IOWN GLOBAL FORUM

Toward a Unified Metric for Energy Efficiency and Sustainability in Next-Generation Networks: An IOWN Global Forum's Perspective

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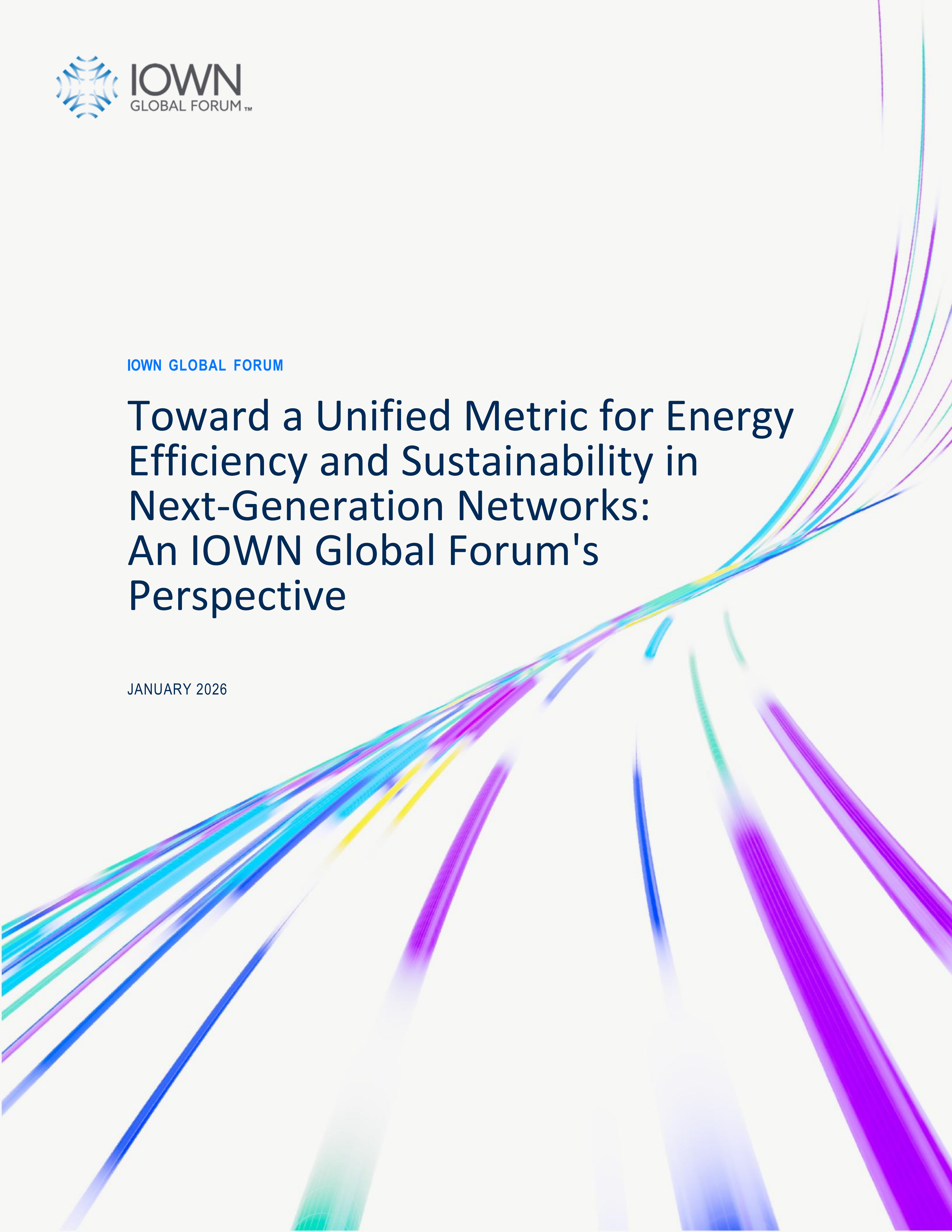

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Contents

Abstract

The exponential growth of digital services and infrastructure, driven by transformative technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and the emerging metaverse, necessitates a fundamental paradigm shift in how we approach, manage, and critically measure energy consumption. The Information and Communication Technology (ICT) sector's energy demand and associated carbon footprint are on an unsustainable trajectory. Recognizing this challenge, the Innovative Optical and Wireless Network Global Forum (IOWN Global Forum) aims to pioneer a sustainable, ultra-high-performance future network, positioning energy efficiency as a non-negotiable cornerstone of its vision. However, a significant barrier persists: the current landscape of energy efficiency metrics is deeply fragmented. Disparate standards and Key Performance Indicators (KPIs) proliferate across numerous organisations—ISO (management systems), IEC (electrical installations), IEEE (temporal emissions), ITU-T (telecom networks), and ATIS (network equipment)—alongside domain-specific metrics for data centers (PUE/DCiE), networks (TEER, NCIe), and compute/storage. This fragmentation critically impedes holistic assessment, prevents meaningful cross-domain comparisons, and thwarts effective, system-wide optimization efforts.

This report presents a comprehensive, in-depth analysis of the existing standards and metrics, exploring their historical context, methodologies, strengths, and inherent limitations. It meticulously identifies and dissects the critical challenges in achieving metric harmonization, delving into definitional inconsistencies, pervasive boundary conflicts, the complexities introduced by multi-tenancy and virtualization, data quality and accessibility issues, and the difficulties in comparing KPIs across vastly different technological layers. Building upon this analysis and grounded in the specific requirements of the IOWN Global Forum ecosystem—including All-Photonics Network (APN) and Data-Centric Infrastructure (DCI); this report proposes a Unified Metric framework.

This multi-layered framework aims to provide a consistent, concise, scalable, and actionable approach to measuring both energy efficiency and broader sustainability impacts. It encompasses component-level, system-level, service-level, and sustainability-level perspectives, integrating and normalizing existing metrics where possible. By establishing clear criteria aligned with overarching sustainability goals (GHG reduction, renewable energy use, circular economy principles) and outlining a strategic roadmap towards standardization and implementation, this report provides a foundational blueprint for IOWN Global Forum to lead the global effort in developing a common language for energy efficiency, thereby enabling the realization of a truly sustainable digital future.

1. Introduction

The proliferation of digital infrastructure has intensified the need for standardized energy measurement across data centers, compute systems, and transport networks. Current energy efficiency standards are fragmented across multiple organisations, creating challenges for comprehensive energy management and comparison. This study examines the landscape of relevant standards bodies including ISO, IEC, IEEE, ITU-T, and ATIS, analyzing their existing Key Performance Indicators (KPIs) and frameworks to identify pathways toward a unified energy metric system. Current standards, while valuable, suffer from fragmentation, inconsistent definitions, and incompatible measurement boundaries. This report analyzes existing metrics from major standards bodies (ISO, IEC, IEEE, ITU-T, ATIS) and industry initiatives (ITI Council, FinOps, CNCF) to propose a harmonized framework that enables cross-domain energy efficiency comparisons.

While organisations like ITU-T have developed specific metrics such as Power Usage Effectiveness (PUE) for data centers, IEEE has introduced standards for electricity emissions calculations, and ATIS has advanced network and lifecycle metrics, significant gaps remain in creating interoperable measurements across different infrastructure types.

The convergence toward a single metric framework requires harmonization of measurement methodologies, standardization of baseline parameters, and development of scalable assessment tools that can accommodate the diverse operational characteristics of modern digital infrastructure.

2. Purpose and Scope

This document aims to serve as a foundational reference for IOWN Global Forum in its quest to define and promote a unified approach to measuring energy efficiency and sustainability. Its core purpose is to establish a unified, standardized framework for measuring and comparing energy efficiency across diverse network infrastructures. The objectives include:

- **Review Existing Standards:** Analyze energy efficiency metrics from ITU-T, ATIS, IEEE, ISO, ETSI, IETF, OIF, ITI Council, FinOps, and CNCF (e.g., PUE, TEER, NCIe).
- **Identify Challenges:** Address inconsistencies in definitions, methodologies, operational contexts, multi-tenancy complexities, and evolving standards that hinder metric comparisons.
- **Develop Unified Metric:** Propose a comprehensive metric accommodating varied network scenarios, enabling clear comparisons through standardized measurements and normalization.
- **Align with Sustainability Goals:** Ensure integration with broader sustainability targets (GHG emissions, renewable energy use, Scope 1/2/3) and compatibility with management systems such as ISO 50001.

- **Guidance for Implementation:** Outline practical steps for adoption, recommending pathways for standardization, stakeholder engagement, and phased integration into both legacy and future digital infrastructure ecosystems.

The scope of this report encompasses the energy efficiency and sustainability metrics relevant to the core infrastructure envisioned by IOWN Global Forum: All-Photonic Networks, Data-Centric Infrastructure (including its compute, storage, and networking facets), and its relationship with advanced wireless networks. While end-user devices are part of the ecosystem, the primary focus here is on the network and data center/cloud infrastructure.

3. Current Landscape of Energy Efficiency Standards and Metrics

International standards bodies play a central role in shaping energy efficiency practices across digital infrastructure. Each organisation contributes by developing metrics and frameworks that address specific domains, ensuring a coordinated global approach.

3.1. International Standards Bodies and Their Contributions

3.1.1. ISO 50001: Energy Management Systems

ISO 50001 establishes a process-orientated framework for organisational energy management, emphasizing continual improvement through policy development, target setting, and data-driven decision-making. While effective for facility-level energy audits, it lacks technical specificity for IT equipment and network infrastructure.

ISO 50001:2018 provides a framework based on the High-Level Structure (HLS) common to other ISO management systems (like 9001 for Quality and 14001 for Environment), facilitating integration. It requires organisations to:

- Develop a policy for more efficient use of energy.
- Fix targets and objectives to meet the policy.
- Use data to better understand and make decisions about energy use.
- Measure the results.
- Review how well the policy works.
- Continually improve energy management.

As companies such as webscallers typically adopt ISO 50001, its impact relies on the specific Energy Performance Indicators (EnPIs) the organisation chooses. It forces a data-driven approach but doesn't prescribe which ICT metrics to use, highlighting its complementary role.

3.1.2. IEC 60364-8-1: Electrical Installation Efficiency

This standard aims to optimize electrical consumption within a facility. It considers factors like transformer efficiency (higher efficiency classes reduce no-load and load losses), conductor sizing (larger cables reduce I2R losses but increase cost), motor efficiency (for pumps and fans in cooling systems), lighting, and measurement points.

IEC′s classification system (EE0–EE5) evaluates electrical installations based on 23 parameters, including cable losses and power factor correction. The EE classes (EE0-EE5) provide a benchmark. Though designed for buildings, its principles inform data center design - e.g., optimizing substation placement to reduce energy losses in hyperscale facilities. However, its static efficiency classes fail to account for dynamic workloads in cloud environments.

Critical for data center power train design. A 1% improvement in electrical distribution efficiency can save megawatts in a hyperscale facility. However, it doesn't address IT load or dynamic power management.

3.1.3. IEEE 1922.2: Temporal Electricity Emissions

IEEE′s standard introduces time-aware emissions calculations, enabling "temporal carbon accounting" and recognizing that grid carbon intensity fluctuates hourly. This enables precise tracking of Scope 2 emissions for cloud providers using regionally variable energy mixes. For instance, a data center in France (nuclear-powered) would report lower nightly emissions than one in Germany (coal-dependent).

It specifies data formats and methodologies for correlating electricity consumption data with time-stamped grid emissions factors. This allows for calculating emissions not just based on how much energy was used, but when.

Enables "carbon-aware" computing. Cloud providers like Google and Microsoft use similar principles to shift non-urgent compute tasks to times or locations with lower grid carbon intensity, demonstrably reducing reported Scope 2 emissions without necessarily reducing energy consumption. It is vital for validating "24/7 Carbon-Free Energy" goals.

3.1.4. ITU-T L.1310 and L.1333: Telecommunications Metrics

This is arguably the most comprehensive suite for telecom networks.

- L.1300 Series (Energy Efficiency): L.1310 (Equipment - defines granular energy efficiency metrics for broadband equipment, mandating throughput-per-watt measurements for DSLAMs, GPONs, and routers.), L.1320 (Networks), L.1325 (Mobile Networks), L.1350 (Data Centers). They provide methodologies for measuring energy consumption under different load levels (e.g., 0%, 10%, 30%, 50%, 100%) and define metrics, often focusing on data volume per energy unit (Bytes/Joule) or its inverse (Joule/Byte).
- L.1333 (NCIe): As discussed, kgCO2e/GB. Aims to be a high-level indicator.

- L.1330 (Energy efficiency measurement and metrics for telecommunication mobile networks) provides a set of metrics for the assessment of energy efficiency (EE) of telecommunication (TLC) mobile networks, together with proper measurement methods.
- L.1331 (Assessment of mobile network energy efficiency) aims to provide a better understanding of the energy efficiency of mobile networks. The focus of this Recommendation is on the metrics and methods of assessing energy efficiency in operational networks.
- L.1350 (Energy efficiency metrics of a base station site) contains basic definitions of energy efficiency metrics, to evaluate the energy efficiency of a base station site.
- L.1351 (Energy efficiency measurement methodology for base station sites) describes and establishes requirements for energy efficiency measurements applicable to base station sites.
- This Recommendation describes:
    - Measurement points definitions;
    - Conditions of measurement;
    - Instrumentation requirement;
    - Reporting requirement;
    - Use of a monitoring system.
- This Recommendation can be used as a conformity assessment standard for Recommendation ITU-T L.1350.
- L.1400 Series (Sustainability & Circular Economy): L.1470 (GHG Trajectories for ICT sector alignment with Paris Agreement), L.1480 (AI impact), L.1020-1024 (Circular Economy for ICT).
- L.1410 deals with environmental life cycle assessments (LCAs) of information and communication technology (ICT) goods, networks and services. It is organized in two parts: Part I: ICT life cycle assessment: framework and guidance, and Part II: "Comparative analysis between ICT and reference product system (Baseline scenario); framework and guidance". Part I deals with the life cycle assessment (LCA) methodology applied to ICT goods, networks and services. Part II deals with comparative analysis based on LCA results of an ICT goods, networks and services product system, and a reference product system.

These provide the building blocks for network efficiency measurement. L.1310 is crucial for equipment selection, while L.1333 is key for sustainability reporting. Complementing this, L.1333 introduces the Network Carbon Intensity Energy (NCIe) metric, which links data traffic to CO_2 emissions using real-time energy source data. These metrics are critical for telecom operators transitioning to 5G/6G networks, where base station energy consumption varies by 40% between peak and idle states. IOWN Global Forum must align with or enhance these established recommendations.

3.1.5. ATIS TEER and Next G Alliance Metrics

ATIS-0600015.13.2017 defines TEER as Telecommunications Energy Efficiency Ratio (TEER) standardizes throughput-per-Watt comparisons for network hardware, enabling vendor-neutral benchmarking of Wi-Fi access points and radio base stations. It specifies precise test setups and load profiles (often based on packet sizes and traffic types) to ensure comparability.

The Next G Alliance introduces lifecycle greenhouse gas (GHG) tracking, requiring manufacturers to quantify embodied carbon from semiconductor fabrication through system decommissioning. In its “Roadmap to 6G,” the Alliance establishes sustainability and energy efficiency as baseline design principles for next-generation networks. This expands conventional TEER metrics to encompass full lifecycle assessments, explicitly including embodied carbon accounting.

TEER is a practical tool for US operators but highlights the challenge of standardized load profiles not reflecting real-world dynamics. The 6G and IOWN Global Forum’s focus on lifecycle is critical and must be part of any unified metric.

3.1.6. ETSI, IETF, OIF Contributions

ETSI Technical Committee for Environmental Engineering (TC EE) has produced a number of specifications related to power consumption and energy efficiency. The Technical Committee is responsible for defining the environmental and infrastructural aspects for all telecommunication equipment and its environment, including equipment installed in subscriber premises. Wherever possible this will be achieved by references to existing international standards.

- ETSI ES 202 336-12 Environmental Engineering (EE) Part 12: ICT equipment power, energy and environmental parameters monitoring information model.
- ETSI ES 203 199 Environmental Engineering (EE); Methodology for Environmental Life Cycle Assessment (LCA) of Information and Communication Technology (ICT) goods, networks and services (ITU-T L.1410 aligned).
- ETSI ES 203 228 Environmental Engineering (EE); Assessment of mobile network energy efficiency (ITU-T L.1331 aligned).
- ETSI TS 103 786 (Energy Efficiency measurement of 5G base station)
- ETSI: ES 203 237 (Green Abstraction Layer), ES 202 336 (Data Centre KPIs), EN 303 470 (Broadband Equipment). ETSI often works closely with ITU-T and provides European-centric standards and technical reports, frequently focusing on practical implementation and testing.
- IETF: RFC 7603 (EMAN) defined an information model and MIBs for monitoring energy, but adoption has been limited. More recent efforts in areas like Computing in the Network (COIN) or protocol optimization implicitly touch on efficiency.
- OIF: Crucial for APN. OIF Implementation Agreements (IAs) specify low-power modes for coherent optical modules (e.g., 400ZR/ZR+), power targets for co-packaged optics

(CPO), and efficient electrical interfaces, directly impacting the component-level efficiency.

3.2. Industry Initiatives and Consortia

3.2.1. The Green Grid (PUE/DCiE Originator)

A non-profit consortium dedicated to advancing energy efficiency in data centers and business computing ecosystems. While famous for PUE, it has also developed metrics like

$$\text{Carbon Usage Effectiveness (CUE)} = \frac{Total\ Carbon\ Emissions}{IT\ Energy}$$

and

$$\text{Water Usage Effectiveness (WUE)} = \frac{Annual\ Water\ Usage}{IT\ Energy}$$

PUE's success demonstrates the power of a simple (even if flawed) metric to drive industry change. CUE and WUE show the need to look beyond energy to broader sustainability.

3.2.2. ITI Council

Represents the global tech industry, advocating on policy issues. Its sustainability work often focuses on harmonizing international regulations, promoting voluntary agreements, and standardizing product energy/environmental disclosures (like eco-labels).

Influences the regulatory environment and international trade rules affecting ICT equipment, making it an important stakeholder for standard adoption.

3.2.3. FinOps Foundation (Sustainability WG)

Focuses on bringing cloud financial management practices to sustainability. This means attributing carbon footprints to specific applications, teams, or products within a cloud environment. It promotes tools and practices for "carbon-aware cost optimization."

Drives the demand for granular, real-time carbon data from cloud providers and tools, pushing for better allocation – a key challenge in multi-tenant environments.

3.2.4. Cloud Native Computing Foundation (TAG ENV Sustainability & Kepler)

The CNCF TAG ENV Sustainability aims to "measure, understand, and minimize the environmental impact of cloud-native infrastructure and applications." Kepler is its flagship project, using eBPF to capture system-level metrics and applying ML models to estimate the energy consumption of individual Kubernetes pods, offering unprecedented granularity in virtualized environments.

Kepler provides a potential tool and methodology for addressing the multi-tenancy challenge (Section 5.3) and providing data for higher-level metrics (like SCI or S2E).

3.2.5. Green Software Foundation (GSF)

A non-profit organisation formed by major tech companies and non-profits, focused on reducing the carbon emissions of software. Its core output is the Software Carbon Intensity (SCI) specification.

SCI Definition $$SCI = \frac{((E \times I) + M)}{R}$$

Where:

- E = Energy consumed by the software (kWh).
- I = Location-based marginal carbon intensity (gCO2e/kWh).
- M = Embodied emissions of the hardware (gCO2e).
- R = Functional unit (e.g., per user, per transaction, per minute).

SCI shifts focus to the application layer, recognizing that software design choices profoundly impact energy use and carbon emissions. It aims to make carbon a key software quality attribute. It directly addresses both operational and embodied carbon.

3.2.6. ECOS (Environmental Coalition on Standards)

ECOS is an international NGO with a network of members and experts advocating for environmentally friendly technical standards, policies and laws. ECOS target to ensures the environmental voice is heard when they are developed and drive change by providing expertise to policymakers and industry players, leading to the implementation of strong environmental principles.

3.3. Domain-Specific Metrics: A Deeper Look

Numerous metrics are used to assess data centre efficiency, each of which focuses on distinct performance and sustainability factors. Additional metrics such as Carbon and Water Usage Effectiveness, Green Energy Coefficient, Energy Reuse Factor, and compute/storage-specific benchmarks have emerged to provide a more complete picture, even though Power Usage Effectiveness (PUE) is still the most widely used metric. These metrics demonstrate how difficult it is to gauge true sustainability in data centres, exposing a dynamic environment but also a fragmentation that prevents comprehensive evaluation.

3.3.1. Data Centers

Data centers remain the focal point of sustainability measurement, with metrics evolving beyond basic efficiency to capture carbon, water, renewable adoption, and energy reuse.

- PUE/DCiE: Covered above. Remains dominant but increasingly supplemented.
- CUE/WUE: Carbon and Water Usage Effectiveness. Broaden the sustainability picture beyond just energy. WUE is critical in water-stressed regions.

- Green Energy Coefficient (GEC) defined as $\text{GEC} = \frac{\text{Ttoal Energy Used}}{\text{Renewable Energy Used}}$. Measures renewable energy adoption.
- Energy Reuse Factor (ERF): Covered in Section 4.

3.3.2. Networks

In networks, sustainability metrics focus on the efficiency of transport and access infrastructure, with established measures like TEER and NCIe being complemented by evolving energy-per-performance indicators.

- TEER: Covered above. Primarily for radio/access and some core equipment.
- NCIe: Covered above. A key sustainability indicator.
- Energy Consumption Rating (ECR): Often used in ETSI standards, similar to ITU-T's Bytes/Joule but with specific methodologies. ECR=Data Volume (bit)Energy (J).
- Latency/Joule: A potential future metric, especially relevant for IOWN Global Forum, linking performance and energy.

3.3.3. Compute/Storage

For compute and storage systems, metrics emphasize performance-per-watt across servers, storage arrays, and HPC/AI clusters, with increasing granularity down to container-level energy attribution.

- SPECpower_ssj2008: An industry-standard benchmark measuring performance (Server-Side Java operations) per watt for servers. Provides a standardized comparison but uses a specific workload.
- IOPS/Watt: A common metric for storage systems, measuring Input/Output Operations Per Second per watt. Critical for storage array efficiency.
- GB/Watt: Measures storage density efficiency.
- Kepler: Provides granular energy (Joules) per container/pod.
- FLOPS/Watt: Crucial for High-Performance Computing (HPC) and AI/ML clusters.

This landscape analysis clearly shows a wealth of activity but a critical lack of cohesion. Each metric provides a piece of the puzzle, but no single metric or body provides the complete picture.

3.4. Regulatory requirements

3.4.1. EU legislation for Data Centre Energy Efficiency reporting

COMMISSION DELEGATED REGULATION (EU) 2024/1364,of 14 March 2024, on the first phase of the establishment of a common Union rating scheme for data centres. This EU regulation provides requirements on data centre operators to report energy efficiency metrics of their data centres. The data that must be reported depends on the size of the data centre (based on the data centre's information technology installed power).

Annex II details the KPI's to be measured and measurement methodologies, including ICT capacity indicators and data traffic indicators. Annex III details the Data Centre Sustainability indicators and calculation methodologies such as PUE. Full details of the reporting are found here: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401364#ntr4-L_202401364EN.000801-E0004

4. Core Energy Efficiency Metrics: In-Depth Analysis

4.1. Power Usage Effectiveness (PUE) & Data Center Infrastructure Efficiency (DCiE)

Definition and formulae:

- **Power Usage Effectiveness (PUE):** Ratio of total facility energy to IT energy. The definition ignores workload efficiency and geographic/climatic factors.
    - PUE=IT Equipment Energy/Total Facility Energy
    - PUE is between 1.4–1.6 in modern hyper-scale facilities
- **Data Center Infrastructure Efficiency (DCiE):** Inverse of PUE, focusing on IT energy as a percentage of total consumption.
    - $\mathrm{DCiE} = \frac{\text{Total Facility Energy}}{\text{IT Equipment Energy}} = \mathrm{PEU}^{-1}$

Evolution and Levels - PUE has evolved, with The Green Grid defining PUE Levels 1 (Basic), 2 (Intermediate), and 3 (Advanced), differing in measurement points (Utility feed vs. PDU output) and frequency (Monthly vs. Continuous). This variation means PUE values are not always directly comparable unless the level is specified. PUE has undeniably driven significant improvements in data center cooling and power distribution, pushing the industry towards free cooling, hot/cold aisle containment, and efficient UPS/PDU systems.

However, its primary flaw is its lack of visibility as to what happens within the IT load. It doesn't penalize a facility full of idle servers (or more in colloquial terms "zombie") servers (powered on but effectively not doing any work) and can even be gamed by increasing IT load (which often improves PUE while increasing total energy). Additionally, accounting for climate or the use of renewable energy is not included.

4.2. Telecommunications Energy Efficiency Ratio (TEER)

Definition and Weighted Power:

Telecommunications Energy Efficiency Ratio (TEER): Throughput-per-watt for routers/base stations, however it is based on peak-load assumption. Example: 0.8–1.2 Gbps/W in 5G RAN context.

$$\text{TEER} = \frac{\text{Weighted Power [W]}}{\text{Throughput [Gpbs]}}$$

Where:

- $P_w = \sum_{i=1}^{n} w_i \times Pload_i$ and
- w_i are weighting factors (e.g., w100%=0.5, w50%=0.3, w10%=0.2)
- $Pload_i$ is power at that load.

The specific weights and load points are defined by the standard.

While the ratio provides an excellent manner for comparisons, for example an operator can request a particular minimum TEER value in an RFP and thus forcing vendors to compete on efficiency under predefined conditions.

The standardised load profile is TEER's biggest weakness, because real network traffic is bursty, unpredictable, and rarely matches the defined test profile. Efficiency in the field, especially during off-peak hours, can be much lower compared to peak hours. Furthermore, it doesn't capture the efficiency of the control plane operations or advanced features.

4.3. Network Carbon Intensity Energy (NCIe)

Definition and Calculation:

Network Carbon Intensity Energy (NCIe): Links data traffic to CO_2 emissions using real-time grid data (ITU-T L.1333)

$$NCIe = \frac{V_{total}}{\sum_j E_j \times EF_j} \frac{kgCO_{2e}}{GB}$$

Where E_j is the energy consumed by network element j, EF_j is the emission factor applicable to E_j (which can be temporal and location-based), and V_{total} is the total data volume traversing the defined network boundary.

The parameter directly addresses the carbon aspect of sustainability as it allows progress tracking towards decarbonization goals and can inform "green routing" decisions.

This approach requires extensive data, including granular energy consumption across many network elements and access to accurate, often real-time, emission factors. In addition, defining the system boundary, specifically what counts as "Total Energy" and "Data Traffic"; is both non-trivial and essential for ensuring comparability.

4.4. IT Equipment Utilization Efficiency (ITUE)

ITUE conceptually aims to measure how effectively the IT equipment is using the power it draws.

$$ITUE = \frac{\sum Power_{\ active} + \ Power_{idle}}{\sum Power_{active}}$$

The definition of measuring "active" power vs. "idle" power at a granular level (CPU, memory, storage, NICs) in a dynamic, virtualized environment is extremely difficult. Proxies like CPU utilization are often used, but they don't capture the full picture.

Despite difficulties, the concept drives initiatives like server power management, workload consolidation, and decommissioning of idle servers, which yield significant savings.

4.5. Energy Reuse Factor (ERF)

Definition:

$$ERF = \frac{Total\ Energy\ Consumed}{Reused\ Energy}$$

ERF promotes a circular economy mindset. Waste heat isn't just waste; it's a potential resource. High ERF values can significantly improve a facility's overall environmental profile, even if its PUE isn't world-class. Examples include Meta's Odense data center heating the local community or QScale in Canada providing heat to greenhouses.

ERF is complementary to $\frac{PUE}{TEER}$. A facility should aim for high efficiency and high reuse.

4.6. Energy Reuse Factor (ERF)

- Energy per Bit/Function: Critical for cloud providers but lacks service-specific allocation.
- Capacity per Watt: Evaluates storage efficiency (e.g., 50–80 GB/W for NVMe SSDs) but struggles with cold data

Definition:

$$SCI = R((ExI) + M$$

Enabling developers and architects to make carbon-aware decisions requires tools and frameworks that link workload deployment choices to their environmental impact. Key questions arise in this process: should the feature run continuously or only on-demand, depending on its energy intensity and necessity? Deployment location also matters, as regions with low carbon intensity (“I”) may be preferable even if energy consumption (“E”) is higher, while in other cases a region with high energy usage but lower carbon intensity may still deliver lower overall emissions. Finally, reducing resource requirements (“R”) by optimizing the function’s efficiency can directly lower both energy consumption and carbon impact, reinforcing the importance of energy-efficient design alongside smart workload placement.

Bridges the gap between infrastructure metrics and application performance. It allows businesses to understand the carbon cost of features and services, not just hardware. Its inclusion of 'M' (embodied carbon) is crucial. Its major challenge is obtaining accurate E, I, and especially M data per R.

5. Key Challenges in Metric Harmonisation

This section provides more detailed examples and discussions for each challenge.

5.1. Definitional Inconsistencies and Boundary Conflicts

A data center PUE calculation stops at the network port, while a network NCIe calculation might start there but needs to extend across WAN links to another data center or the end-user. Where is the energy consumed by the edge routers, security appliances, and optical transceivers accounted for? Example: A CDN delivers 1 TB of data. PUE measures the DC energy. NCIe measures the network energy. If the CDN caches heavily at the edge, the DC energy might be low, but the edge network energy could be high. A unified metric needs a consistent end-to-end boundary or clear hand-off points.

System Boundaries - Embodied carbon (M in SCI) requires a cradle-to-gate boundary, while operational metrics use a gate-to-gate or operational boundary. How do we combine these without double-counting or missing key impacts?

Terminology: Is "Throughput" measured at Layer 2, Layer 3, or the Application Layer? Does "IT Equipment" include network switches inside the data center, or only servers and storage? These seemingly minor differences can lead to significant variations in reported metrics.

5.2. Temporal Variability and Workload Dynamics

As IEEE 1922.2 highlights, an NCIe value calculated with an annual average grid emission factor can be wildly different from one calculated with hourly factors, especially in grids with high renewable penetration. A "green" data center might have a high carbon footprint if its peak load coincides with nighttime (when solar is offline) in a fossil-fuel-heavy grid.

Traffic Variability: TEER uses fixed load points, but a real 5G base station might spend 70% of its time in low-load or idle states, where its Gbps/W efficiency is much lower than its TEER rating. A unified metric must account for actual load profiles or use dynamic efficiency curves.

Workload Profiles: An AI training workload has a very different energy profile (sustained high GPU usage) than a web-serving workload (bursty CPU/Network usage). Simply measuring "IT Energy" or "Data Traffic" masks these differences. A meaningful metric needs to consider the type of work being done.

5.3. Multi-Tenancy and Service-Specific Allocation

Virtualization - In a cloud environment, dozens of Virtual Machines (VMs) or hundreds of containers share the same physical server, storage, and network infrastructure. How can we accurately allocate the energy consumed by the shared cooling fans, power supplies, network switches, or even the hypervisor itself to a specific tenant or application?

Cloud/Edge: Cloud providers currently offer only high-level carbon footprint estimates. FinOps is pushing for more granularity, but technical challenges remain. Tools like Kepler are promising but still face errors (e.g., ±5-15%) and don't capture all shared resources (like network fabric or storage arrays).

In the context of IOWN Global Forum the APN offers a solution for network allocation through wavelength isolation, allowing per-tenant energy metering. However, DCI, with its shared CXL memory pools and GPU clusters, presents new allocation challenges.

5.4. Data Quality, Measurement Precision, and Tool Fragmentation

Sensor Accuracy: Power meters have error margins (often ±2-5%). Temperature sensors drift. Aggregating data from thousands of potentially inaccurate sensors can lead to significant uncertainty in final metrics. AI-driven anomaly detection can help identify issues but requires a robust baseline.

APIs & Formats: Each vendor (Cisco, Juniper, Dell, HPE, Intel, AMD) has its own telemetry system and APIs (EnergyWise, Telemetry Interface, Redfish, RAPL). There is no universal standard for exporting granular power, utilization, and performance data, forcing operators to build complex, brittle integration layers.

PUE calculators, network monitors, APM tools, carbon calculators, and tools like Kepler or SCI calculators often operate in silos. A unified metric requires tools that can ingest and process data from all these sources coherently.

5.5. Comparing KPIs Across Diverse Network Components and Layers

Optical versus Wireless: How do we compare the W/Gbps of an APN link with the W/Gbps/km² of a 6G cell site? They serve different functions and have different performance characteristics.

Hardware versus Software: As Network Function Virtualization (NFV) and Software-Defined Networking (SDN) become prevalent, functions move from dedicated hardware (with measurable power draws) to software running on general-purpose servers. How do we measure the energy cost of a virtual router or firewall? This links back to the multi-tenancy challenge.

5.6. Lifecycle Assessment and Scope 3 Emissions

Embodied Carbon i.e. manufacturing semiconductors, building data centers, and laying fiber optic cables consume vast amounts of energy and resources. This "embodied" carbon can often rival the operational carbon footprint over a device's lifetime, yet it is rarely included in traditional efficiency metrics (SCI is an exception).

Supply Chain Data: Calculating embodied carbon requires detailed data from complex, global supply chains, which is often proprietary, unavailable, or unreliable. Standardized methodologies (like Product Environmental Footprints - PEF) are emerging but not yet widely adopted in ICT.

Scope 3: For most ICT companies, Scope 3 emissions (indirect emissions from the value chain, including hardware manufacturing and customer use) are the largest category (often >80%). Measuring and reducing Scope 3 is essential for true sustainability but incredibly complex, requiring industry-wide collaboration and transparency.

Addressing these challenges is essential for developing any credible unified metric. The following sections on the IOWN Global Forum's scope, comparative analysis, and the HUM Framework proposal will require significant elaboration. This includes mapping specific IOWN APN/DCI features to relevant metrics and providing detailed mathematical definitions for HUM levels.

6. Comparative Analysis of KPIs and Metric

Having explored the diverse landscape of existing energy efficiency and sustainability metrics and the challenges in their harmonization, this section undertakes a comparative analysis. The goal is to synthesize the information, highlight the relative strengths and weaknesses of key indicators, and critically identify the gaps that a unified framework, particularly for IOWN Global Forum, must address.

6.1. A Synthesis of Common Metrics: Categorization

The numerous metrics discussed can be broadly categorized based on their primary focus, which helps in understanding their intended purpose and scope:

- Power Metrics (Instantaneous/Peak):
    - Examples: Instantaneous Power (W), Maximum Power (W), Idle Power (W).
    - Focus: Real-time or maximum potential electrical demand.
    - Use: Hardware design limits, power infrastructure sizing, real-time control.

- Energy Metrics (Cumulative):
    - Examples: Cumulative Energy Consumption (kWh), Energy per Bit (J/bit), Energy per Transaction.
    - Focus: Total energy consumed over a period or a specific task.
    - Use: Billing, operational cost analysis, fundamental energy cost of operations.
- Infrastructure Efficiency Metrics:
    - Examples: PUE, DCiE, CUE, WUE, ERF.
    - Focus: Overhead associated with supporting the core ICT function (cooling, power distribution, water, reuse).
    - Use: Facility design and operations optimization.
- ICT Equipment Efficiency Metrics:
    - Examples: TEER, SPECpower, IOPS/W, GB/W, W/Gbps (Optical).
    - Focus: Performance output (throughput, operations) per unit of power for specific hardware.
    - Use: Hardware procurement, component-level design, benchmarking.
- Utilization & Software Efficiency Metrics:
    - Examples: ITUE, Kepler Metrics, SCI.
    - Focus: How effectively IT resources (hardware and software) are being used and the carbon impact of software itself.
    - Use: Virtualization optimization, software development, workload management, application-level carbon tracking.
- Sustainability & Carbon Intensity Metrics:
    - Examples: NCIe, IEEE 1922.2 (Temporal Emissions), GEC, CI (from HUM proposal).
    - Focus: Environmental impact, particularly carbon emissions, relative to activity or energy source.
    - Use: Sustainability reporting, decarbonization strategies, green energy alignment.

This categorization reveals that while many aspects are measured, they often remain within their categories, lacking the cross-cutting links needed for holistic assessment.

6.2. Strengths and Weaknesses Matrix: A Detailed View

To further clarify the trade-offs, the following table provides a comparative analysis of some of the most prominent metrics:

Metric	Primary Domain	Strengths	Weaknesses
PUE	Data Centers	Simple, widely adopted, drives facility infrastructure efficiency.	Ignores IT efficiency, workload, climate; can be gamed.
TEER	Networks	Standardized hardware comparison, vendor-neutral (under test conditions).	Static load profiles, poor reflection of real-world dynamics, hardware-only.

NCIe	Networks / Services	Directly links traffic to carbon, supports sustainability goals.	Data-intensive (energy + grid data), boundary definition is critical/complex.
ITUE	Compute / IT	Focuses on *useful* work vs. idle power, targets IT waste.	Hard to define/measure "useful," lacks standardization, complex in VMs.
ERF	Data Centers / Industry	Promotes circular economy, measures waste heat reuse.	Applicability is site-dependent, doesn't measure initial efficiency.
SCI	Software / Services	Links software to carbon, includes embodied carbon, action-oriented for devs.	Complex calculation, relies on E, I, M data (often estimated), R unit varies.
Kepler	Cloud-Native / Compute	High granularity (pod-level), uses eBPF for lower overhead.	Still model-based (estimation), focuses on K8s, limited scope (CPU/RAM).

This matrix highlights that no single metric is universally superior. Each serves a purpose but comes with significant limitations, especially when considered from a holistic, end-to-end perspective as required by IOWN Global Forum.

6.3. Identifying Gaps in Current Frameworks Relative to IOWN Global Forum Goals

When we evaluate the existing landscape against the specific vision and technological focus of IOWN Global Forum, several critical gaps emerge:

- **Lack of End-to-End (E2E) Metrics:** Most metrics are technological domain-specific. There is no widely accepted standard for measuring the energy efficiency or carbon footprint of a complete end-to-end service that traverses wireless access, APN transport, DCI compute/storage, and software layers. And equally important, an end to end service can span mulitple technology domains and multiple network owners.
- **Inadequacy for Photonic Networks:** Metrics like TEER are not directly applicable to the unique characteristics of APNs. New L1 metrics (J/λ·km, J/switch) are needed, and system-level metrics must account for optical bypass and reduced O-E-O.
- **Challenges with Composable Disaggregated Infrastructure (CDI):** Existing compute/storage metrics often assume server-level granularity. They struggle to capture the efficiency of dynamically composed systems from disaggregated pools of CXL memory, GPUs, and NVMe-oF, or the energy cost of the DCI fabric itself.
- **Poor Handling of Dynamic Behaviour:** Many standard metrics (PUE, TEER) rely on static or averaged values, failing to capture the crucial impact of temporal grid variations (IEEE 1922.2 helps but isn't a full metric) and dynamic traffic/workload fluctuations.
- **Limited Lifecycle (Embodied Carbon) Integration:** While SCI and Next G Alliance acknowledge embodied carbon, it remains extremely difficult to measure and is not integrated into most mainstream operational metrics. For IOWN Global Forum, whose hardware might have a different manufacturing footprint, this is a major gap.

  - **Multi-Tenancy Allocation Black Box:** While Kepler and FinOps initiatives are making progress, there is still no standardized, widely accepted, and accurate way to allocate shared infrastructure (power, cooling, network fabric, hypervisors) energy/carbon costs to specific tenants or services, a crucial need in cloud and future IOWN Global Forum environments.
  - **Integration of Performance and Efficiency:** IOWN Global Forum aims for both high performance (low latency, high bandwidth) and high efficiency. Current metrics rarely capture this relationship explicitly (e.g., Latency×Joules). A unified metric should ideally allow for co-optimization.

7. Developing a Unified Metric

To address the fragmentation of existing energy and sustainability metrics, this section introduces a new multi layered framework based on the Unified Energy Metric (UEM) and the Unified Power Metric (UPM).

The two unified metrics are each suitable for different types of workloads:

- While the Unified Energy Metric is best suited for best suited for transactional, bursty, or batch workloads such as file transfers, AI inference, or API calls,
- The Unified Power Metric is suitable for continuous or persistent services such as video streaming, real-time gaming, or virtual meetings.

Together, they provide a comprehensive, scalable, and actionable approach to measuring energy efficiency and environmental impact across diverse digital infrastructure and service types—including both transactional and continuous workloads.

7.1. Design Principles

Both UEM and UPM are grounded in the following principles:

- End-to-End Scope: Metrics span the full-service path—from user access through APN transport, DCI compute/storage, to application execution.
- Layered Abstraction: Metrics are defined at multiple layers (component, system, service, sustainability) to support both granular optimization and high-level reporting.
- Normalization for Comparability: Metrics are normalized to functional units (e.g., per GB, per user, per session) to enable cross-domain comparisons.
- Temporal and Spatial Sensitivity: Metrics incorporate time-varying and location-specific factors (e.g., grid carbon intensity, cooling efficiency).
- Lifecycle Integration: Both operational and embodied emissions are considered to reflect full environmental impact.

- Multi-Tenancy Awareness: Designed to support energy/carbon allocation in shared environments using isolation techniques (e.g., APN wavelengths, container-level telemetry).

7.2. Unified Energy Metric (UEM)

The Unified Energy Metric captures the total energy and carbon impact of delivering a digital service or workload. It is best suited for transactional, bursty, or batch workloads such as file transfers, AI inference, or API calls, in comparison to the static measurements and fixed test loads in the standards as discussed in the above sections.

Metric Structure

Different layers of the unified energy metric are introduced, from individual components or subsystems for UEM-1, through system efficiency at UEM-2 and carbon intensity at UEM-3, to a sustainability index at UEM-4. Details are listed on the table below.

Layer (Group or Class)	Name	Focus	Example Metric
UEM-1	Component Efficiency	Energy per function	J/bit, FLOPS/W, IOPS/W
UEM-2	System Efficiency	Energy per service unit	J/transaction, J/GB
UEM-3	Service Carbon Intensity	Carbon per service unit	kgCO_2e/GB, kgCO_2e/API call
UEM-4	Sustainability Index	Composite score	SCI + ERF + GEC

General Formula

At the system level (Level 2), a generalized Unified Energy Metric can be expressed as:

$$UEM_{system} = \frac{\sum_i E_i + \sum_j M_j}{R}$$

Where:

- E_j : operational energy component I,
- M_j: Embodied energy or carbon of component j,
- R : Functional output)e.g. BG delivered, Transactions processed)

7.3. Unified Power Metric (UPM)

The Unified Power Metric is designed for continuous or persistent services such as video streaming, real-time gaming, or virtual meetings. It reflects the real-time power demand of maintaining active sessions and is expressed in Watts per user/session.

Metric Structure

Different layers of the unified power metric are introduced, from individual components or subsystems for UPM-1, through system efficiency at UPM-2 and service carbon intensity at UPM-3, to a sustainability index at UPM-4. Details are listed in the table below.

Layer (Group or Class)	**Name**	**Focus**	**Example Metric**
UPM-1	Component Power	Instantaneous power draw	W/stream, W/core
UPM-2	System Power Intensity	Power per active session	W/user, W/session
UPM-3	Streaming Carbon Intensity	Carbon per hour per user	$\mathrm{kgCO_2e}$/hour/user
UPM-4	Real-Time Sustainability Index	Composite score	SPI + SCI + ERF

General Formula

At the system level (Level 2), a generalized Unified Power Metric can be expressed as:

$$\mathrm{UPM}_{\mathrm{system}} = \frac{\mathrm{P}_{\mathrm{total}}}{\mathrm{N}_{\mathrm{active}}}$$

Where:

- P total : Total Power consumed by infrastructure,
- Nactive : Number of concurrent active users or sessions.

For carbon-aware streaming:

$$\mathrm{UPM}_{\mathrm{carbon}} = \frac{\mathrm{P}_{\mathrm{total}} \times \mathrm{EF}(\mathrm{t})}{\mathrm{N}_{\mathrm{active}}}$$

Where:

- EF(t) is the time-varying gred emission factor.

7.4. Integration with IOWN Technologies

IOWN Component	Batch Workloads (UEM)	Realtime Workloads (UPM)
APN:All-Photonics Network	J/λ·km, optical bypass savings	W/λ, per-wavelength metering
DCI: Data-centric Infrastructure	J/transaction across disaggregated compute	W/session for persistent workloads
Software Layer	SCI, Kepler-based energy per function	Real-time power per container/pod

7.5. Implementation Roadmap

To operationalize the Unified Metric, the following steps are recommended:

- Pilot Use Cases: Apply UEM and UPM to representative IOWN Global Forum scenarios (e.g., AI inference, immersive streaming).
- Telemetry Integration: Extend monitoring tools (e.g., Redfish, Kepler, RAPL) to support metric calculation.
- Standards Collaboration: Align with ITU-T, ETSI, IEEE, CNCF, and others.
- Stakeholder Enablement: Provide training and documentation for operators, developers, and vendors.
- Iterative Refinement: Use real-world data to calibrate models and evolve the framework.

7.6. Enhancing the Unified Power Metric with Real-Time Optical Telemetry

The availability of real-time, component-level power reporting in optical network infrastructures – such as transceivers (APT-T), amplifiers, ROADMs, and optical switches – enables a significant advancement in the precision and responsiveness of the Unified Power Metric (UPM). This capability allows for live, per-session energy accounting, carbon-aware routing, and dynamic optimization of network operations.

Real-Time Optical Power Aggregation

With telemetry in place, the total power consumption of the optical layer can be expressed as:

$$P_{Optical}(t) = \sum_{i=1}^{n} P_i^{measured}(t)$$

Where:

- $P_i^{measured}(t)$: Real-time power drawn of the optical component i.

This replaces static or estimated values with live measurements, improving accuracy and enabling temporal granularity.

Updated System-Level UPM

The system-wide power intensity metric becomes:

$$UPM_{System\ (t)} = \frac{P_{optical}(t) + P_{compute}(t) + P_{storage}(t)}{N_{active}(t)}$$

This formulation supports:

- Real-time monitoring of energy per user/session
- Cross-layer optimization (e.g., shifting compute closer to low-power optical paths)

- Energy-aware orchestration in disaggregated infrastructures

- λ

Carbon-Aware Streaming and Routing

By integrating time-varying emission factors:

$$UPM_{carbon} = \frac{P_{total}(t) . EF(t)}{N_{active}(N)}$$

Where:

- EF(t): Grid emission factor at time t.

This enables:

- Carbon-aware routing: Prefer optical paths with lower carbon intensity
- Temporal load shifting: Schedule non-urgent traffic during greener grid periods

Per-Wavelength Power Metrics

In architectures like IOWN's All-Photonics Network (APN), where wavelength-level isolation is possible, a per-wavelength metric can be defined:

$$UPM_{\lambda}(t) = \frac{P_{\lambda}(t)}{N_{\lambda}(t)}$$

Where:

- $P_{\lambda}(t)$: Power used by the wavelength λ;
- $N_{\lambda}(t)$: Number of services or Gbps carried on λ.

7.7. Mathematical Progression Across Metric Layers

To ensure consistency and traceability, both the Unified Energy Metric and Unified Power Metric are designed to aggregate and normalize data progressively from the component level (Layer 1) to a holistic sustainability index (Layer 4). Below are the representative equations for each layer transition. In this example, we analyze the static case. When applying this in real-time measurements, multiple parameters would become time dependent, and sums would be replaced with integrals.

7.7.1. Unified Energy Metric (UEM)

UEM-1 → UEM-2: Component to System Efficiency

Aggregate energy consumption across all components involved in delivering a service:

$$E_{system} = \sum\nolimits_{i=1}^{n} E_i = \sum_{i=1}^{n} P_i \,.\, t_i$$

Where:

- E_i : energy consumed by component i,
- P_i : Power draw of component I,
- T_i : Time of activity.

Then normalize by the functional output R (e.g., GB, transactions):

$$UEM_{system} = \frac{E_{system}}{R}$$

UEM-2 → UEM-3: System to Carbon Intensity

$$UEM_{carbon} = \frac{\sum_{i=1}^{n} E_i \,.\, EF_i}{R}$$

Where:

Ef_i : Emission factor for component I ($KgCO_{2e}$/kWh)

The emission factor in this static example is assumed to be constant.

UEM-3 → UEM-4: Carbon Intensity to Sustainability Index

An overall sustainability index is typically calculated by combining carbon intensity with other sustainability indicators like e.g. an energy reuse factor or a green energy constant as illustrated below:

$$UEM_{sustainability} = w_1 \,.\, UEM_{carbon} + w_2 \,.\, (1 - ERF) + w_3 \,.\, (1 - GEC)$$

Where:

- ERF : Energy Reuse Factor
- GEC: Green Energy Coefficient
- w_1, w_2, w_3 : Weighting factors (sum to 1)

Weighting factors are chosen based on applications and overall impact of the different indicators. This is an example provided for illustrative purposes and not within scope of this document.

7.7.2. Unified Power Metric (UPM)

UPM-1 → UPM-2: Component to System Power Intensity

Aggregate real-time power across all components:

$$P_{system} = \sum_{i=1}^{n} P_i$$

Then normalize by the number of active sessions/users:

$$UPM_{system} = \frac{P_{system}}{N_{active}}$$

UPM-2 → UPM-3: Power to Carbon Intensity

Multiply by time and emission factor:

$$UPM_{carbon} = \frac{P_{system} \,. EF(t)}{N_{active}}$$

Or over a time window T:

$$UPM_{carbon} = \frac{\int_0^T P(t). EF(t)\, dt}{\int_n^T N_{active}(t)\, dt}$$

UPM-3 → UPM-4: Carbon Intensity to Real-Time Sustainability Index

An overall sustainability index is typically calculated by combining the carbon intensity with reuse and renewable indicators like e.g. an energy reuse factor or a green energy constant as illustrated below:

$$UEM_{sustainability} = w_1 \,. UPM_{carbon} + w_2 \,. (1 - ERF) + w_3 \,. (1 - GEC)$$

Weighting factors are chosen based on applications and overall impact of the different indicators. This is an example provided for illustrative purposes and not within scope of this document.

7.8. Temporal Considerations and Measurement Windows

A critical dimension of both the Unified Energy Metric (UEM) and Unified Power Metric (UPM) is time—specifically, how and over what intervals measurements are taken, aggregated, and interpreted. Without clearly defined measurement windows, metrics risk being inconsistent, incomparable, or misleading, especially in dynamic, multi-tenant, and real-time environments.

7.8.1. Measurement Windows in UEM

The UEM framework relies on cumulative energy consumption over a defined time interval:

$$E_i \ = \ \int_{t_0}^{t_1} P_i(t)\,dt$$

Where:

- $[t_o\,, t_1]$ is the measurement window,
- $P_{i(t)}$ is the instantaneous power draw of component i.

This approach allows for:

- Comparability across workloads of different durations
- Temporal normalization of energy efficiency (e.g., J/GB over 1 hour vs. 24 hours)
- Batch workload profiling (e.g., AI training, data processing)

7.8.2. Measurement Windows in UPM

The UPM framework is inherently time-sensitive, as it reflects real-time power intensity. A measurement window defines the averaging period for both power and active session counts:

$$UPM_{system}(t) = \left(\frac{1}{\Delta t}\right)\int_{t}^{t+\Delta t} \frac{\left(P_{total}(\tau)\right)}{N_{active}(\tau)}\,d\tau$$

Where:

- Δt is the measurement window (e.g. 5 seconds, 1 minute)
- $P_{total}(\tau)$: total power at time τ,
- $N_{active}(\tau)$: Number of active sessions at time τ.

This enables:

- Real-time monitoring and alerting
- Adaptive control (e.g., load shedding, quality scaling)
- Carbon-aware scheduling based on grid intensity fluctuations

7.8.3. Recommended Measurement Intervals

Use Case	**Recommended Window**	**Rationale**
Streaming Services	5–10 seconds	Captures user churn and bitrate adaptation
Batch Processing	1–5 minutes	Reflects energy over job duration
AI Inference	1 hour	Suitable for long-running training or inference

Virtual Meetings	10 seconds	Tracks continuous media flow
CDN Delivery	1 minute	Balances granularity with network variability

7.8.4. Harmonization and Reporting

To ensure consistency:

- All metric reports should explicitly state the measurement window used.
- Standardized intervals (e.g., 1 min, 5 min, 1 hour) should be adopted across domains where possible.
- Time-synchronized telemetry is essential for accurate cross-layer aggregation (e.g., aligning APN, DCI, and software metrics).

8. Conclusion

This study has argued that while the current ecosystem of energy-efficiency and sustainability indicators is extensive, it remains methodologically fragmented across facilities, networks, and compute domains, which impedes robust comparison and coordinated optimization. Addressing this limitation requires the consolidation of definitions, measurement boundaries, temporal treatment, and multi-tenant attribution into a coherent, end-to-end methodology that aligns with IOWN Global Forum's APN/DCI paradigm.

To that end, the document proposes a layered, service-oriented framework centered on the Unified Energy Metric (UEM) for transactional and batch workloads and the Unified Power Metric (UPM) for continuous services. The framework is expressly end-to-end, traversing access, APN transport, DCI compute/storage, and the software layer; it normalizes to functional units to enable cross-domain comparability; it incorporates time- and location-varying grid carbon intensity; and it integrates both operational and embodied impacts to better reflect life-cycle burdens. In addition, multi-tenancy is treated as a first-class concern (e.g., wavelength-level isolation in APN; container-level telemetry in cloud-native environments), thereby supporting auditable per-tenant allocation. Collectively, these attributes are intended to reconcile the strengths of established metrics with the cross-layer requirements of modern digital infrastructure.

Operationalizing the framework entails disciplined, incremental practice. Specifically, we recommend piloting UEM/UPM on representative IOWN use cases (e.g., AI inference, immersive streaming), extending telemetry integration across optics, compute, and software (e.g., Redfish, RAPL, Kepler), adopting explicit measurement windows for comparability, and engaging with standards bodies (ITU-T, ETSI, IEEE, CNCF) to promote convergence rather than proliferation. A light-weight governance mechanism within IOWN GF should curate profiles, reference datasets, and conformity guidance, while public PoCs (e.g., via Wavelengths and IOWN GF channels) can accelerate external validation. Taken together, these steps delineate a practical path from principle to practice: a unified, end-to-end measurement system that links architectural choices to demonstrable efficiency and carbon outcomes, and thereby supports carbon-aware orchestration, transparent reporting, and continuous improvement across APN and DCI domains.

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Abbreviations and acronyms

APN: All-Photonics Network

CPO: co-packaged optics

CUE: Carbon Usage Effectiveness

DCI: Data-Centric Infrastructure

DCiE: Data Center Infrastructure Efficiency

ECR: Energy Consumption Rating

ERF: Energy Reuse Factor

GEC: Green Energy Coefficient

GHG: Greenhouse Gas

ITUE: IT Equipment Utilization Efficiency

Kepler: Kubernetes-based Efficient Power Level Exporter

NCIe: Network Carbon Intensity Energy

PUE: Power Usage Effectiveness

SCI: Software Carbon Intensity

TEER: Telecommunications Energy Efficiency Ratio

UEM: Unified Energy Metric

UPM: Unified Power Metric

WUE: Water Usage Effectiveness

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History

Revision	Release Date	Summary of Changes
1	January 2026	Initial Release