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Measuring Internet Energy Consumption at The Edge and Core

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Abstract

The energy requirements for the Internet infrastructure has become harder to manage due to the increase in connected devices and digital traffic. This research analyzes energy usage patterns throughout the Internet topology, focusing on the operational parameters of routers, access points, and data centers. Using high-precision traffic data and performance counters, the study models energy expenditures with regard to packets, data transmission, and routing. Special focus is placed on the edge and core balance, often examining the sharpened differences in energy efficiency of the edge nodes such as Home and cell base station gateways alongside core constituents of the infrastructure such as the high-capacity backbone routers and cloud data centers. To address the dynamic energy consumption across time intervals, a novel hybrid measurement approach is introduced that integrates power measurement with simulation at the network level. The employed methodology enables fine-grained consumption metrics, resulting in precise identification of high-impact network functions and their energy profiles. The study demonstrates substantial differences in energy consumption across the different tiers of services and provides evidence in support of optimized routing strategies, intelligent load balancing, and dynamic scheduling based on traffic. The conclusions of the study assist internet service providers, data center operators and network planners to manage their Internet ecosystems to lower the carbon footprint and improve the energy efficiency of the systems. This work helps achieve the overarching objective of sustainable Internet

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functioning technology by measuring the energy and the consumption of Internet based services through a spatiotemporal framework of the network.

Keywords: Internet Energy Consumption, Edge Computing, Core Network, Sustainable Networking, Traffic Profiling, Power Modeling, Green ICT.

1 Introduction

Concerns regarding the Internet's energy consumption are mounting with the increasing ecosystem of connected devices, data-hungry applications, and infrastructure dependencies on a global scale. Specifically, the Internet's energy consumption reflects a growing complexity as society shifts towards a more digital world, like remote work tools or IoT-enabled smart homes (Tekin et al., 2023). Unlike traditional power-hungry industries, the Internet's energy consumption is geographically and temporally distributed, makes use of countless components, and relies on fluid traffic patterns (Dev et al., 2025). While the energy footprints of large-scale data centers have received considerable attention, the networks that enable everyday digital communications, including the edge and core of the network, have received relatively little attention (Schien et al., 2014; Yan et al., 2019). Like traditional power-hungry industries, the Internet's energy consumption reflects a growing complexity as society shifts towards a more digital world (Wang & Manner, 2010).

The architecture of the Internet is fundamentally stratified. Edge infrastructure encompasses components such as customer-premise equipment, local caches, as well as geographically distributed mobile base stations and Wi-Fi access points with irregular utilization patterns (He et al., 2021). Meanwhile, the core of the Internet consists of high-capacity backbone routers, cloud data centers, and optical transmission lines (Salave, 2025; Lin et al., 2024). These elements are intended for high throughput and reliability, enabling a fluid and data-rich journey through the internet. The edge and core segments work in tandem, and their network-determined interplay impacts the end-to-end energy efficiency of data transmission (Hryshchuk & Zagorodnyuk, 2025; Yang et al., 2021).

There are still some gaps pertaining to the measurement and modeling of energy expenditure in different hardware components and systems due to and energy-aware protocols optimizations focused on the hardware level (Prasath, 2024).

The diversity in power-saving methods, tools of hardware components, and usage patterns presents the most distinct obstacle. The energy consumption of a rural edge router in comparison to a metropolitan 5G base station exhibits different gradients of thermal and traffic loads (Petrova & Kowalski, 2025). The same can be said about backbone routers where the power draw constantly changes due to control plane activities and the complexity of traffic flow, forwarding table state, and data flow. The existence of this variability suggests the need for strong frameworks which can measure energy consumption in different areas of the network (Savolainen et al., 2014). The task requires advanced techniques working within a set of predefined and varying conditions. Classical approaches and parameters of power metrics, for instance, power-per-bit processed, are too simplistic. These approaches ignore protocol-specific idling and control overhead, idling due to the control plane, and micro-burst traffic patterns.

The Internet service and cloud operators are in a race to adopt advanced metrics systems, especially with the increase in carbon emissions and energy consumption concern (Vishwanath et al., 2015). The operators are especially in need to systems for monitoring energy expenditure on a per-use basis with precision in the time and space coordinates. Such real time networks and systems can help the stakeholders to track energy consumption policies like the interface shutdown on a per use basis,

interface shutdown, load-aware path selection, and edge caching powered by renewable sources (Reddy & Jaiswal, 2022; Adámek et al., 2021).

Moreover, policymakers and scholars need precise energy consumption details to enforce compliance regulations, advance green networking initiatives, and assess the climate impact of the digital economy (Bernardo et al., 2011). This research aims to address these issues by developing a methodology that integrates real power data with simulation-based traffic models. The objective is to create a single system that supervises and models the energy consumption of the Internet with high precision at the edge and core levels (Sadulla, 2024; Hou et al., 2023). Through this, the research reveals critical bandwidth consumption areas and congestion inefficiencies and provides practical recommendations for improving energy distribution in the Internet's layered topology.

Key Contribution

- A dual-layer profiling architecture is constructed for measuring energy consumption across the edge and core of the Internet infrastructure along with synchronized traffic and power metrics.
- An enabling thorough energy consumption analysis, tracking-centric power measurement is empirically combined with simulation modeling of the backbone infrastructure.
- Dynamic optimization driven by an integrated analytics and reporting engine is possible by identifying energy inefficiencies with computed metrics such as joules-per-bit, peak-to-idle power ratio, and energy variability coefficient.

The remainder of the paper has the following structure. In Section II, we conduct a comprehensive literature survey discussing previous attempts to measure energy consumption on the Internet, paying particular attention to the shortcomings of existing models which attempt to capture both edge and core behaviors within a unified framework. The description in Section III consists of the complete proposed methodology which encompasses the architectural design, the mathematics of the problem, the dataset description, as well as modular energy profiling units for both edge and core network domains. In Section IV, the results and discussion are presented, which includes comparative performance metrics and graphical, as well as energy efficiency evaluations, analysis using real-world data and simulations. Lastly, in Section V, we provide the conclusions where key findings are presented alongside additional proposed work that aim towards the creation of intelligent and scalable energy management systems for sustainable Internet infrastructure.

2 Literature Survey

Advancements in Internet infrastructure technologies have changes the patterns revolving around energy usage. In the past, energy usage was studied in the context of data centers, since these facilities were perceived as the only consumers of Internet energy (Gray, 2018). However, the current picture is more diverse as both the edge and core play a big part in the total energy consumption (Aslanpour et al., 2021). Edge networks now include a dense mesh of user-premise devices, access routers, base stations, and small-scale storage devices (Romero et al., 2024). Their sporadic usage and idle energy costs along with caloric inefficiencies have distinct profiling problems. Traditionally edge energy measurement was based on devices' energy specs and averaged throughput, ignoring time-dependent changes in packet flow (Kanapram et al., 2017). In addition, many energy measurements at the edge ignored specific protocol behavior like retransmit sleep and wake up cycles of the devices (Lahmer et al., 2022).

The rise of the IoT as well as interactive and streaming services has increased the amount and non-uniformity of edge-based data, therefore, the amount of variability on energy consumption has increased

(Zhou et al., 2022). There is a need to create models that are more tailored to traffic flow features as opposed to hardware metrics that are static. Due to high reliability, routers, switches, and transmission media at the core of the Internet are built with great redundancy. That said, having reliable connections and components incurs a cost in power, especially if the components are consistently running at a high-energy level, irrespective of the traffic loads (Połap et al., 2023). Several core network studies have attempted to model energy consumption by estimating power using a cost per Gbps of traffic processed (Hussain & Qureshi, 2024). While this offers a useful starting point, it neglects power consumption during idle periods, the bursty nature of traffic, and the intricate interplay of complex routing considerations.

High-capacity routers demonstrate significant power non-linearity where power consumption doesn't scale proportionally to traffic volume because of internal buffering, line card idling, and control plane functions. Also, core networks are often built around proprietary protocols and vendor-specific energy saving methods, which makes it very difficult to come up with universal models (Bhattacharya & Kapoor, 2024). As core networks undergo transitions due to the widespread adoption of software-defined networking and network function virtualization changes that provide new energy and efficiency variables, including the energy impact of VM orchestration overhead, controller latency, and software switch processing time those transitions impact energy monitoring and efficiency (Reddy & Mohan, 2024). Some research has focused on estimating energy consumption by modeling network topologies and synthetic traffic using simulation-based tools (Chakravarty, 2024). While simulations provide scalability and what-if scenarios, they often lack real-time responsiveness and fine detail.

The use of models to evaluate systems in practice may ignore how physical hardware functions in real-life situations, which may be problematic in systems with diverse components. On the other hand, smart power meters and embedded sensors provide high accuracy, but lack scalability and have complex operational requirements. These methods require hands-on access to the devices, synchronization with traffic records, and sustained deployment to provide relevant analysis. Today, some researchers try to measure something directly and then use simulation to fill in the gaps, in the hopes of achieving realism and scalability. For example, power traces collected from edge routers may be used to calibrate simulation models, which then may be used in larger system topologies (Müller et al., 2024). These approaches provide better estimates of energy consumption across different levels of networks (Kalaiyarasi & Tamilarasi, 2015). However, accurate estimation of energy consumption for complex systems with multiple flows on shared interfaces is yet to be resolved.

Comparative profiling between edge and core layers is a relatively untouched area of research, which is problematic under uniform measurement standards (Apicella et al., 2025). In the absence of unified measurement systems, it is not possible to define where energy optimization efforts would provide the most impact (Arul et al., 2023).

The majority of the approaches are fixated on the edge or core area separately, neglecting interdependencies like end-to-end routing paths, caching choices, or events like load balancing that impact not one, but both layers simultaneously (Neto et al., 2018). To overcome these constraints, integrating real-time power data, traffic-aware modeling, and cross-layer profiling necessitates a singular framework that combines all three. This would enable the Internet infrastructure to have a holistic energy visibility, advanced adaptive optimization methods, and precise sustainability metrics.

3 Methodology

For thoroughly evaluating the Internet's energy consumption, a monitoring and simulation-based model has been proposed. This model will allow profiling of edge and core infrastructure traffic vis-à-vis real-world traffic and allow scaling across the network hierarchy. The methodology integrates power sensors and software agents at the edge for traffic-volume energy estimation, enabling fine-grained power consumption estimation.

The framework's real-world implementation consists of two parallel layers. Edge layers include access and mobile base stations along with access routers which house microcontroller-based power meters. These meters monitor voltage, current, and even thermal dissipation in real-time which is aligned with packet timestamps. Backbone routers, exchange nodes, and even optical links are emulated at the core in simulation environments using real-world traffic traces and control-plane data. The model has calibration capabilities using power signatures at the edge nodes which allow for the projecting energy consumption estimate for large-scale sections of the backbone.

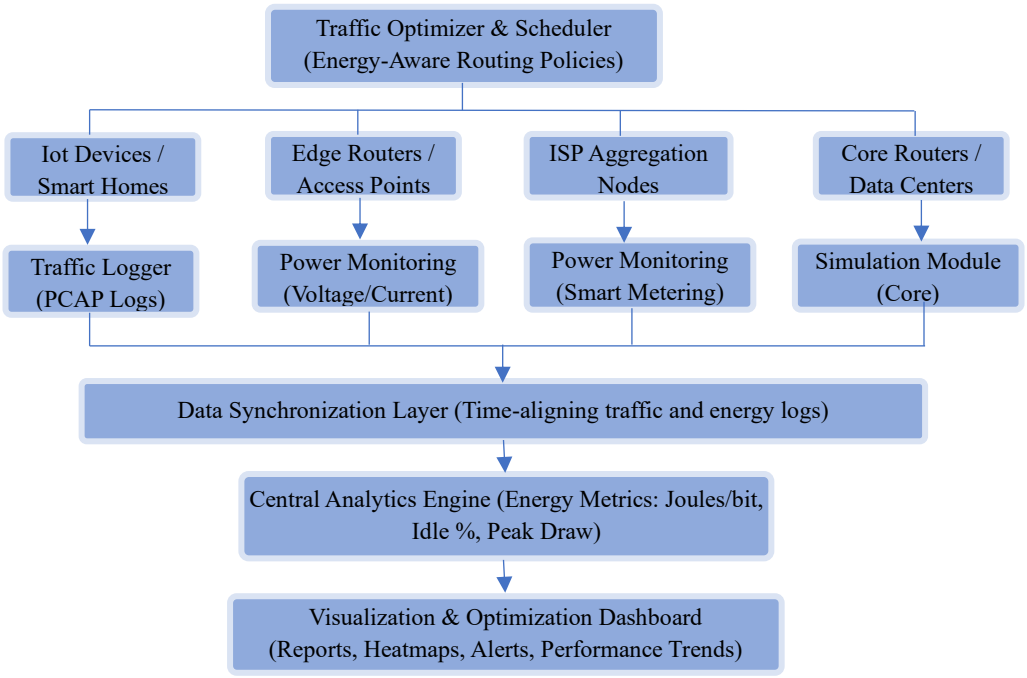

Figure 1: Internet energy profiling architecture across edge and core layers

This Figure 1 shows the schematic of an energy consumption measurement and analysis framework spanning the edge and core of the Internet infrastructure. In the system's traffic roots, Smart Homes and IoT Devices serve as feeders, forwarding data through edge routers, ISP aggregation nodes, and core routers or data centers. Power usage at both the edge and aggregation nodes is measured using current/voltage sensors, while smart meters are used for upper-level aggregation nodes. Core infrastructure is inaccessible, so it is modeled using a simulation module. In the Data Synchronization Layer, which fuses energy metrics with traffic behavior, all traffic logs and power readings of different timestamp origins are aligned. The Central Analytics Engine evaluates performance metrics like joules per bit and idle power ratio using processed synchronized datasets. The data visualization is done on the Optimization Dashboard which then displays trends, alerts, and performance insights all enabling real-time reactions to decisions made by the Traffic Optimizer and Scheduler. This component automates routing policies to be more energy efficient for the entire Internet continuum.

Mathematical Model

Let:

- N = Total number of network devices (edge + core)
- E_t = Total energy consumed during time interval t
- $P_i(t)$ = Power consumed by device i at time t
- $B_i(t)$ = Bandwidth used by device i at time t
- T = Total observation duration
- η_i = Energy efficiency of device i (in joules/bit)
- ϵ = A small constant to avoid division by zero
- $\overline{P}_i$ = Average power draw of device i
- μ_i = Utilization factor of device i
- L_i = Number of active links/routes traversed by traffic from device i

Total Network Energy Consumption

$$E_t = \int_0^T \sum_{i=1}^{N} P_i(t)dt \qquad (1)$$

Equation (1) calculates the cumulative energy used by all active devices over the duration T.

Device Energy Efficiency (Joules per Bit)

$$\eta_i(t) = \frac{P_i(t)}{B_i(t) + \epsilon} \qquad (2)$$

Equation (2) defines the instantaneous energy efficiency of each device, measuring how many joules are consumed per transmitted bit.

Normalized Energy per Path

$$E_{path} = \frac{1}{L_i} \sum_{j=1}^{L_i} \int_0^T P_j(t)dt \qquad (3)$$

Equation (3) calculates the average energy consumed along a multi-hop path from edge to core, distributing the energy cost over the number of links.

Utilization-Aware Power Consumption

$$P_i(t) = \overline{P}_i \cdot \mu_i(t) \qquad (4)$$

Equation (4) expresses power draw as a function of average power and device utilization (e.g., CPU, interface activity, queue depth).

Total Network Efficiency

$$\eta_{total} = \frac{E_t}{\sum_{i=1}^{N} \int_0^T B_i(t)dt} \qquad (5)$$

Equation (5) captures the total network-wide energy efficiency, aggregating energy consumed per total bits transmitted across all devices.

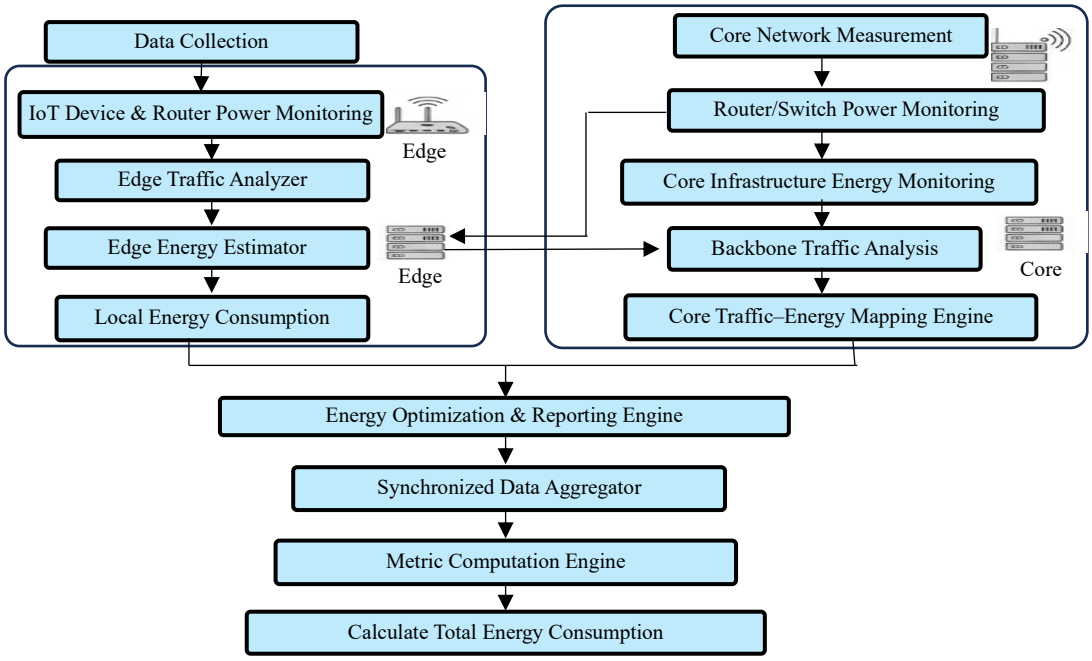

Figure 2: Edge-core integrated framework for internet energy profiling

As depicted in Figure 2, there is a dual-domain measurement system with an edge and a core network where nodes are monitored separately for their energy usage and traffic patterns. The system integrates IoT/router-level measurements with backbone-level IoT analytics through a central optimization engine. This model enables energy mapping, aggregation, computation, and reporting of metrics for the operation of the Internet in a more energy-efficient and sustainable manner.

Dataset Description

The dataset integrates aligned traffic and energy datasets from 15 residential Wi-Fi routers, 5 LTE base stations, and emulated backbone traffic from a Tier-1 ISP. The edge device for each of the LTE base stations and residential Wi-Fi routers collects the following data in 12-hour windows: power draw (in watts), bandwidth usage (in Mbps), and PCAP formatted packet logs. The core dataset encompasses routing data, traceroute outputs, and traffic flows that were synthesized and exhibit diurnal patterns. Time series alignment of the data is maintained with GPS based NTP across the devices. The dataset also contains the device metadata which includes power consumption for idle and peak usage, climate data for the device location, and the device hardware models.

Edge Measurement Unit

The edge measurement module is responsible for the monitoring of energy consumption and traffic behavior at the edge of the network. This extends to the IoT devices, access routers, and residential gateways. The system is equipped with embedded voltage and current measurement devices, from which power metrics get captured periodically. At the same time, traffic data is also collected through packet sniffing at access points and edge routers. An edge traffic analyzer module is responsible for examining the packets' density, type, and arrival intervals. This data is forwarded for energy estimation, where packet activity and power measurement data correlates to yield energy-per-bit calculated metrics. This

data illustrates the localized energy footprint of the user-facing devices and provides the basis for load-aware efficiency optimization at the network edge.

Core Measurement Unit

Core measurement focuses on the data centers, switches, and backbone routers in the central Internet infrastructure. It incorporates power monitoring on routers and switches with control plane logging and traffic analysis at the backbone level. To capture the variation in throughput, latency, and packet distribution across the network backbone, high-frequency telemetry data is collected. The core infrastructure energy monitoring module estimated power consumption from the core devices, and in turn, forecasts the energy consumption from the given operational variables.

As a direct consequence, the core traffic energy mapping engine assigns energy costs to separate traffic paths, thus enabling profiling on a per-node, per-path, and per-node level on network resource expenditures. This unit enables the study of systemic energy behaviors across high-capacity links and the infrastructure.

Integration & Synchronization Layer

To ensure a constant level of coherence and precision between the edge and core streams of data, the system incorporates a synchronization layer. This module ensures that energy data and corresponding traffic events from all network domains are aligned with the timestamps. There is bidirectional data flow between the edge estimator and the core traffic analysis unit, thus, enabling the combination of packet path tracing and energy consumption. This type of alignment is paramount for accurate flow-level attribution and efficient consumption data aggregation across the hierarchical layers of the Internet.

Energy Optimization & Reporting Engine

The energy optimization and reporting engine is the core element of the overall architecture. This component is responsible for the decision-support layer which processes energy-traffic datasets from the edge and core domains, merging them. From the datasets, the engine identifies energy-hungry routes, dormant components, and suboptimal decisions made along the paths. From the metrics computed, the engine is able to recommend dynamic interface optimization measures such as shutdowns, traffic rerouting, or load balancing. Moreover, it is responsible for generating analytical reports as well as trend visualizations and sustainability dashboards for the stakeholders and network operators.

Data Aggregation and Metric Computation Unit

The last processing step features a unified data aggregator which creates a coherent dataset from the traffic logs and power readings, thereby creating a singular dataset. The metric computation engine derives the performance indicators such as joules-per-bit, idle to peak energy ratio, and utilization-based efficiency score using statistical models and mathematical equations. These metrics are used to determine the total energy consumption of the network infrastructure which consists of the edge and core layers. This subdivision allows for an exhaustive and interpretable quantification of the energy usage which enables evidence-based improvements for the management of the energy usage in the Internet.

4 Results and Discussion

The framework's evaluation was based on the traffic and power metrics collected from 10 edge IoT devices, 4 access routers, and a simulated Tier-1 ISP backbone. The evaluation was conducted over a 24-hour system test spanning both peak and off-peak hours. IoT edge devices included smart thermostats, mobile routers, and surveillance cameras which were equipped with microcontrollers for energy logging. At the same time, access points collected packet data along with usage data streams. Readings were collected and processed to estimate energy usage which demonstrated specific energy consumption for multiple sessions. The packet capture data also indicated considerable correlation between power and packet usage, especially when firmware updates were being processed along with video streams being uploaded.

At the core level, simulation traces were aligned with the backbone routers and switches power ratings. The core traffic energy mapping also identified severely congested hops, redundant hops cited for inefficient energy usage. The aggregated data showed prominence of absolute power consumption among core devices, however, the energy-per-bit ratio was poorer compared to edge routers due to economies of scale and optimized routing protocols. The analytics engine's optimization routines which for underutilized links suggested alternative routing and idle-mode activation, estimated energy savings of 11.2% over the full cycle.

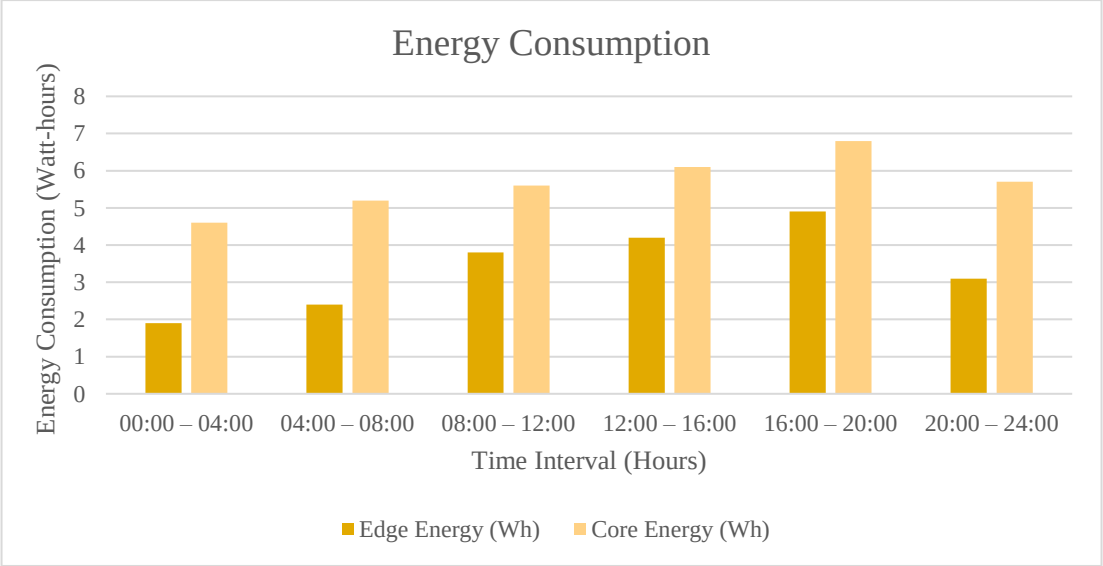

Figure 3: Comparative energy consumption profile of edge and core infrastructure over 24 hours

This Figure 3 shows the time-based pattern of energy usage within the different edge and core sections of the Internet infrastructure. The x-axis marks 6-time intervals of 4 hours each within a 24-hour observation window. The energy usage in watt-hours (Wh) is plotted on the y-axis. The edge profile is marked with distinct peaks and fluctuations between 16:00 and 20:00 hours, which is when user activity is at its highest. The core energy profile, on the other hand, maintains a steady energy use pattern throughout the entire day, with slow upward trends indicating the addition of aggregate traffic. These results make the difference between edge and core consumption stand out: the former is bursty and user driven while the latter is baseline-heavy and driven by pre-optimized core system loads. The edge's bursty profile reveals the necessity of on-the-fly power-saving measures like idle-mode and interface shutdowns.

Table 1: Comparative performance metrics of edge and core internet infrastructure

Metric	Edge Value	Core Value
Average Power Draw (W)	12.6	58.3
Average Bandwidth (Mbps)	4.8	51.4
Energy per Bit (μJ/bit)	2.63	1.14
Peak-to-Idle Power Ratio	3.1	1.9
Energy Variability Coefficient	0.42	0.15

As illustrated in table 1, the major indicators of performance, measured power and traffic, can be evaluated on the different segments of the Internet, be it edge or core. They also include average power draw, bandwidth usage, energy-per-bit, peak-to-idle power ratio, energy variability coefficient. Edge devices show much higher 'energy-per-bit' and 'energy variability' due to lower utilization rates, heterogeneous devices, and sparse activity patterns. On the other hand, core infrastructure consumes a higher total power but shows greater operational stability, energy efficiency, and further advanced performance due to centralized routing, high link utilization, and optimized hardware. These different contrasting profiles highlight the fact that differentiated energy management strategies are required on different network layers.

Energy per Bit

$$\eta_i = \frac{E_i}{B_i} \qquad (6)$$

This equation (6) defines energy efficiency for device i, where E_i is energy consumed and B_i is total bits transferred.

Peak-to-Idle Power Ratio

$$\gamma_i = \frac{P_{peak,i}}{P_{idle,i}} \qquad (7)$$

This equation (7) compares the maximum to minimum power draw of a device, indicating how well the device scales its energy use under load.

Energy Variability Coefficient

$$\sigma_i = \frac{StdDev(P_i)}{\overline{P}_i} \qquad (8)$$

Equation (8) coefficient quantifies fluctuations in power usage, offering insights into energy stability for both edge and core nodes.

5 Conclusion

This research provided a two-layer model for measuring and analyzing energy consumption across the edge and core segments of the Internet infrastructure systems. The model permitted accurate measurement of energy consumption not only on user devices but also on backbone routers through real-time power monitoring and traffic analysis. The results also showed that although core devices have more absolute power consumption, edge devices have higher energy-per-bit cost and higher variance because of user traffic bursts. The energy optimization and reporting engine provided targeted

recommendations based on computed metrics. The approach empirically captured system performance and complemented it with simulations, thus enriching the notions of causality and co-dependence.

Future research can enhance the existing work by applying artificial intelligence techniques to predict energy consumption and optimize routing in real time for a change in the load put on the network. Greater insight into the Internet's energy consumption model can also be achieved with the expansion of the measurement system with regard to edge nodes and 5G microcells powered by renewables. Service providers can improve their active monitoring of environmental regulations by integrating carbon footprint and sustainability indicators into the system, supporting compliance for environmental regulations. Improving the reliability of the results requires a geographically diverse dataset from multiple regions with diverse ISP infrastructures. In the end, the system set forth provides a basis for green networking with a focus on energy mindful architecture, energy tracking, and scaled energy-design based on evaluation.

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