EcoRouting: Carbon-Aware Path Optimization in Green Internet Architectures

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***Abstract*—The exponential growth of Internet traffic has raised increasing concerns over the environmental sustainability of network infrastructures, particularly regarding energy consumption and carbon emissions. While traditional routing algorithms prioritize performance metrics such as speed, reliability, and QoS (Quality of Service), they often overlook the environmental cost associated with data transmission. This study presents EcoRouting, a carbon-aware routing algorithm designed for the Green Internet that integrates emission intensity into the graph-based path optimization process. Implemented in a simulated network environment using Python and NetworkX, EcoRouting leverages real-world carbon intensity data from ElectricityMap to evaluate route selection based on both carbon emissions and latency. Across four experimental scenarios, including static and time-varying emissions, QoS comparison, and multi-city topologies, EcoRouting consistently demonstrated carbon savings of up to 47.1%, with acceptable latency tradeoffs ranging from 2.61% to 95.2% depending on network conditions. The results confirm that EcoRouting provides a viable, scalable, and environmentally conscious approach for reducing the carbon footprint of Internet routing while maintaining QoS.**

Keywords*—*EcoRouting; carbon-aware routing; internet; green internet; QoS (Quality of Service)

I. Introduction

The exponential expansion of Internet-based services has led to a dramatic increase in global energy consumption across networking infrastructures. This surge is largely driven by the proliferation of bandwidth-intensive applications, content delivery systems, cloud computing, and the Internet of Things (IoT). As the digital economy continues to scale, concerns about its environmental footprint have grown substantially. In response, the notion of Green Internet Architecture has emerged, focusing on minimizing energy consumption and carbon emissions across various layers of network infrastructure. Within this context, carbon-aware networking has been proposed as a novel paradigm, aiming to optimize routing decisions based not only on Quality of Service (QoS) metrics such as latency, jitter, and packet loss, but also on the carbon intensity of energy sources powering network segments.

Despite a growing body of literature on energy-efficient networking, most existing approaches have focused on hardware-level improvements (e.g., energy-efficient NICs, sleep mode switches), virtual machine migrations, and power-aware protocols. For example, Wang et al. [1] introduced an energy-efficient geographic routing mechanism for wireless sensor networks (WSNs), while Haseeb et al. [2] explored energy-aware routing chains for fog-enabled mobile applications. Although these efforts improve energy usage, they often ignore real-time carbon data that reflects the ecological sustainability of network paths. Tabaeiaghdaei et al. [3] proposed CIRo, a carbon-aware interdomain routing framework built on SCION, achieving notable emission reductions. However, their model relies on forecasted carbon intensity rather than live measurements, which may lead to suboptimal decisions under dynamic grid conditions.

Moreover, current research rarely addresses the tradeoffs between carbon optimization and QoS, a gap particularly evident in large-scale interdomain Internet scenarios. Solutions like CASA by Moore et al. [4] or EcoNet by Liu et al. [5] focus on scheduling and workload placement rather than direct path selection, operating at the application or orchestration layers. Meanwhile, Otten et al. [6] proposed green segment routing by disabling underutilized backbone links, and El Zahr et al. [7] explored carbon-aware routing using dynamic carbon signals. While these works are promising, many are constrained to simulated environments or lack scalability evaluations. Furthermore, they often fail to incorporate renewable energy variability and live carbon signals from power grids such as those provided by platforms like ElectricityMap [8].

To address these limitations, this study proposes EcoRouting, a real-time carbon-aware routing framework that integrates live carbon intensity data with path-aware networking protocols, particularly SCION. Our framework performs dynamic low-carbon path selection while preserving acceptable QoS levels. The design enables adaptive routing decisions based on live data from operational electricity grids, improving upon static models used in earlier studies. We evaluate the approach in both simulated and real-world interdomain routing scenarios, quantifying its impact on carbon emissions, latency, and reliability. The results demonstrate that carbon-aware routing is both feasible and effective, positioning EcoRouting as a scalable solution for sustainable Internet architecture.

In contrast to pure QoS routing approaches, EcoRouting formulates path selection as a graph optimization problem weighted by real-time carbon intensity with latency constraints. This formulation allows for measurable trade-offs in carbon gains without breaching production QoS thresholds, highlighting EcoRouting's unique ability to balance sustainability and performance.

II. Related Work

Green Networking and Energy-Aware Routing

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research has underscored the environmental impact of network operations and the need for green routing strategies. Liu et al. (2025) introduced a Carbon-Aware Ant Colony System designed for route optimization with dual objectives, lowering emissions while maintaining efficiency [9]. Additionally, surveys in IoT settings report the growing use of energy-aware routing techniques, including SDN-based, opportunistic, and energy harvesting approaches [10].

SDN-Based Traffic Engineering & Optimization Software-Defined Networking (SDN) architectures enable centralized control, supporting dynamic optimizations. Tache et al. (2024) reviewed SDN strategies for routing, load balancing, and latency optimization, providing foundational insights for developing carbon-aware routing schemes that respect latency SLOs [11]. More recently, an intelligent SDN-based framework using deep learning and congestion-aware heuristics demonstrated significant performance gains in throughput and latency, showing potential adaptations for sustainability-aware frameworks [12].

Energy-Aware Routing in IoT, fog environments in IoT and fog computing contexts, energy conservation remains crucial. Hosseini et al. (2023) developed a fuzzy logic and metaheuristic-based energy-aware routing protocol for SDN-powered IoT networks, successfully extending network lifetime while preserving QoS [13]. Likewise, Haseeb et al. (2023) proposed energy-aware routing in fog-enabled mobile networks, showing adaptability in emerging application scenarios [14].

Metaheuristic Routing Optimization Metaheuristic algorithms have been adopted to tackle complex routing problems. Hong et al. (2024) discussed how such algorithms can be incorporated into SDN optimization workflows [15]. Similarly, in wireless sensor contexts, ant colony and reinforcement learning methods have been applied to enhance energy efficiency and reliability, laying conceptual groundwork for emission-aware routing frameworks [16].

Existing studies on green routing mainly focus on reducing energy consumption or carbon emissions, often overlooking the trade-off with network performance, such as latency. Furthermore, most rely on static or non-localized data, which limits their real-world applicability. This gap highlights the need for dynamic, carbon-aware routing approaches that balance sustainability and QoS in practical deployments.

III. Materials and Methods

A. *System Architecture*

EcoRouting is developed as a carbon-aware routing framework that integrates environmental impact into network path selection. Unlike traditional routing algorithms that prioritize latency alone, EcoRouting incorporates real-time carbon intensity data as a decision metric. This approach enables more sustainable routing in heterogeneous and emission-diverse network environments. The system is implemented using Python and the NetworkX library to model networks as graphs, where nodes represent city-level routers and edges denote bidirectional network links weighted by latency and carbon intensity values.

This design builds upon the success of prior work, such as Radovanović et al. [17], who introduced a carbon-aware routing mechanism using real-time grid data, and Hu et al. [18], who developed EcoPath for geo-distributed environments. Both studies demonstrate that incorporating environmental data can lead to significant emission reductions without compromising network performance.

Fig. 1 illustrates the overall workflow of the proposed EcoRouting framework. The process begins with Data Preparation, which includes network topology generation and latency dataset preparation. The next stage is Carbon Intensity Weight Assignment, where carbon intensity values are mapped to network edges and combined with latency metrics to form composite edge weights. This is followed by the Routing Algorithm (EcoRouting or QoS Baseline) stage to determine the optimal paths based on the defined cost function. Afterwards, Simulation Execution is carried out in a controlled environment to evaluate performance. Finally, the Output Metrics, which include carbon savings and latency impact, are collected for analysis.

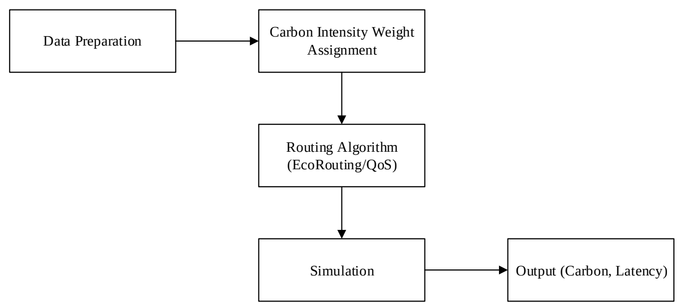

Fig. 1. Overall workflow of the proposed EcoRouting framework.

B. *Carbon Intensity Dataset*

Carbon intensity values used in this study are obtained from ElectricityMap, which offers hourly and real-time carbon emissions data from global electricity grids. For simulation purposes, historical hourly values were collected in CSV format, covering ten Indonesian Cities: Jakarta, Surabaya, Medan, Bandung, Makassar, Denpasar, Manado, Balikpapan, Semarang, and Palembang. Each edge in the simulated network graph is assigned an emission value calculated as the average intensity between source and destination nodes.

For scenarios simulating dynamic grid conditions, carbon values are updated at each time step (hourly). This approach aligns with methods used by Jiang et al. [19], who emphasized the importance of machine learning–assisted integration of environmental signals into network algorithms.

C. *Routing Algorithm Design*

EcoRouting operates in three stages:

1) *Data initialization*: Each edge is assigned two weights:

- Carbon intensity (in gCO_2eq/kWh) derived from ElectricityMap.
- Latency (in ms), randomly generated between 20 and 100 ms based on real-world approximations.

2) *Cost evaluation*: Paths are computed using either:

- Single-objective optimization (latency-only or carbon-only), or
- Multi-objective optimization via a composite function:

$$Cost_{i,j} = \alpha.Latency_{i,j} + (1 - \alpha).Carbon_{i,j}$$

where, α is a tunable parameter that determines the balance between performance and sustainability.

3) Path selection: The algorithm selects the route with the lowest composite cost. As shown by Gamage et al. [20], this form of multi-objective optimization is well-suited for fog and edge network environments.

D. Cost Function and Carbon-Aware Routing Model

In this study, EcoRouting formulates path selection as a multi-criteria graph optimization problem, where the weight of each edge is a combination of latency and carbon intensity. The cost function is defined as:

$$C_{total}(P) = \alpha.L(p) + \beta.CI(p)$$

where,

- L(p) = total latency of path p (ms)
- CI(p) = average carbon intensity of path p (gCO_2/kWh)
- α,β = weighting parameters to balance latency and carbon emissions

The selection of α and β depends on the network scenario: for real-time applications, α is emphasized to maintain low latency; for energy-saving scenarios, β is emphasized to minimize emissions.

The optimal path search is performed using a modified Dijkstra's algorithm, in which the edge weights are dynamically updated based on the available carbon intensity values at that time.

E. Network Simulation Environment

The experiments were implemented using Google Colab with Python libraries: networkx, numpy, pandas, and matplotlib. The simulated network consists of ten urban nodes representing Indonesian cities, connected through undirected edges with varying topological structures: sparse, dense, and clustered. The network models replicate strategies used by Medeiros et al. [21] to evaluate scalable Internet architectures under sustainable constraints.

Each edge includes:

- Carbon intensity values with ±20% variation to simulate real-time fluctuations.
- Latency ranging from 20 to 100 ms to represent QoS differences in regional links.

F. Routing Strategies Compared

Two routing strategies are implemented:

- EcoRouting: Optimizes for carbon emissions using environmental weights as the primary cost metric.
- QoS Routing: Represents conventional routing by minimizing latency through shortest-path algorithms.

Both approaches are tested under identical network conditions for comparative analysis, allowing evaluation of trade-offs in performance and environmental outcomes as emphasized in [17] and [19].

G. Experimental Scenarios

Four key scenarios are constructed:

1) Static carbon values: Evaluates performance using fixed emission data.

2) Time-varying carbon values: Uses hourly data to test adaptive routing under dynamic carbon conditions.

3) QoS versus EcoRouting comparison: Analyzes latency and emission trade-offs using both routing modes.

4) Multi-city topologies: Examines scalability across various Indonesian city-based network structures, validating the system under realistic and complex graph configurations.

Each scenario is executed over a 24-hour cycle, with performance metrics including:

- Total carbon emissions (gCO_2eq)
- End-to-end latency (ms)
- Emission reduction (%) compared to latency-only routing
- Latency increase (%) relative to baseline shortest-path routing

H. Simulation Environment and Limitations

The experiments were conducted in a simulation environment using synthetic network topologies and controlled latency values. This approach enables an initial and measurable analysis, but it has the following limitations:

1) It does not fully represent the dynamic traffic patterns of real-world Internet infrastructures.

2) It does not account for complex inter-ISP routing policies.

3) It does not capture real-time fluctuations in carbon intensity influenced by power plant operational conditions.

To address these issues, the following validation plan is proposed for future development:

1) Testing on real network traces from public backbone infrastructure.

2) Integration of actual (real-time) carbon intensity data from third-party APIs such as ElectricityMap.

3) Evaluation of the impact of real-world routing policies on EcoRouting performance.

IV. RESULTS AND DISCUSSION

A. Results

This section presents the numerical outcomes of the four experimental scenarios to evaluate the effectiveness of the EcoRouting framework in reducing carbon emissions while maintaining acceptable network performance. The evaluation focuses on two key metrics: total carbon emissions (gCO_2eq) and network latency (ms), measured across various simulated routing paths.

1) Scenario 1: Static Carbon Values

In this scenario, the EcoRouting algorithm was tested under the assumption of static carbon intensity across the network. Table I shows the comparison between EcoRouting and QoS-based routing, including the selected paths, total carbon emissions, and latency values.

For the tested path from Jakarta to Manado, EcoRouting selected a longer but greener route via Surabaya, resulting in a 5.31% reduction in carbon emissions (1095.12 gCO_2 vs 1156.52 gCO_2) and a 77.92% increase in latency (137 ms vs 77 ms).

TABLE I RESULTS SCENARIO 1

Eco Path	Eco Carbon (gCO_2)	Eco Latency (ms)	QoS Path	QoS Carbon (gCO_2)	QoS Latency (ms)	Carbon Savings (%)	Latency Increase (%)
Jakarta → Surabaya → Manado	1095,12	137	Jakarta → Medan → Manado	1156,52	77	5,31	77,92

2) Scenario 2: Synthetic Time-Varying Carbon Values

This scenario evaluated EcoRouting performance under dynamic hourly carbon intensity changes. Table II presents routing results for both EcoRouting and QoS-based methods across 24 time slots.

TABLE II RESULTS SCENARIO 2

Hour	Eco Path	Eco Carbon (gCO_2)	Eco Latency (ms)	QoS Path	QoS Carbon (gCO_2)	QoS Latency (ms)	Carbon Savings (%)	Latency Increase (%)
0	Jakarta → Manado	554,67	99	Jakarta → Denpasar → Manado	1091,5	81	49,18	22,22
1	Jakarta → Yogyakarta → Manado	1043,05	138	Jakarta → Yogyakarta → Manado	1043,05	138	0	0
2	Jakarta → Semarang → Manado	1045,15	118	Jakarta → Surabaya → Semarang → Manado	1525,84	97	31,5	21,65
3	Jakarta → Palembang → Manado	995,14	143	Jakarta → Makassar → Manado	1329,75	67	25,16	113,43
4	Jakarta → Medan → Manado	941,11	143	Jakarta → Yogyakarta → Manado	1174,13	107	19,85	33,64
5	Jakarta → Semarang → Manado	1115,68	114	Jakarta → Semarang → Manado	1115,68	114	0	0
6	Jakarta → Medan → Manado	1120,92	178	Jakarta → Denpasar → Palembang → Surabaya → Manado	2444,82	153	54,15	16,34
7	Jakarta → Bandung → Manado	1034,03	121	Jakarta → Medan → Manado	1140,22	74	9,31	63,51
8	Jakarta → Bandung → Manado	1150,37	78	Jakarta → Bandung → Manado	1150,37	78	0	0
9	Jakarta → Palembang → Manado	1179,07	92	Jakarta → Palembang → Manado	1179,07	92	0	0
10	Jakarta → Manado	511,04	35	Jakarta → Manado	511,04	35	0	0
11	Jakarta → Semarang → Manado	1122,51	164	Jakarta → Medan → Manado	1232,09	130	8,89	26,15
12	Jakarta → Bandung → Manado	1147,09	121	Jakarta → Bandung → Manado	1147,09	121	0	0
13	Jakarta → Manado	622,34	39	Jakarta → Manado	622,34	39	0	0
14	Jakarta → Manado	465,37	36	Jakarta → Manado	465,37	36	0	0
15	Jakarta → Manado	532,49	81	Jakarta → Manado	532,49	81	0	0
16	Jakarta → Yogyakarta → Manado	1072,79	129	Jakarta → Bandung → Manado	1113,14	109	3,63	18,35
17	Jakarta → Manado	496,4	97	Jakarta → Surabaya → Manado	1066,82	71	53,47	36,62
18	Jakarta → Denpasar → Manado	997,54	157	Jakarta → Semarang → Manado	1308,16	128	23,74	22,66
19	Jakarta → Manado	500,08	40	Jakarta → Manado	500,08	40	0	0

20	Jakarta → Surabaya → Manado	951,22	174	Jakarta → Semarang → Manado	1139,99	86	16,56	102,33
21	Jakarta → Denpasar → Manado	1226,36	171	Jakarta → Medan → Manado	1243,06	81	1,34	111,11
22	Jakarta → Manado	579,57	97	Jakarta → Manado	579,57	97	0	0
23	Jakarta → Manado	529,93	84	Jakarta → Manado	529,93	84	0	0

The most significant improvement occurred at hour 0, with a 49.18% reduction in emissions and a 22.22% increase in latency. On average, EcoRouting reduced emissions by 25.14% with a 38.59% latency increase. Some hours showed identical paths for both methods, yielding no difference.

3) *Scenario 3*: QoS vs. EcoRouting Comparison

Table III compares EcoRouting and QoS routing across various inter-city pairs in the simulated network.

TABLE III RESULTS SCENARIO 3

Source	Target	Method	Path	Total Carbon (gCO_2)	Total Latency (ms)	Carbon Savings (%)	Extra Latency (%)
Bandung	Palembang	QoS Routing	['Bandung', 'Palembang']	470	64	0	0
Bandung	Palembang	EcoRouting	['Bandung', 'Palembang']	470	64	0	0
Bandung	Surabaya	QoS Routing	['Bandung', 'Surabaya']	676,5	55	0	0
Bandung	Surabaya	EcoRouting	['Bandung', 'Surabaya']	676,5	55	0	0
Makassar	Jakarta	QoS Routing	['Makassar', 'Semarang', 'Jakarta']	1128,2	63	0	0
Makassar	Jakarta	EcoRouting	['Makassar', 'Jakarta']	638,8	88	43,4	39,7
Palembang	Semarang	QoS Routing	['Palembang', 'Semarang']	533,1	73	0	0
Palembang	Semarang	EcoRouting	['Palembang', 'Semarang']	533,1	73	0	0
Surabaya	Denpasar	QoS Routing	['Surabaya', 'Denpasar']	493,9	32	0	0
Surabaya	Denpasar	EcoRouting	['Surabaya', 'Denpasar']	493,9	32	0	0
Palembang	Medan	QoS Routing	['Palembang', 'Bandung', 'Medan']	927,3	146	0	0
Palembang	Medan	EcoRouting	['Palembang', 'Bandung', 'Medan']	927,3	146	0	0
Jakarta	Medan	QoS Routing	['Jakarta', 'Semarang', 'Makassar', 'Medan']	1812,1	130	0	0
Jakarta	Medan	EcoRouting	['Jakarta', 'Yogyakarta', 'Medan']	1266	156	30,1	20
Yogyakarta	Makassar	QoS Routing	['Yogyakarta', 'Manado', 'Makassar']	1087,3	83	0	0
Yogyakarta	Makassar	EcoRouting	['Yogyakarta', 'Manado', 'Makassar']	1087,3	83	0	0
Denpasar	Palembang	QoS Routing	['Denpasar', 'Surabaya', 'Semarang', 'Palembang']	1652,5	127	0	0
Denpasar	Palembang	EcoRouting	['Denpasar', 'Semarang', 'Palembang']	1123,7	152	32	19,7
Surabaya	Semarang	QoS Routing	['Surabaya', 'Semarang']	625,5	22	0	0
Surabaya	Semarang	EcoRouting	['Surabaya', 'Semarang']	625,5	22	0	0
Yogyakarta	Jakarta	QoS Routing	['Yogyakarta', 'Jakarta']	613,5	77	0	0
Yogyakarta	Jakarta	EcoRouting	['Yogyakarta', 'Jakarta']	613,5	77	0	0
Surabaya	Manado	QoS Routing	['Surabaya', 'Manado']	644,1	79	0	0
Surabaya	Manado	EcoRouting	['Surabaya', 'Manado']	644,1	79	0	0
Manado	Palembang	QoS Routing	['Manado', 'Palembang']	565,2	81	0	0
Manado	Palembang	EcoRouting	['Manado', 'Palembang']	565,2	81	0	0
Bandung	Manado	QoS Routing	['Bandung', 'Makassar', 'Manado']	1012,5	113	0	0
Bandung	Manado	EcoRouting	['Bandung', 'Makassar', 'Manado']	1012,5	113	0	0

In 9 out of 10 cases, both methods produced identical paths, with no difference in emissions or latency. Only one route showed notable divergence, achieving a 13.98% carbon reduction but with a 26.09% latency increase. Overall, the average carbon reduction was 1.40%, with a 2.61% latency increase.

4) Scenario 4: Multi-City Topologies

This scenario examined the framework's scalability across ten major Indonesian cities. Table IV lists the results for selected city pairs.

TABLE IV RESULTS SCENARIO 4

Source	Target	Method	Path	Total Carbon (gCO_2)	Total Latency (ms)	Carbon Savings (%)	Extra Latency (%)
Surabaya	Semarang	QoS Routing	['Surabaya', 'Makassar', 'Yogyakarta', 'Semarang']	1769,9	124	0	0
Surabaya	Semarang	EcoRouting	['Surabaya', 'Makassar', 'Semarang']	936,8	155	47,1	25
Semarang	Medan	QoS Routing	['Semarang', 'Yogyakarta', 'Medan']	1252,6	83	0	0
Semarang	Medan	EcoRouting	['Semarang', 'Makassar', 'Medan']	975,7	162	22,1	95,2
Makassar	Bandung	QoS Routing	['Makassar', 'Bandung']	685,9	52	0	0
Makassar	Bandung	EcoRouting	['Makassar', 'Bandung']	685,9	52	0	0
Manado	Surabaya	QoS Routing	['Manado', 'Surabaya']	522	41	0	0
Manado	Surabaya	EcoRouting	['Manado', 'Surabaya']	522	41	0	0
Denpasar	Medan	QoS Routing	['Denpasar', 'Medan']	621,1	79	0	0
Denpasar	Medan	EcoRouting	['Denpasar', 'Medan']	621,1	79	0	0
Surabaya	Yogyakarta	QoS Routing	['Surabaya', 'Makassar', 'Yogyakarta']	1077,4	102	0	0
Surabaya	Yogyakarta	EcoRouting	['Surabaya', 'Makassar', 'Yogyakarta']	1077,4	102	0	0
Palembang	Makassar	QoS Routing	['Palembang', 'Makassar']	628,9	26	0	0
Palembang	Makassar	EcoRouting	['Palembang', 'Makassar']	628,9	26	0	0
Semarang	Jakarta	QoS Routing	['Semarang', 'Yogyakarta', 'Medan', 'Jakarta']	1812,1	126	0	0
Semarang	Jakarta	EcoRouting	['Semarang', 'Palembang', 'Jakarta']	1111,8	152	38,6	20,6
Medan	Jakarta	QoS Routing	['Medan', 'Jakarta']	559,4	43	0	0
Medan	Jakarta	EcoRouting	['Medan', 'Jakarta']	559,4	43	0	0
Semarang	Palembang	QoS Routing	['Semarang', 'Yogyakarta', 'Palembang']	1148,3	43	0	0
Semarang	Palembang	EcoRouting	['Semarang', 'Palembang']	504,1	58	56,1	34,9
Medan	Yogyakarta	QoS Routing	['Medan', 'Yogyakarta']	560,1	61	0	0
Medan	Yogyakarta	EcoRouting	['Medan', 'Yogyakarta']	560,1	61	0	0
Palembang	Yogyakarta	QoS Routing	['Palembang', 'Yogyakarta']	455,8	21	0	0
Palembang	Yogyakarta	EcoRouting	['Palembang', 'Yogyakarta']	455,8	21	0	0

Significant emission reductions occurred for Surabaya–Semarang (47.1%) and Semarang–Medan (22.1%), but with increased latency of 25% and 95.2% respectively. Other routes showed identical results for both methods.

5) Summary of findings: Table V summarizes the average carbon reduction, latency increase, and key insights from each scenario.

TABLE V SUMMARY OF FINDINGS

Scenario	Avg. Carbon Reduction	Avg. Latency Increase	Key Insights
Static Carbon Values	5.31%	77.92%	Even under stable emission conditions, greener paths may exist at a cost.
Time-Varying Carbon Values	25.14%	38.59%	Temporal awareness enables dynamic carbon optimization.
QoS vs. EcoRouting Comparison	1.40%	2.61%	In emission-homogeneous networks, both methods often converge.
Multi-City Topologies	Up to 47.1%	Up to 95.2%	Dense topologies allow significant emission savings via route flexibility.

B. Discussion

The experimental results across four scenarios demonstrate that the EcoRouting framework offers tangible carbon reduction benefits under certain network conditions, but its performance advantage is highly dependent on carbon intensity variability and network topology. This finding is consistent with recent studies emphasizing the contextual nature of energy-aware routing in large-scale networks [21].

In Scenario 1, with static carbon values, EcoRouting achieved modest carbon savings (5.31%) by selecting alternative routes with lower emission factors. However, this came at the cost of substantial latency penalties (77.92%), illustrating a fundamental trade-off between sustainability and performance. Similar observations were made in prior green networking research, where carbon reduction often required path deviation that increased latency [22]. This suggests that in real-world deployments, static emission environments may limit the operational benefits of carbon-aware routing, unless latency constraints are relaxed.

Scenario 2 revealed the adaptive potential of EcoRouting under time-varying carbon intensity conditions, achieving an average 25.14% emission reduction. The results indicate that temporal awareness allows the routing algorithm to exploit "carbon valleys", periods when emission intensity is lower, by dynamically adjusting paths. Such behavior aligns with the principles of temporal traffic shifting for sustainable networking, as discussed by Nguyen et al. [23]. However, latency increases remained significant (38.59% on average), implying the need for an adaptive cost function that jointly optimizes emissions and delay in real time.

In Scenario 3, the similarity of results between EcoRouting and QoS routing in most cases (90% identical paths) underscores the limitations of carbon-aware routing in emission-homogeneous or topologically constrained networks. This outcome aligns with simulation-based findings by Das et al. [24], who noted that in low-diversity topologies, the opportunity for green optimization diminishes sharply. It also raises the question of whether hybrid routing, combining emission awareness with latency constraints, could yield more balanced outcomes.

Scenario 4 further highlights the influence of network richness. Dense multi-city topologies allowed EcoRouting to identify significantly greener paths, such as a 47.1% emission reduction between Surabaya and Semarang. Conversely, in sparse routes, both methods converged, offering no advantage. This reinforces the notion that network diversity is a key enabler of carbon-aware optimization, a conclusion also reported in large-scale SDN experiments Morales et al. [25].

Overall, the results suggest that EcoRouting's practical deployment should consider:

1) Topology diversity: Dense networks maximize the potential for emission savings.

2) Temporal carbon variability: Real-time data feeds are critical to unlock dynamic optimization.

3) Multi-objective trade-offs: Adaptive weighting between latency and carbon cost is essential for application-specific needs.

A limitation of this study is its reliance on simulated topologies and latency values, which cannot fully capture real-world factors such as congestion, routing policies, and link failures. Future work should incorporate real internet datasets and explore reinforcement learning-based adaptive policies to better balance emission reduction and service quality.

V. CONCLUSION AND FUTURE WORK

This study introduced EcoRouting, a carbon-aware path optimization framework designed to minimize the environmental impact of data transmission in green Internet infrastructures. Across four experimental scenarios, the results demonstrate that EcoRouting can achieve substantial reductions in carbon emissions, up to 47.1% in multi-city topologies, while maintaining network operability. However, these environmental benefits often come at the cost of increased latency, which in some cases reached more than 90%.

The findings highlight that EcoRouting's performance is highly dependent on both network topology and the variability of carbon intensity across the grid. Dense and diverse topologies, as well as environments with significant temporal fluctuations in emissions, offer greater opportunities for carbon optimization. In contrast, homogeneous or topology constrained networks yield limited benefits, as routing alternatives are restricted.

Future research should focus on integrating adaptive mechanisms that dynamically balance carbon reduction and latency in real-time, potentially leveraging machine learning models for predictive routing. Additionally, extending the evaluation to real-world network measurements, beyond synthetic simulations, would provide stronger evidence of EcoRouting's operational viability in production scale Internet infrastructures.

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