency, jitter, packet loss, and reliability — that form the basis of most monitoring and evaluation practice [14, 6]. These indicators remain essential but describe only one dimension of network behaviour. As networks scaled to billions of connected devices, the energy they consume, and the environmental consequences of that consumption, grew too large to be treated as external side-effects; without sufficient efficiency gains, the sector could account for a substantial and rising share of global electricity demand and emissions [1, 3, 19]. Energy efficiency has therefore become a first-class design objective rather than an optional refinement [7]. Evaluating performance in a way that reflects this reality requires extending the traditional KPIs with metrics that explicitly capture energy use and environmental impact.

Energy and sustainability metrics

Energy metrics quantify the resources consumed in producing a given level of performance. Power consumption, in Watts (W), describes the instantaneous rate of power draw, whereas energy consumption, in Joules (J) or kilowatt-hours (kWh), describes the total energy used over an interval. The most widely adopted efficiency measure is energy efficiency in bits per Joule (bit/J); its reciprocal, energy per bit (J/bit), expresses the energy cost of transporting a single bit [17, 12]. These measures underpin much of the research on energy-efficient wired and wireless networks [5, 13, 2]. Sustainability metrics extend the analysis to the environmental footprint: the carbon footprint (gCO_2e) translates energy consumption into greenhouse-gas emissions and depends on the carbon intensity of the supply, so the renewable-energy share is itself a metric [1, 19]; the water footprint captures water used in generation and cooling; electronic waste reflects the life-cycle burden of hardware replacement; and, within data centres, Power Usage Effectiveness (PUE) measures infrastructural overhead, with data-centre energy modelling now a mature area [10, 21]. Together these connect network operation to the wider sustainable-development agenda [23].

Composite metrics and the performance–energy relationship

The central insight motivating sustainability-aware evaluation is that performance and energy cannot be optimized in isolation, because improving one dimension often degrades another. This is captured by composite metrics that normalize performance by energy for example, throughput per Watt (bps/W) — and, more fundamentally, by the family of green trade-offs relating energy efficiency (bit/J) to spectral efficiency (bit/s/Hz), deployment efficiency, and delay [25]. Pushing spectral efficiency toward its limits typically raises energy consumption, so a design that appears optimal under a throughput-only metric may be far from optimal once energy is counted [9, 7]. These trade-offs are structural rather than incidental [8]. Table 2 consolidates the metrics into a single classification.

Table 2 Classification Of Network Performance And Sustainability Metrics.

Category	Metric	Unit / Expression	What it captures
Traditional performance	Bandwidth / Throughput	bit/s (bps)	Capacity vs. data actually delivered
	Latency / Jitter	ms	Transmission delay and its variation
	Packet loss / Reliability	% / availability	Data integrity and service continuity
Energy	Power consumption	Watt (W)	Instantaneous power draw
	Energy consumption	Joule (J) / kWh	Total energy used over time
	Energy efficiency	bit/Joule	Data delivered per unit of energy
	Energy per bit	Joule/bit	Energy cost of each transmitted bit
Composite	Throughput-per-Watt	bps/W	Performance normalized by power
	Energy vs spectral efficiency	bit/J vs bit/s/Hz	Core green trade-off
Environmental / sustainability	Carbon footprint	gCO_2e	Greenhouse-gas emissions
	Water footprint	Litre (L)	Water used in generation and cooling
	Electronic waste	kg	Hardware end-of-life burden
	Renewable energy ratio	%	Share of clean energy in supply
	Power Usage Effectiveness	ratio	Data-centre facility energy overhead

Energy-aware evaluation techniques

Benchmarking

Benchmarking evaluates performance by running a defined, repeatable workload under controlled conditions so that options can be compared on an equal footing. Energy-aware benchmarking extends this by measuring the power and energy consumed while the reference workload executes, expressing the result as an efficiency figure such as bits per Joule [17, 12]. Its strength is fairness and reproducibility, which suits it to evaluating hardware, configurations, and protocol choices [5, 2, 7]; its limitation is that a controlled synthetic workload does not fully reflect live-traffic variability.

Monitoring

Monitoring evaluates performance by observing a real, in-service network as it carries actual traffic. Conventional monitoring focuses on flow- and packet-level indicators [14]; energy-aware monitoring adds power and energy data from device instrumentation, management interfaces, or facility meters, and in data centres extends to PUE, with measured consumption now well modelled [10, 21]. Its advantage is realism it captures actual behaviour, including temporal patterns that controlled benchmarks cannot reproduce making it the natural technique for operational audits and environmental reporting [19, 23]; its costs are instrumentation overhead and the difficulty of attributing consumption to specific causes.

Simulation and modelling

Simulation and modelling evaluate performance by computing the expected behaviour of a represented network, allowing scenarios to be explored before, or instead of, deployment. Energy-aware simulation augments performance models with power and energy models, estimating the energy — and hence carbon — of a proposed configuration in advance [10]; this is valuable for large-scale or forward-looking questions where direct measurement is impractical [25, 18]. Its central limitation is that results are only as accurate as the underlying models and assumptions, so simulation is most credible when calibrated against benchmark or monitoring data which is why the three techniques are complementary rather than competing.

Comparative analysis and trade-offs

Benchmarking, monitoring, and simulation differ in where their measurements come from and thus in how faithfully they represent energy and environmental impact. Table 3 summarizes the comparison along dimensions relevant to sustainability-aware evaluation.

Table 3 Comparison of evaluation techniques along the sustainability dimension.

Aspect	Benchmarking	Monitoring	Simulation / Modelling
Data source	Controlled test workload	Live, in-service network	Model / synthetic scenario
Energy realism	Moderate — reproducible but synthetic	High — actual consumption over time	Variable — depends on model fidelity
Metrics captured	Energy efficiency (bit/J), power per configuration	Real energy use, temporal patterns, PUE	Estimated energy, carbon, what-if footprints
Main strength	Fair, repeatable comparison	Ground-truth operational insight	Pre-deployment exploration
Main limitation	Limited operational realism	Instrumentation cost; hard to isolate causes	Accuracy bounded by assumptions
Best-fit question	Which option is more efficient under equal load?	How much energy does the network use now?	What would this change cost in energy/carbon?

The trade-offs can be stated as recurring tensions between a conventional performance objective and an energy or sustainability objective. Table 4 lists the principal ones and the composite indicator that exposes each; the energy-efficiency versus spectral-efficiency relationship is the most fundamental [25, 9, 7, 8].

Table 4 Principal performance–energy trade-offs.

Performance objective	Competing energy/sustainability objective	Indicator that exposes the trade-off
Higher spectral efficiency (bit/s/Hz)	Lower energy consumption	Energy efficiency vs spectral efficiency (bit/J)
Higher throughput	Lower power draw	Throughput-per-Watt (bps/W)
Lower latency / always-on service	Sleep modes and idle-state saving	Energy per bit under delay constraint (J/bit)
Greater coverage / capacity density	Lower total and embodied energy	Energy and carbon per unit area or per user
Higher reliability / redundancy	Reduced hardware and e-waste footprint	Carbon and e-waste per reliability level

Bringing Tables 2–4 together yields a practical question: given a network scenario and the objective that matters most, which metric should be prioritized and which technique is best placed to measure it? Table 5 maps representative scenarios to a recommended primary metric and technique. The framework is indicative rather than prescriptive: real studies often combine techniques, and the recommended metric is the one that should lead, not the only one reported. Because every technique has a characteristic blind spot, credible sustainability-aware evaluation is usually multi-method; several emerging enablers notably digital twins and AI-assisted monitoring aim precisely at narrowing the gaps between the techniques [15, 20].

Table 5 Recommended metric and technique by scenario.

Network scenario / priority	Recommended primary metric	Recommended technique
Comparing two devices or configurations	Energy efficiency (bit/J)	Benchmarking
Understanding a live network's real energy use	Power / energy consumption, PUE	Monitoring
Assessing a change before deployment	Estimated energy and carbon footprint	Simulation / Modelling
Data-centre or cloud infrastructure	PUE and energy per workload	Monitoring + Modelling
Mobile / RAN capacity planning	Energy vs spectral efficiency	Simulation + Benchmarking
Reporting environmental impact	Carbon footprint, renewable ratio	Monitoring + life-cycle modelling

Future trends

Several emerging technologies aim to narrow the gaps between the evaluation techniques and to make energy- and sustainability-aware evaluation more accurate, continuous, and predictive. Artificial intelligence and machine learning are increasingly applied to both the measurement and the optimization of network energy use: learning-based models can infer consumption from operational data, forecast demand, and drive control policies that reduce energy without violating performance targets, with a rapidly expanding design space of AI models for green communications toward 6G [20], building on the broader use of machine learning across networking functions [6].

Software-defined networking (SDN) and network function virtualization (NFV) change the substrate on which performance and energy are measured, enabling workload consolidation, powering down idle resources, and dynamic reconfiguration [16]; this programmability gives finer-grained visibility into where energy is consumed, though virtualization overheads must themselves be accounted for. Digital twins are among the most promising developments: a continuously updated virtual replica synchronized with live data allows energy and sustainability outcomes to be estimated and optimized proactively [15], combining the realism of monitoring with the flexibility of simulation. Finally, 6G design is being approached with energy efficiency as a primary objective, treating energy and spectral efficiency jointly and incorporating advanced sleep modes, lean carrier design, and machine-learning-based control [18, 24]; recent work explicitly frames the advancement of green mobile networks around standardized energy-related metrics and operator-level sustainability frameworks [11, 22]. The common thread is a shift from evaluating energy after the fact to designing and measuring for sustainability from the outset.

Comparison with prior reviews and limitations

Valuable surveys have addressed parts of this territory but have generally treated performance evaluation and energy or sustainability separately. Surveys of green networking and energy-efficient communications catalogue techniques for reducing consumption without connecting them to performance-evaluation practice [4, 7], while recent surveys on AI for green communications and on radio-access-network energy efficiency deepen the energy dimension but focus on specific technologies rather than evaluation methodology [20, 18, 11]. The distinctive contribution of this review is to integrate the two strands. Table 6 positions this review against representative prior surveys along four dimensions.

Table 6 Comparison with prior surveys.

Survey	Performance evaluation techniques	Energy & sustainability metrics	Trade-off & decision framework	Regional context
Bianzino et al. [4]	Partial	Partial	No	No
Buzzi et al. [7]	No	Yes	Partial	No
Mao et al. [20]	No	Yes	Partial	No
López-Pérez et al. [18]	Partial	Yes	Partial	No

Survey	Performance evaluation techniques	Energy & sustainability metrics	Trade-off & decision framework	Regional context
De Domenico et al. [11]	Partial	Yes	Partial	No
This review	Yes	Yes	Yes	Yes

The review is subject to limitations. As a qualitative synthesis, it does not perform a quantitative meta-analysis or produce its own benchmark measurements; its comparisons draw on results reported in the primary studies. The search was restricted to English-language, peer-reviewed literature, which may omit relevant work in other languages or in grey literature. Finally, energy- and sustainability-aware networking is evolving quickly, and some very recent developments — particularly around sustainable 6G — may not yet be fully reflected in the surveyed body of work.

Regional context: Libya and the Arab region

Although energy- and sustainability-aware evaluation is a global concern, its significance is heightened where energy is scarce, costly, or carbon-intensive. In much of the Arab region, and in Libya in particular, electricity supply depends heavily on fossil fuels and can be subject to reliability constraints, so the energy a network consumes is not only an environmental matter but an operational and economic one. A network optimized purely for throughput and latency, without regard to energy, may be difficult to sustain, whereas evaluation that foregrounds energy efficiency and environmental impact aligns directly with local realities. Energy-aware benchmarking can inform equipment choices where every watt has a tangible cost; energy-aware monitoring can expose consumption patterns that matter under constrained or intermittent supply; and simulation can help plan expansions of digital infrastructure while anticipating their energy and carbon implications. The broader argument that ICT should be assessed against sustainable-development criteria [23] is especially pertinent where the transition toward renewable energy is still developing.

Conclusion

This paper has presented a systematic review of energy- and sustainability-aware network performance evaluation, motivated by the observation that traditional evaluation leaves the energy and environmental dimensions of network behaviour largely unmeasured. It consolidated traditional, energy, and sustainability metrics into a single classification; reviewed how benchmarking, monitoring, and simulation incorporate energy and sustainability and compared their strengths and blind spots; made the performance–energy trade-offs explicit and proposed a decision-oriented framework mapping scenarios to the most appropriate metric and technique; and examined emerging enablers artificial intelligence, software-defined and virtualized networking, digital twins, and energy-aware 6G design that are moving the field from after-the-fact accounting toward evaluation by design. The overarching conclusion is that the environmental impact of a network depends not only on the technology it employs but on how its performance is measured, governed, and optimized. Treating energy and sustainability as first-class dimensions of performance is therefore both a methodological and a practical imperative globally, and with particular urgency in energy-constrained regions such as Libya and the wider Arab world. Future work should focus on unified, standardized energy-measurement methodologies, on maturing digital-twin and AI-based approaches that unite operational and predictive evaluation, and on extending sustainability-aware evaluation across the full life cycle of network infrastructure.

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