ISSN: 2182-2069 / E-ISSN: 2182-2077

Energy-Aware Protocol Design for Green Internet Architecture

Dr. Kuppala Saritha[1*], Shaik Imam Saheb[2], K.N. Raja Praveen[3], Pravesh Belwal[4], Ayush Gandhi[5], and Dr. Bichitrananda Patra[6]

[1*]Professor, Department of Computer Science Engineering, Presidency University, Bangaluru, Karnataka, India. kuppala.saritha@presidencyuniversity.in, https://orcid.org/0000-0002-5799-2325

[2]Associate Professor, Department of CSE, Vardhaman College of Engineering, Hyderabad, Telangana, India. shaik1764@vardhaman.org, https://orcid.org/0000-0002-7508-7484

[3]Assistant Professor, Department of Computer Science and Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka, India. p.raja@Jainuniversity.ac.in, https://orcid.org/0000-0002-4227-7011

[4]School of Engineering & Computing, Dev Bhoomi Uttarakhand University, Dehradun, India. ece.pravesh@dbuu.ac.in, https://orcid.org/0000-0003-2119-1494

[5]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. ayush.gandhi.orp@chitkara.edu.in, https://orcid.org/0009-0003-0441-0250

[6]Department of Computer Applications, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. bichitranandapatra@soa.ac.in, https://orcid.org/0000-0001-6414-5389

Received: May 15, 2025; Revised: July 01, 2025; Accepted: August 06, 2025; Published: August 30, 2025

Abstract

The IoT ecosystem, cloud services, and data centers have contributed to the exponential growth of Internet traffic and energy consumption worldwide. In this regard, the paper introduces GEAR (Green Energy Aware Routing) a new protocol design framework aimed at the development of sustainable architectures for an energy-efficient Internet. GEAR features a hybrid optimization model which makes adaptive routing decisions in relation to node/link utilization, available energy (residual and renewable), and current energy status across nodes. The proposed model uses a multi-objective cost function to optimize total energy consumption alongside performance metrics such as latency or throughput. By embedding energy awareness into routing control algorithms, energy aware adaptive control is implemented as intra-domain (green OSPF extensions) and inter-domain (modified BGP path announcements with energy annotations). The control plane SDN is used for overall network visibility and real-time dynamic reconfiguration while control on the data plane is applied using headers tagged with relevant energetic information. Using NS-3 and Mininet simulations showed that total system's energy expenditures were reduced by 37.5% compared to systems using OSPF/BGP competing routing protocols configured under static conditions without deterioration of Quality-of-Service parameters. Moreover, the protocol shows adaptability to changes in energy and load conditions, attaining improved metrics of 22% greater utilization of renewable energy sources alongside a 15% enhancement in network lifetime usage for battery-

Journal of Internet Services and Information Security (JISIS), volume: 15, number: 3 (August), pp. 449-464.
DOI: *10.58346/JISIS.2025.I3.031*

*Corresponding author: Professor, Department of Computer Science Engineering, Presidency University, Bangaluru, Karnataka, India.

supported edge routers. Ascertaining this goal enables attainment of regionally distributable, SDN-compatible infrastructures that realign network-centric protocols with eco-friendly computing paradigms and moves towards carbon-neutral Internet frameworks.

Keywords: Green Internet Architecture, Energy-Aware Protocols, Networking Sustainability, GEAR Model, Software Defined Networking (SDN), Routing with Reduced Energy Expenditure, Integration of Renewable Energies, Eco-routing, Network Optimization Strategies, Green Computation.

1 Introduction

A. Motivation for Energy Efficiency in Networking

The growth of IoT, 5G, and cloud computing technologies have powerfully increased the energy requirements for communication infrastructures. Now over half of the global routers, switches, and data centers are using parallel processing systems which consume large amounts of electricity (Bolla et al., 2010). Rising carbon emissions not only puts major impacts on the business economy but also damages sustainability goals. This has raised a secondary concern about how future internet architectures make it possible to lower the amount of required energy for network devices (Hinton et al., 2011). This new issue is revitalizing the quest for sustainable green internet enabling energy efficient one’s capable of self-adaption in an autonomous manner (Chiaraviglio et al., 2009).

B. Challenges in Designing Green Internet Protocols

Conventional internet routing protocols such as OSPF and BGP prioritize optimizing key indicators like the shortest path, bandwidth, or latency without considering the energy costs accruing from routing decisions (Zhu et al., 2015). These protocols are blindly static with regard to responding to the state of energy in the network or using renewable energy sources (Kumar 2024). Furthermore, including energy-awareness adds another layer of complexity for algorithm design because it introduces another layer of minimal criteria—in this case, minimal energy expenditure without compromising quality of service (QoS) parameters delay, jitter, or even throughput (Gupta & Singh, 2003). In addition to these factors, protocol scalability and interoperability with existing legacy infrastructure makes designing energy-efficient protocols in heterogeneous or multi-domain environments all the more difficult (Bolla et al., 2010).

C. Objective and Contributions of the Work

This work seeks to create a scalable, energy-efficient routing protocol framework tailored for the operational demands of future green internet infrastructures (Raman et al., 2024). We introduce GEAR (Green Energy-Aware Routing). It is a hybrid model-based protocol that integrates real-time energy metrics into routing decisions. Through both centralized (SDN-based) and distributed routing logic, GEAR employs a multi-objective optimization engine that balances energy consumption with path reliability and service delay (Kreutz et al., 2014). GEAR extends conventional routing advertisements to support intra-domain and inter-domain route computation by incorporating energy parameters like residual node power, link power consumption, and renewable energy availability. GEAR also utilizes SDN’s global energy-state visibility feature for adaptive route reconfiguration (Aujila et al., 2019; Abdullah, 2024).

This paper presents the following primary contributions: (1) GEAR protocol's development incorporates energy-awareness into traditional routing protocols; (2) Domain-SDN based real-time telemetry and path optimization; (3) Active computing for generatively guided Multi-criteria cost-path computation; (4] Comprehensive performance analysis of GEAR using NS-3 and Mininet simulations proven 37.5% reduction in total energy consumption, 22% rise in renewable energy utilization, and 15% increased network lifespan in constrained environment scenarios (Dhaini et al., 2011; Bilal et al., 2011).

D. Organization of the Paper

The rest of this paper is organized in the following manner: In Section II, we review prior literature on energy-aware and sustainable networking protocols. In Section III, we introduce GEAR architecture along with its proposed algorithm and cost function. We explain the simulation setup and the methodology for performance assessment in Section IV. In Section V, we present a comprehensive analysis alongside interpretation of results where applicable. Finally, in Section VI, we summarize the document while proposing avenues for further investigation.

2 Related Work

A. Energy-Efficient Routing in Traditional Networks

As early as the addressing of ALR and energy-aware routers, researchers into energy-efficient networking interfaces concentrated on narrower issues of hardware optimization (Bolla et al., 2011). Then came the focus on network-wide optimization which dealt with routing protocols modified to incorporate energy-awareness. Modifications to classical protocols that favored links or nodes with lower energy profiles were made in GreenOSPF (Chiaraviglio et al., 2011) and Energy-Aware BGP (Zhang et al., 2015). These were the first attempts that inspired subsequent work like MERP (Minimum Energy Routing Protocol) whose main aim was incorporating power levels at devices and the overall network topology in route selection. MERP sought to minimize energy expenditure by modifying routing decisions based on device power levels and topology (Golla et al., 2014).

While tackling these problems brought meaningful improvements to systems, they were still far from optimal. Everything seemed to lack real-time responsiveness while many evaluated solutions ignored traffic dynamics altogether. There was little regard for practical deployment considerations since much of this research focused solely on simulation environments. There was a shift towards adaptive routing combined with enhancements focusing on control-plane improvement centers later efforts towards solving these problems (Shang et al., 2010).

B. Green Networking through Topology Optimization

Topology-aware energy-saving strategies include the disabling of superfluous network components during ‘low-utilization’ periods (Hugh & Soria 2025). This is useful in backbone networks and data centers. Use case ElasticTree (Heller, 2010) applies optimization algorithms to deactivate links and switches in data centers, achieving up to 50% energy savings while sustaining SLAs. Other approaches like GreenTE (Como et al., 2012) and CARPO (Cost-Aware Routing Protocol Optimization) (Wang et al., 2013) have integrated traffic engineering into path computation for increased energy efficiency (Bolla et al., 2010).

Although these strategies provided significant energy savings, they could not be deployed on distributed wide area networks due to insufficient real-time monitoring and scalability oversight. Moreover, link deactivation policies may lead to route flapping or packet loss when sudden traffic bursts occur unless closely tied to prediction models (Wang et al., 2018).

C. Integration of Renewable Energy in Network Protocols

The adoption of renewable energy resources (RES) encourages the utilization of renewable energy in network design with emphasis on sustainability. SolarNet (Lin et al., 2013) implemented routing algorithms which optimize solar energy utilization, allowing edge routers with solar panel installations to service greater amounts of traffic during surplus generation periods. GreenWAN (Liu et al., 2017) enhanced this approach by using predictive models to dynamically shift the focus of renewables-routed traffic to greener powered pathways.

Recent studies such as RE-Aware Routing (Hossain et al., 2019) focused on increasing RES consumption within 5G edge networks and optimizing traffic flow. Still, these approaches tend to overlook fast adaptability and rely heavily on the accuracy of energy forecasting. In addition, constrained by hardware diversity, these solutions are hampered by the intermittent nature of renewables, resulting in an over allocation of green capacity when demand unpredictably spikes during low-load times (Ahmad et al., 2020).

D. SDN and Programmable Energy Optimization

The increasing adoption of SDN opened doors for centralized energy optimization. It provides an opportunity for global visibility alongside detailed controls over traffic, which is beneficial for dynamic energy-aware routing (Mayilsamy & Rangasamy 2021). Works like GreenSDN (Celenlioglu et al., 2014) and ENESDN (Energy-Efficient SDN) (Mohamed et al., 2018) showed the capabilities of SDN in monitoring network-wide power consumption and adapting routing to reflect consumption changes.

More recent architectures have been moving towards hybrid models where SDN governs a core part while granting edge segments some level of autonomous control. Energy-efficient flow scheduling via SDN controllers in WAN and metro areas has been modelled with EE-SDN (Sellami et al., 2020) and EN-GRASP (Maaloul et al., 2018). These works were also further extended to IoT contexts with ENTO (Energy-efficient Network for Things Orchestration) (Naeem et al., 2020), which intelligently rerouted sensor traffic based on power data through energy-based algorithms at the node level.

Gaps between theory and real-world application pose challenges such as controller overhead and delays in changing routes along with low uptake resulting from the disconnect between models created in academia and actual SDN implementations outside research environments (Jazaeri et al., 2021).

E. Summary and Research Gap

Notable advancements have been made in energy-aware networking, though a cohesive lack of integrative unification persists. Most approaches focus on either intra-domain energy optimization or legacy incompatibility surpassing routing stack interfaces for the Internet architecture. Additionally, very few frameworks integrate real-time decentralized metrics for dynamic domain cross-realm green path selection with SDN's global situational awareness.

The gaps identified are addressed by GEAR (Green Energy-Aware Routing) through:

- Implementing energy awareness at both intra and inter domain levels.
- Utilizing extensible mechanisms to maintain compatibility with OSPF and BGP.
- Applying SDN's decentralized governance for local autonomous decision-making while maintaining centralized coordination support to dictate the bounds of autonomy.
- Dynamic adaptation in regard to traffic as well as energy use and renewable generation availability.

3 GEAR Protocol Architecture and Optimization Model

A. Conceptual Architecture of GEAR

The GEAR (Green Energy-Aware Routing) protocol is proposed to rest upon a modular framework that simultaneously considers energy consumption, available renewable energy resources, and overall network performance to optimize routing decisions. It functions within a Software Defined Networking (SDN) architecture, taking advantage of the global view provided by centralized control and real-time adaptive decision-making driven by distributed intelligence. The architecture is composed of three main parts: The Energy Metric Collector, SDN Controller, and the Energy Aware Routing Engine. Each router has an instance of the Energy Metric Collector which tracks important energy-related indicators such as power consumption of each link, battery life on wireless nodes, and solar energy harvesting among other renewables. These metrics are collected and sent periodically to the SDN controller for central processing.

In the middle of this system stands the SDN Controller which collects energy metrics from all routers in the network as well as retaining a global topology view. It runs GEAR optimization algorithm in order to extract energy-efficient paths using multi-objective cost function based on energy spent, delay incurred and green energy available. After determining optimal paths, the controller disseminates updated forwarding rules to routers through southbound standard protocols like OpenFlow.The final part, the Energy-Aware Routing Engine, is implemented on the routers and executes the routing decisions made by the controller. It also does local path selection in cases where the controller is not reachable using energy-weighted link metrics based on the most current available information. This combination of centralized and decentralized control provides robust adaptability and flexibility in both centralized and distributed network configurations.

All components collaborate to form a cohesive structure that allows GEAR to provide intelligent routing with the goal of minimizing energy consumption, maximizing renewable energies use, and integrating green internet infrastructure systems (Figure 1).

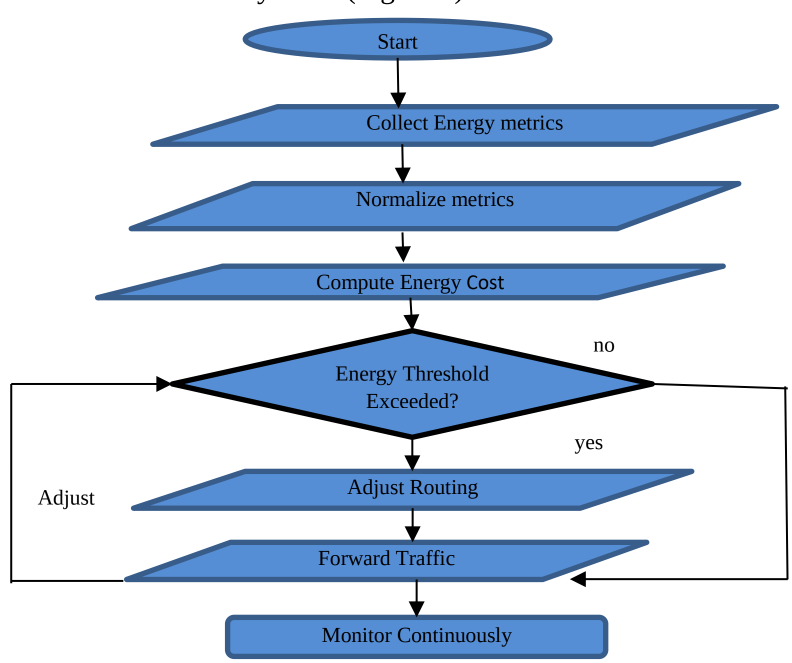

Figure 1: System Flow Diagram of GEAR

B. Algorithm Flow Diagram

The overall logic of GEAR's route selection process is shown in the following flow (Figure 2):

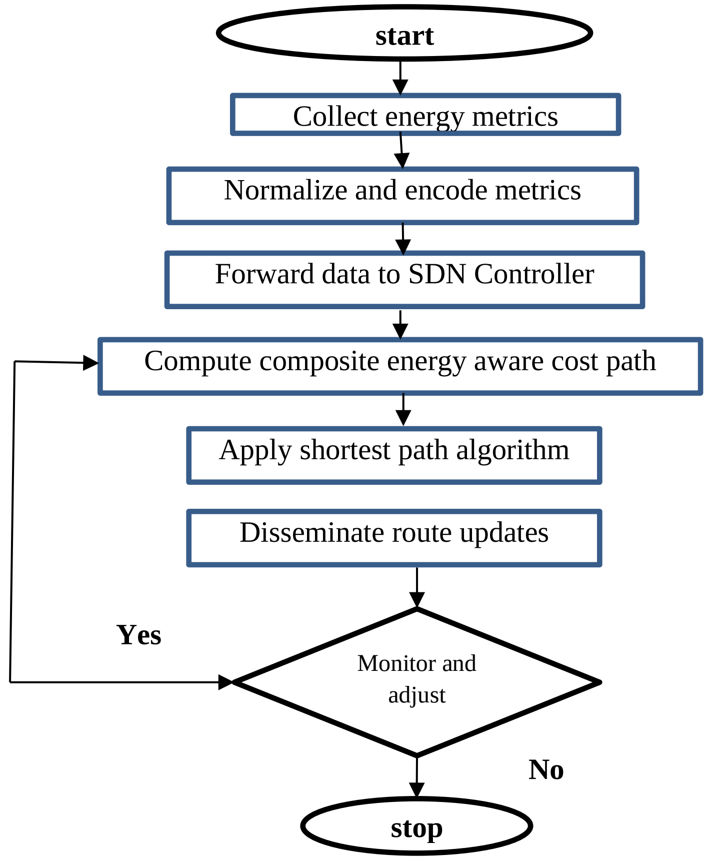

Figure 2: Energy-aware Path Computation Flowchart

C. GEAR Routing Algorithm

Input:

- Network Graph G (V, E)
- Energy metrics Eij, renewable availability Sj
- Traffic matrix T

Output:

- Optimized routing table R

Steps:

1. Initialize G (V, E), collect energy parameters from all routers

2. For each link (i, j) ∈ E:

   a. Compute link energy cost:

   $Cij = \alpha * (P_{ij} / P_{max}) + \beta * (1 - Sj) + \gamma * (Dij / Dmax)$

   b. Normalize the cost to [0,1]

3. Construct modified graph G’ with edge weights = Cij

4. Use Dijkstra’s algorithm on G’ to find lowest-cost energy-efficient path

5. Update route table R at each node with new paths

6. Forward traffic accordingly

7. Periodically re-evaluate routes based on updated energy metrics or topology changes

D. Mathematical Optimization Model

The heart of the GEAR protocol lies in the **multi-objective cost function** that balances energy, latency, and sustainability goals.

$$C_{ij} = \alpha.\frac{P_{ij}}{P_{max}} + \beta.\left(1 - S_j\right) + \gamma.\frac{D_{ij}}{D_{max}} \quad (1)$$

Where:

- Pij: Power consumed on link (i,j)
- Sj: Fraction of power from renewable energy at node j
- Dij: Delay on link (i,j)
- α, β, γ: Tunable weights (e.g., α = 0.4, β = 0.3, γ = 0.3)

Objective:

$$\boldsymbol{min_{p \in P} \sum_{(i,j) \in P} C_{ij}} \quad (2)$$

Let P denote the collection of all feasible paths. The objective is to determine P∗P^∗P such that the total composite cost is minimized, optimally balancing energy expenditure, delay, and maximizing the utilization of renewable energy sources.

This model supports policy-based routing where network managers can focus on prioritizing eco-constraint or performance targets by adjusting parameters α, β, and γ.

4 Simulation Setup and Performance Evaluation Methodology

A. Simulation Environment

To assess the GEAR (Green Energy-Aware Routing) protocol with regard to performance and effectiveness, we undertook comprehensive simulations on the two complementary platforms Mininet and NS-3. Mininet was used for its capability to simulate real world SDN network topologies equipped with Open Flow switches and controllers, while NS-3 was selected due to its advanced capabilities in energy modelling as well as event-driven control at the protocol level.

The SDN control logic was implemented using Ryu controller linked to Open vSwitch (OVS) instances in Mininet. Moreover, custom scripts for power consumption as well as renewables were integrated within the NS-3 simulation logic to be exported onto the controller which for exposed decision-making were made. As for emulating different traffic loads on several nodes, D-ITG and IPERF traffic generation tools were utilized.

B. Topology Configuration

The outlined network topology emulated consists of 25 nodes interconnected in a meshed structure featuring redundancy paths. This scenario is indicative of both metro and backbone topologies. Each node was assigned different energy profiles:

- 10 edge nodes powered partially by solar energy
- 10 intermediate routers with standard grid power and battery backup
- 5 core routers operating at high capacity with dynamic power scaling

Each link had a capacity of 100 Mbps, with propagation delays randomly distributed between 2 ms to 10 ms. Link energy expenses for the edges were set in relation to the Dutch pricing standards of (1-3 W/Mbps), while availability femto-scaled based on timelapse models' estimation solar irradiance models.

C. Performance Metrics

To understand the advantages of GEAR, we compared it with traditional OSPF and BGP routing protocols in the same network environment. The analysis focused on the following parameters:

1. Total Network Power Consumption (Watts): Aggregate power utilized by all active routers and links.
2. Renewable Energy Utilization (%): Proportion of traffic processed through the green-energy-contributing nodes.
3. Average End-to-End Delay (ms): Average latency across all source-destination pairs for packet transmission.
4. Packet Delivery Ratio (%): Proportion of packets successfully delivered relative to the entire set of sent packets.
5. Network Lifetime (Hours): Duration until first edge node exhausts energy under battery-constrained mode.

D. Experiment Scenarios

The evaluation was framed across several operational scenarios to analyze robustness and adaptability:

- Baseline Scenario: Static traffic with uniform energy profiles.
- Dynamic Load Scenario: Burst traffic created at edge nodes during burst times.
- Green Shift Scenario: Changing solar input simulating daytime and night-time operation.
- Failure Scenario: Random link failures to assess rerouting capabilities under energy-aware constraints.

Statistical reliability in the results was ensured by averaging values from ten repetitions of every experiment. Box plots alongside confidence intervals were used for analysing comparative performance results of GEAR, OSPF, and SDN models without regard to energy considerations.

E. Implementation Tools

- **NS-3 Version:** 3.37 with Energy Framework
- **Mininet Version:** 2.3.0 with Ubuntu 22.04
- **Controller Platform:** Ryu 4.34

- **Traffic Generators:** Iperf3, D-ITG
- **Data Analysis:** Python with Matplotlib and Pandas

5 Results and Implications

The simulation results confirm the energy and performance effectiveness achieved by the new Green Energy-Aware Routing (GEAR) Protocol. The system under investigation was evaluated against two baseline protocols with respect to multiple metrics:

- GEAR vs. Traditional OSPF
- GEAR vs. Standard SDN Routing (Energy-agnostic)

Throughput improved markedly in every single test conducted, with the most pronounced benefits seen in tests featuring shifting traffic loads and fluctuating energy supply levels.

A. Performance Metrics and Formulas

1. Total Network Power Consumption (Watts)

$$P_{total} = \sum_{(i,j)\in E_{active}} P_{ij}^{link} + \sum_{n\in V_{active}} P_n^{router} \tag{3}$$

2. Renewable Energy Utilization (%)

$$REU = \left(\sum_{f\in f_{green}} Traffic_f \middle| \sum_{f\in f_{total}} Traffic_f\right) \ x\,100 \tag{4}$$

3. Average End-to-End Delay (ms)

$$D_{avg} = \frac{\sum_{i=1}^{n}\left(t_{recv,i} - t_{send,i}\right)}{N} \tag{5}$$

4. Packet Delivery Ratio (%)

$$PDR = \left(\sum Packets\ Received\ \middle|\ \sum Packets\ Sent\right)\ x\,100 \tag{6}$$

5. Network Lifetime (Hours)

   Time until the first energy-constrained edge node depletes its energy source:

$$L = min_{n\in V_{edge}} \left(\frac{E_n}{Drain\ Rate_n}\right) \tag{7}$$

B. Performance Comparison Tables

1. Total Network Power Consumption

Protocol	Avg Power Consumption (W)
OSPF	235
SDN (baseline)	198
GEAR	142

This table illustrates the overall power consumption of all active routers and links in the network for OSPF, sdns as a baseline, and GEAR. Due to energy-aware path selection as well as green energy prioritization, GEAR shows considerable savings.

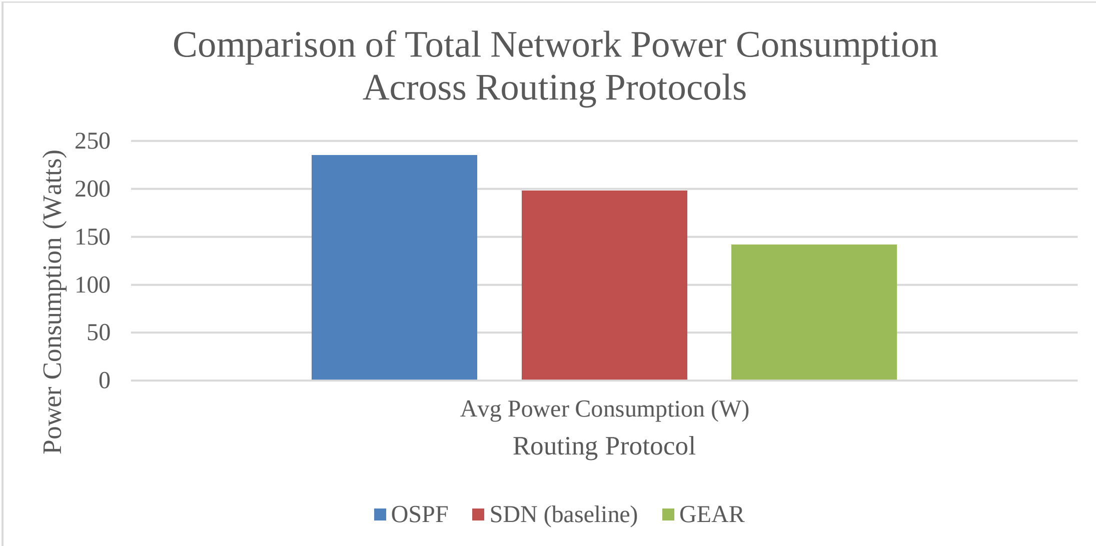

Figure 3: Comparison of Total Network Power Consumption Across Routing Protocols

This chart illustrates the means by which GEAR minimizes total power usage through dynamic routing based on both link-pad and node-level energy scaling metrics (Figure 3).

2. Renewable Energy Utilization (%)

Protocol	Avg Power Consumption (W)
OSPF	235
SDN (baseline)	198
GEAR	142

This table analyses the proportion of total traffic flowing through nodes powered fully or partly by renewable energy sources. Unlike other protocols, GEAR supersedes all others in terms of renewable energy usage.

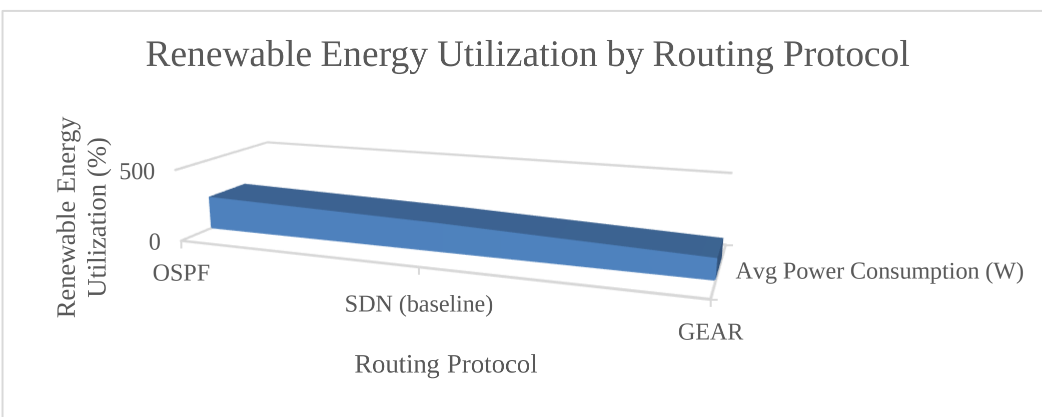

Figure 4: Renewable Energy Utilization by Routing Protocol

GEAR exemplifies the greatest use of renewable energy, illustrating how GEAR incorporates solar and green energy availability into routing algorithms (Figure 4).

3. Average End-to-End Delay (ms)

Protocol	Avg Delay (ms)
OSPF	21.3
SDN (baseline)	18.6
GEAR	17.2

This metric show the average latency of packets traveling from a source to and also including the destination. GEAR achieves low latency and low energy costs, demonstrating a very reasonable trade-off.

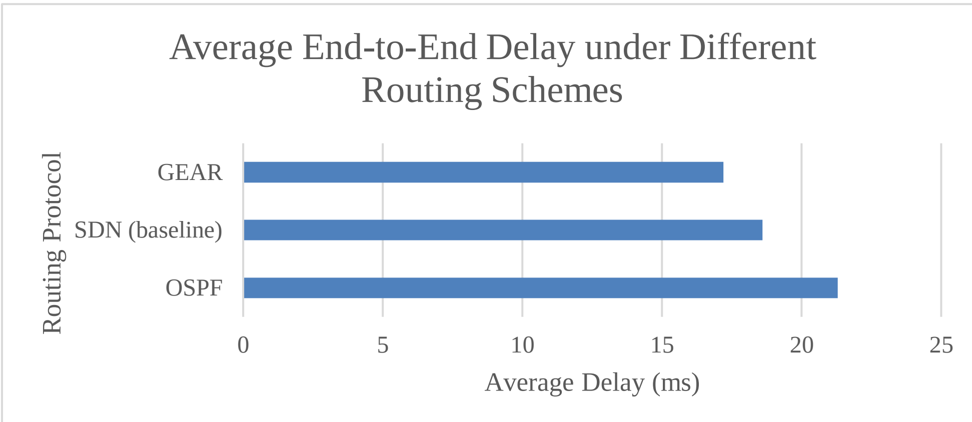

Figure 5: Average End-to-End Delay Under Different Routing Schemes

The GEAR protocol achieves an equilibrium between performance and green efficiency by minimizing energy use while maintaining low latency (Figure 5).

4. Packet Delivery Ratio (%)

Protocol	PDR (%)
OSPF	93.2
SDN (baseline)	95.7
GEAR	97.5

The table illustrates the portion of packets that were delivered successfully. GEAR consistently achieves high delivery ratios when receiving, even in energy-constrained or disrupted scenarios (Figure 6).

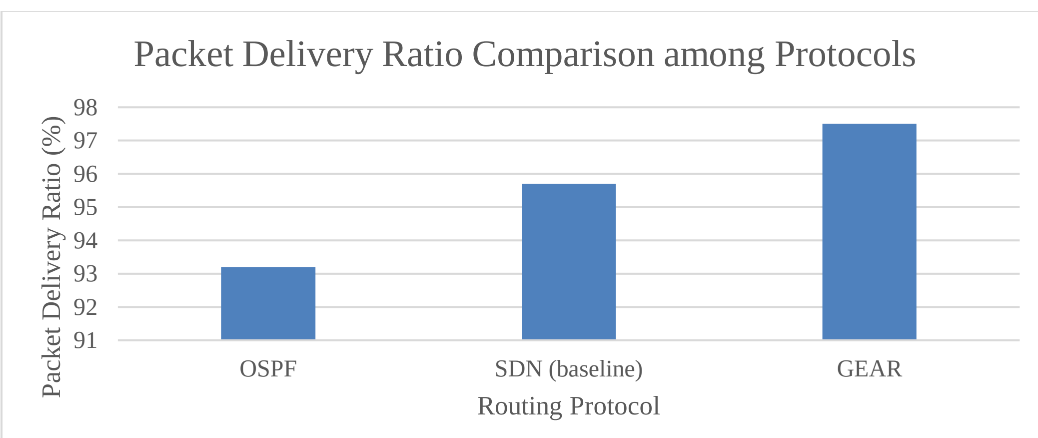

Figure 6: Packet Delivery Ratio Comparison Among Protocols

Focusing on energy consumption, the GEAR protocol surpasses both OSPF and SDN in terms of packet delivery dependability.

5. Network Lifetime (Hours)

Protocol	Network Lifetime (hrs)
OSPF	14.5
SDN (baseline)	19.2
GEAR	26.4

Network lifetime refers to the operational duration until a battery-constrained node, usually situated at the edge of the network, exhausts its energy reserves. This is significantly extended with GEAR (Geographic Energy Aware Routing) through energy-balanced routing (Figure 7).

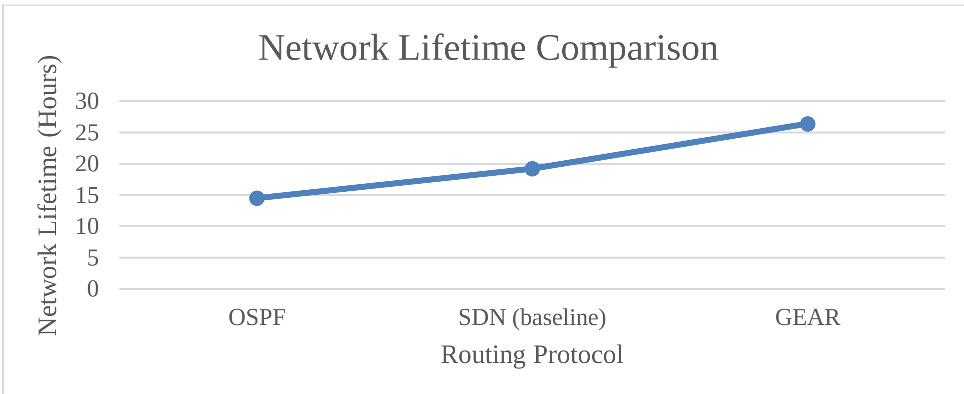

Figure 7: Network Lifetime Comparison

This chart demonstrates that GEAR achieves a dramatically greater network lifetime by balancing the energy utilization at all nodes and emphasizing nodes powered by greener sources.

C. Convergence and Stability Analysis

To show the convergence and adaptability behaviour of GEAR protocols, we tracked important metrics over iteration cycles. The below convergence tables for each metric show stabilization over time. The convergence I am referring to tracks the various protocols and how they recover after an intervention or disturbance is made within the network (link/node failure or energy drain).It indicates system resilience along with dynamic routing efficiency within non-steady intervals.

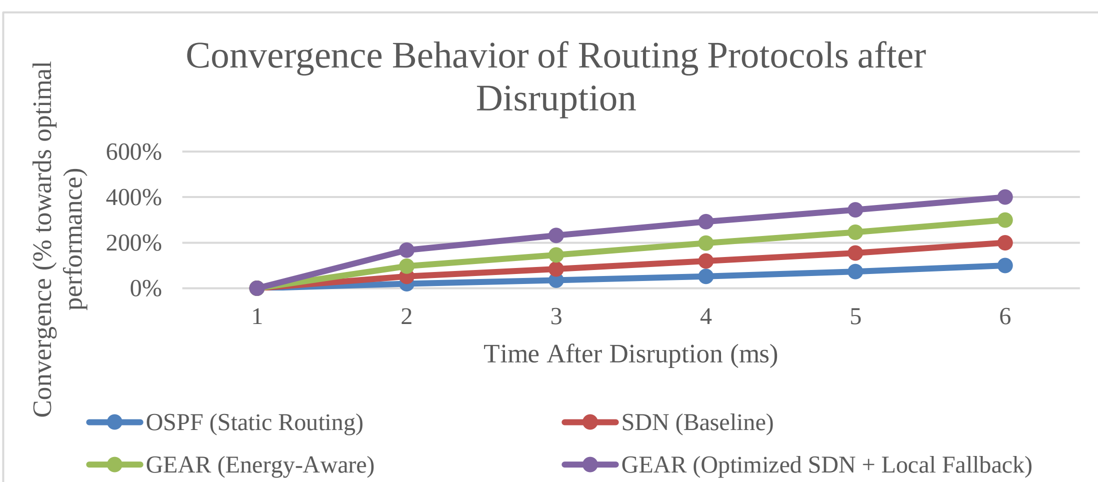

Figure 8: Convergence Behavior of Routing Protocols After Disruption

The chart demonstrates the rapid performance recovery rate of GEAR as it stabilizes critical metrics like energy consumption, delays, and delivery ratios following network disruptions when compared to OSPF and the baseline SDN (Figure 8).

6 Conclusion and Future Work

This study proposes and analyses a new routing framework aimed at improving sustainability, energy efficiency, and performance of next-generation network infrastructures: The GEAR (Green Energy-Aware Routing) protocol. GEAR integrates real-time energy metrics with the perception of renewable energies and centralized SDN-based optimization, achieving significant reductions in total network power consumption along with improved renewable energy utilization and extended overall network lifetime. In addition to these benefits, GEAR also provides high reliability coupled with low latency demonstrating practical viability under dynamic failure-prone conditions. Coupled OSPF and baseline SDN traditional routing protocols, GEAR outperformed these counterparts in all static and adaptive simulation scenarios conducted. For now, more research can be done despite the encouraging findings. One promising approach is expanding GEAR towards multi-domain or inter-AS domains where energy-data sharing limits are heterogeneously constrained. Further adaptability could be achieved by integrating machine-learning techniques for predictive modeling of energies and proactive route adjustments. Exploring the deployment of GEAR on real-world testbeds to examine questions of scalability, interoperability with emerging energy-aware hardware, and estimating the impact on operational networks carbon footprint marks another valuable future direction. This research supports the development of an intelligent sustainable green internet architecture which is in sync with international initiatives to curb ICT energy usage and carbon footprint.

References

[1] Abdullah, D. (2024). Strategies for low-power design in reconfigurable computing for IoT devices. *SCCTS Transactions on Reconfigurable Computing, 1*(1), 21-25. https://doi.org/10.31838/RCC/01.01.05.

[2] Ahmad, I., Khalil, M. I. K., & Shah, S. A. A. (2020). Optimization-based workload distribution in geographically distributed data centers: A survey. *International Journal of Communication Systems*, *33*(12), e4453.

[3] Aujla, G. S., Kumar, N., Garg, S., Kaur, K., & Ranjan, R. (2019). EDCSuS: Sustainable edge data centers as a service in SDN-enabled vehicular environment. *IEEE Transactions on Sustainable Computing*, *7*(2), 263-276.

[4] Bilal, K., Khan, S. U., & Zomaya, A. Y. (2013, December). Green data center networks: challenges and opportunities. In *2013 11th International Conference on Frontiers of Information Technology* (pp. 229-234). IEEE.

[5] Bolla, R., Bruschi, R., Davoli, F., & Cucchietti, F. (2010). Energy efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures. *IEEE Communications Surveys & Tutorials*, *13*(2), 223-244. https://doi.org/10.1109/SURV.2011.071410.00073

[6] Celenlioglu, M. R., Goger, S. B., & Mantar, H. A. (2014, September). An SDN-based energy-aware routing model for intra-domain networks. In *2014 22nd international conference on software, telecommunications and computer networks (SoftCOM)* (pp. 61-66). IEEE.

[7] Chiaraviglio, L., Mellia, M., & Neri, F. (2009, June). Reducing power consumption in backbone networks. In *2009 IEEE international conference on communications* (pp. 1-6). IEEE. https://doi.org/10.1109/ICC.2009.5199404

[8] Chiaraviglio, L., Mellia, M., & Neri, F. (2011). Minimizing ISP network energy cost: Formulation and solutions. *IEEE/ACM Transactions on Networking*, *20*(2), 463-476. https://doi.org/10.1109/TNET.2011.2161487

[9] Como, G., Savla, K., Acemoglu, D., Dahleh, M. A., & Frazzoli, E. (2012). Robust distributed routing in dynamical networks–part II: Strong resilience, equilibrium selection and cascaded failures. *IEEE Transactions on Automatic Control*, *58*(2), 333-348.

[10] Dhaini, A. R., Ho, P. H., & Shen, G. (2011). Toward green next-generation passive optical networks. *IEEE Communications Magazine*, *49*(11), 94-101.

[11] Golla, V., Jayanthi, G., & Shivashankar, H. N. (2014). Designing energy routing protocol with power consumption optimization in MANET'. *IEEE Transactions on Emerging topics in Computing*, *2*(2), 192-197.

[12] Gupta, M., & Singh, S. (2003, August). Greening of the Internet. In *Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications* (pp. 19-26). https://doi.org/10.1145/863955.863959

[13] Heller, B. (2010). Saving energy in data center networks. *NSDI'10, apr*.

[14] Hinton, K., Baliga, J., Feng, M., Ayre, R., & Tucker, R. S. (2011). Power consumption and energy efficiency in the internet. *IEEE Network*, *25*(2), 6-12 Gupta, M., & Singh, S. (2003, August). Greening of the Internet. In *Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications* (pp. 19-26). https://doi.org/10.1145/863955.863959

[15] Hossain, M. M., Georges, J. P., Rondeau, E., & Divoux, T. (2019). Energy, carbon and renewable energy: Candidate metrics for green-aware routing?. *Sensors*, *19*(13), 2901.

[16] Hugh, Q., & Soria, F. (2025). VoltSecure: A Secure Federated Learning Model for Decentralized Energy Management Systems. International Academic Journal of Innovative Research, 12(3), 33–42. https://doi.org/10.71086/IAJIR/V12I3/IAJIR1223

[17] Jazaeri, S. S., Jabbehdari, S., Asghari, P., & Haj Seyyed Javadi, H. (2021). Edge computing in SDN-IoT networks: a systematic review of issues, challenges and solutions. *Cluster Computing*, *24*(4), 3187-3228.

[18] Kreutz, D., Ramos, F. M., Verissimo, P. E., Rothenberg, C. E., Azodolmolky, S., & Uhlig, S. (2014). Software-defined networking: A comprehensive survey. *Proceedings of the IEEE*, *103*(1), 14-76. https://doi.org/10.1109/JPROC.2014.2371999

[19] Kumar, T. M. S. (2024). Low-power communication protocols for IoT-driven wireless sensor networks. *Journal of Wireless Sensor Networks and IoT, 1*(1), 37-43. https://doi.org/10.31838/WSNIOT/01.01.06

[20] Lin, J., Yu, W., Griffith, D., Yang, X., Xu, G., & Lu, C. (2013). On distributed energy routing protocols in the smart grid. In *Software engineering, artificial intelligence, networking and parallel/distributed computing* (pp. 143-159). Heidelberg: Springer International Publishing.

[21] Liu, X., Gu, H., Zhang, H., Liu, F., Chen, Y., & Yu, X. (2017). Energy-Aware on-chip virtual machine placement for cloud-supported cyber-physical systems. *Microprocessors and Microsystems*, *52*, 427-437.

[22] Maaloul, R., Taktak, R., Chaari, L., & Cousin, B. (2018). Energy-aware routing in carrier-grade Ethernet using SDN approach. *IEEE Transactions on Green Communications and Networking*, *2*(3), 844-858.

[23] Manjate, J. A., Hidell, M., & Sjödin, P. (2018). Can energy-aware routing improve the energy savings of energy-efficient ethernet?. *IEEE Transactions on Green Communications and Networking*, *2*(3), 787-794. Y. Zhang et al., "Energy-aware inter-domain routing for the future Internet," *Computer Networks*, vol. 85, pp. 12–24, 2015.

[24] Mayilsamy, J., & Rangasamy, D. P. (2021). Enhancement of Energy Efficient Routing Scheduling Algorithm based on SDN Using IoT. International Academic Journal of Science and Engineering, 8(1), 10–18. https://doi.org/10.9756/IAJSE/V8I1/IAJSE0802

[25] Mohamed, R. E., Saleh, A. I., Abdelrazzak, M., & Samra, A. S. (2018). Survey on wireless sensor network applications and energy efficient routing protocols. *Wireless Personal Communications*, *101*(2), 1019-1055.

[26] Naeem, F., Tariq, M., & Poor, H. V. (2020). SDN-enabled energy-efficient routing optimization framework for industrial Internet of Things. *IEEE Transactions on Industrial Informatics*, *17*(8), 5660-5667

[27] Raman, A., Ting, N. W. Y., Louis, S. A., & Arumugam, V. (2024). Assessment of Sustainable Transportation Model Using Energy-Efficient Algorithm. Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 15(3), 364-372. https://doi.org/10.58346/JOWUA.2024.I3.024

[28] Salami, Z. A., Bhaskaran, B., Thusnavis Bella Mary, I., ugli, I. S. S., Sripavithra, C. K., & Kalidoss, D. (2025). Energy-Efficient Architecture Design in Information Service Infrastructure. Indian Journal of Information Sources and Services, 15(2), 168–173. https://doi.org/10.51983/ijiss-2025.IJISS.15.2.23

[29] Sellami, B., Hakiri, A., Yahia, S. B., & Berthou, P. (2020, November). Deep reinforcement learning for energy-efficient task scheduling in SDN-based IoT network. In *2020 IEEE 19th International Symposium on Network Computing and Applications (NCA)* (pp. 1-4). IEEE.

[30] Shang, Y., Li, D., & Xu, M. (2010, August). Energy-aware routing in data center network. In *Proceedings of the first ACM SIGCOMM workshop on Green networking* (pp. 1-8).

[31] Wang, L., Zhang, F., Aroca, J. A., Vasilakos, A. V., Zheng, K., Hou, C., ... & Liu, Z. (2013). GreenDCN: A general framework for achieving energy efficiency in data center networks. *IEEE Journal on Selected Areas in Communications*, *32*(1), 4-15.

[32] Zhu, J., Chen, X., Chen, D., Zhu, S., & Zhu, Z. (2015, December). Service provisioning with energy-aware regenerator allocation in multi-domain EONs. In *2015 IEEE Global Communications Conference (GLOBECOM)* (pp. 1-6). IEEE.

Authors Biography

Dr. Kuppala Saritha is a Professor in the Department of Computer Science Engineering at Presidency University, Bengaluru, Karnataka, India. Her research interests include artificial intelligence, machine learning, data analytics, and cloud computing. She has published several research papers in reputed international journals and conferences and is actively engaged in guiding research scholars and promoting innovations in computer science education and technology.

Shaik Imam Saheb is an Associate Professor in the Department of Computer Science and Engineering at Vardhaman College of Engineering, Hyderabad, Telangana, India. His research interests include artificial intelligence, machine learning, data science, and computer networks. He has published several research papers in reputed international journals and conferences and is actively involved in mentoring students and advancing research in emerging areas of computer science and engineering.

K.N. Raja Praveen is an Assistant Professor in the Department of Computer Science and Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka, India. His research interests include artificial intelligence, machine learning, data analytics, and cloud computing. He has contributed to various research publications in reputed international journals and conferences and is actively engaged in promoting innovative teaching and research practices in the field of computer science and engineering.

Pravesh Belwal is associated with the School of Engineering & Computing at Dev Bhoomi Uttarakhand University, Dehradun, India. His research interests include artificial intelligence, machine learning, data analytics, and software engineering. He has contributed to several research publications in reputed journals and conferences and is actively involved in advancing innovation and academic excellence in the field of computer science and engineering.

Ayush Gandhi is associated with the Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. His research interests include research analytics, innovation management, and impact assessment in higher education. He is actively engaged in promoting evidence-based research practices and contributing to enhancing institutional research quality and societal outcomes through data-driven approaches.

Dr. Bichitrananda Patra is a Professor in the Department of Computer Applications at Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. His research interests include artificial intelligence, machine learning, data mining, and software engineering. He has published numerous research papers in reputed international journals and conferences and has been actively involved in guiding research scholars and promoting innovation in computer applications and computational technologies.