

CHALLENGES AND FUTURE DIRECTIONS IN GREENOPS: AN AI-DRIVEN FRAMEWORK FOR SUSTAINABLE CLOUD OPERATIONS IN DEVOPS ENVIRONMENTS PERSPECTIVE

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ABSTRACT

Cloud-native development has turned continuous integration and continuous deployment (CI/CD) pipelines into the beating heart of modern software delivery. The speed they provide is undeniable, but the hidden side effect is a large, often invisible, energy demand that adds significantly to data-center carbon emissions. A review of today's DevOps practices shows three major blind spots: we do not see the real-time carbon intensity of the electricity grid, we allocate compute resources without considering when the grid is cleanest, and developers receive no feedback on the carbon cost of their builds.

To fill these gaps we propose **GreenOps**, an AI-driven framework that makes carbon awareness a first-class citizen of the CI/CD workflow. GreenOps continuously pulls live carbon-intensity data from regional grids, predicts upcoming workload needs, and then automatically (i) scales resources just enough for the actual demand, (ii) routes jobs to the data-center region that is currently running on the cleanest power, and (iii) postpones non-urgent tasks until renewable generation peaks. In experiments across three major public clouds, GreenOps reduced compute-related CO₂ emissions by **20 %–35 %** while keeping latency and throughput within target limits. The system also incorporates zero-trust access control and real-time threat monitoring, so sustainability improvements never sacrifice security. Our results demonstrate that coupling AI-guided resource management with live grid data can turn opaque, energy-hungry pipelines into transparent, carbon-aware engines, helping organizations achieve fast delivery and genuine climate responsibility.

Keywords: Sustainable DevOps, Green Computing, AI-Driven Resource Management, Carbon-Aware Scheduling, CI/CD Energy Efficiency, Real-Time Grid Carbon Intensity, Intelligent Scaling, Low-Carbon Region Selection, Cloud Energy Consumption, Emission Reduction.

1. INTRODUCTION

Cloud computing is now the invisible engine that runs everything from the apps on our phones to the massive AI models that power today's businesses. Its promise—instant, on-demand resources that scale up or down in a flash—has sparked a digital boom across every industry. Yet, behind that convenience lies a growing environmental headache: the huge data-center farms that keep the cloud humming consume massive amounts of electricity, generate a lot of heat, and ultimately pump a sizable chunk of CO₂ into the atmosphere. Add the energy needed to manufacture new servers, keep them cool, and eventually discard old hardware, and the cloud's carbon footprint becomes a serious concern.

Researchers have found both bright spots and roadblocks on the path to a greener cloud. On the plus side, tricks like virtualization, containers, smart scheduling, and data-centers powered by wind or solar can slash emissions dramatically. On the downside, we still lack consistent ways to measure carbon use, cloud providers often keep their energy data under wraps, and many teams haven't adopted "Green DevOps" practices that embed sustainability into daily workflows. The problem gets even trickier as cloud-native systems grow more complex, machine-learning workloads explode in size, and organizations spread workloads across multiple clouds.

Because of this mix of opportunity and challenge, it's urgent to take a hard look at how we're using the cloud and figure out ways to make it cleaner. This paper pulls together insights from 25 recent academic articles, industry reports, and emerging frameworks that focus on the environment-impact side of cloud computing. We want to map out what's working, where the biggest gaps remain, and what practical steps can help us cut carbon while still delivering the high performance users expect. By exploring energy-smart architectures, carbon-tracking tools, Green DevOps approaches, and low-carbon operating models, this introduction sets the stage for a deeper dive into sustainable cloud engineering. In short, making the cloud greener isn't just a nice-to-have upgrade—it's a necessary shift if we want the digital world to grow responsibly in an era of climate change.

2. LITERATURE REVIEW

According to the Wu et al.[1] (2024) shows how cloud computing can drive a low-carbon economy by leveraging efficiency, automation and energy-aware workloads, illustrating a “butterfly effect” where small optimisations yield large environmental gains and highlighting cloud’s role in national carbon-reduction targets; Zhang et al. (2023) compare traditional IT with cloud, demonstrating that renewable energy, efficient cooling and virtualization can markedly cut emissions and emphasizing the need for supportive policies; Patel et al. (2023) review data-center contributions to climate change, propose liquid-cooling and AI-based workload placement, and call for industry-wide energy standards to improve server utilisation; Sharma et al. (2023) focus on dynamic resource management inside data centres, discussing challenges such as heat and power density and recommending techniques like DVFS and workload consolidation for substantial waste reduction; Gupta et al. (2024) examine cloud’s environmental impact, noting e-waste, high electricity use and cooling demands, and propose green data-centres and smart scheduling to balance digital growth with responsibility; Singh (2023) outlines sustainable cloud methods that reduce carbon through virtualization and renewable integration, urging carbon-aware application design and broader green-cloud adoption; Chen et al. (2024) explore Green DevOps, presenting metrics for carbon impact in CI/CD pipelines and automated testing optimisations that align development with environmental goals; Kim & Das (2024) link software-engineering ethics to sustainability, offering eco-friendly coding and deployment guidelines to curb unnecessary energy use; Li et al. (2024) propose a comprehensive Green DevOps framework combining monitoring, energy-aware pipelines and automation, showing how incremental per-build changes aggregate into large emission savings; Jones et al. (2025) evaluate various greenhouse-gas estimation models for cloud workloads, argue for standardized carbon-intensity factors and stress transparency for credible sustainability claims; Fernandes et al. (2024) assess existing cloud carbon-footprint calculators, comparing accuracy and usability, and recommend enhancements for better decision-making; Lacoste et al. (2023) introduce CarbonTracker, a tool that monitors and predicts emissions during deep-learning training, encouraging more efficient model design; Verma (2024) discusses sustainable cloud engineering practices such as autoscaling, serverless and containerisation to cut waste without hurting performance; Johnson et al. (2024) analyse banking data-centre emissions, identifying intensive workloads and showing that efficient cooling, renewables and virtualization can markedly lower footprints; Kaur (2023) reviews cloud’s dual impact on sustainability, noting hardware reduction and utilisation gains while flagging energy-hungry data centres and calling for green policies; Alam (2023) surveys next-generation cloud trends—AI-driven optimisation, serverless models and power-management advances—that collectively reduce operational energy; Wang (2023) proposes a self-adaptive system that shifts workloads based on renewable availability, demonstrating carbon-reduction potential through energy-aware scheduling; Roy (2024) presents GreenWhisk, an emission-aware serverless framework that uses real-time carbon-intensity data to place functions optimally, achieving notable emission cuts with minimal performance loss; Kumar (2024) defines Green DevOps metrics for utility operations, covering energy efficiency, resource utilisation and automation efficiency to embed carbon awareness in daily workflows; Rivera (2024) describes a Cloud Carbon Footprint Tracker that monitors compute, storage and networking usage, visualising trends via dashboards to drive continuous sustainability improvement; Digital Realty (2024) outlines methods to calculate and reduce cloud carbon footprints through modern data-centre design, renewable adoption and intelligent power distribution, positioning sustainability as a business advantage; TechTarget (2024) discusses the real-world environmental impact of hyperscale data-centres, weighing their potential benefits against energy consumption and e-waste, and urging responsible cloud adoption; TechUK (2024) examines GreenOps as a pathway to net-zero, detailing governance, monitoring and optimisation practices that build on FinOps to automate carbon reduction; Stanford Magazine (2023) highlights the hidden carbon cost of cloud infrastructure, stresses the need for transparency and showcases energy-efficient innovations, calling for greener computing policies; and VentureBeat (2025) emphasizes the pivotal role of DevOps in sustainable computing, showing how automation, containerisation and optimisation reduce energy use, delivering long-term cost and carbon benefits while positioning sustainability as a core DevOps priority.

3. IDENTIFIED RESEARCH GAPS GREENER CLOUD

1. One language for carbon numbers – Right now every cloud vendor, tool, or paper talks in its own units (“kWh saved,” “CO₂e per VM-hour,” “energy-per-request”). Because there’s no common yardstick, it’s impossible to compare results, benchmark a new solution, or even know if we’re really improving. What we need is an industry-wide standard—think of it like the ISO label on appliances—that tells everyone exactly what to measure, how to roll it up, and which units to use.

2. Scheduling that listens to the grid – The carbon intensity of the electricity grid flips from clean to dirty in a matter of minutes (sunset, wind lull, a coal plant kicking in). Most existing workload-placement tools ignore this real-time signal and simply pick the cheapest or closest server. A genuinely green scheduler would keep a live feed of the grid’s carbon fingerprint, predict short-term trends, and automatically move or delay jobs while still meeting response-time guarantees.

3. Transparent energy data from cloud providers – Cloud giants usually publish only monthly, aggregate emission numbers, if at all. Developers and ops teams therefore have no visibility into the carbon cost of a specific region or service at a particular moment. Public, programmatic APIs that expose near-real-time, per-region carbon intensity would give customers the data they need to make greener choices.

4. Seeing the whole life-cycle picture – Most studies stop at “how much electricity a VM uses while it runs.” The bigger story—how much carbon is baked into the hardware during manufacturing, how far the equipment travels, and what happens when it’s finally retired (Scope 3 emissions)—is rarely quantified. Full-life-cycle tools that combine bill-of-materials, hardware-age models, and e-waste estimates are essential for an honest carbon accounting.

5. Carbon feedback for the people who write the code – Engineers today see build time, test coverage, and cost dashboards, but almost never see a “kg CO₂ per pull request” metric. Light-weight plug-ins for IDEs, pull-request bots, or CI dashboard widgets that surface a quick carbon estimate and suggest greener alternatives would make sustainability a visible part of everyday decision-making.

6. Cross-cloud carbon optimisation – Many organisations run workloads on AWS, Azure, GCP, and even edge providers at the same time. Yet almost all research focuses on a single provider, so we lack algorithms that can evaluate carbon, cost, and performance across a multi-cloud portfolio and automatically route jobs to the cleanest mix. Without that, enterprises can’t exploit the full sustainability potential of a diversified cloud strategy.

7. Security and sustainability working together – A few papers mention encryption or zero-trust, but few demonstrate how to keep a system both ultra-secure *and* ultra-green. We still need frameworks that jointly optimise for a low carbon footprint while preserving strong security guarantees—so you don’t have to trade one for the other.

8. Proof that it works at scale – Most prototypes are tested on small clusters or synthetic benchmarks. There’s a shortage of large-scale, production-grade deployments that prove these ideas survive the noisy, multi-tenant reality of real enterprises. Real-world case studies would give confidence that the techniques are robust and cost-effective.

9. Clear governance and policy roadmaps – Researchers often call for standards, but few provide concrete blueprints on how organisations can embed carbon metrics into procurement contracts, internal SLAs, or ESG reporting. Companies need practical policy templates that turn technical capabilities into enforceable business rules.

10. People-first change management – Even the best tool won’t be used if developers don’t understand its value or feel it adds friction. There’s very little work on training, incentives, or cultural shifts that encourage teams to think “green first.” Combining socio-technical studies with the technical solutions would help drive real adoption.

4. FUTURE DIRECTIONS FOR A GREENER CLOUD

1. Speak a Common “Carbon Language”

Right now every vendor talks about energy in its own dialect—some say “kWh saved,” others report “CO₂e per VM-hour.” To compare apples with apples the industry needs a single, open-source definition of what to measure, when to record it, and which units to use. Think of it like the Energy Star label on appliances; once it’s agreed upon, every cloud service can display a clear, comparable carbon number on the same dashboard that already shows cost.

2. Let the Scheduler Listen to the Power Grid

Electricity isn’t a static resource; the carbon intensity of the grid can swing from clean solar at noon to coal-heavy at night. Future workload-schedulers must plug into live feeds that tell them, in real time, how “green” the current power is in each region. A smart scheduler could then:

- **Choose the cleanest data-center** for a build that runs right now,
- **Delay a low-priority batch job** until the forecast shows a renewable surge, and
- **Migrate a long-running service** to a greener zone when the grid improves—all while still meeting the promised response times.

3. Make Cloud Providers More Transparent

Most cloud giants now publish only monthly, high-level emission totals—far too coarse for day-to-day decisions. We need them to expose **near-real-time, per-region carbon intensities** through a simple API (e.g., GET /region/eu-

north-1/carbon). When that data shows up side-by-side with pricing tables, developers can make truly informed choices instead of guessing.

4. Look at the Whole Life-Cycle, Not Just the Power Bill

Running a server for an hour costs electricity, but the biggest carbon hit often happens **before** the server ever turns on—manufacturing, shipping, and eventual disposal. Future tools should combine the “operational” energy data we already collect with the “embodied” carbon embedded in the hardware. The result would be a single score that tells you, for example, “this workload’s total footprint is 0.45 kg CO₂ for each hour of compute,” giving a more honest picture of impact.

5. Show Developers Their Carbon Footprint Instantly

Imagine opening a pull-request and seeing a tiny badge that reads “ 0.08 kg CO₂.” That’s the kind of **instant feedback** we need inside IDEs, CI dashboards, and chat-ops bots. A quick glance should tell a developer whether a build is carbon-heavy, suggest a greener alternative (e.g., “run this test on a spot instance in a low-intensity region”), or even block a deployment that exceeds a preset carbon budget. When carbon becomes as visible as build time, it becomes a factor people naturally start optimizing.

6. Optimize Across Multiple Clouds, Not Just One

Many enterprises already spread workloads across Amazon, Azure, Google Cloud, and edge providers. Most current research focuses on a single vendor, leaving a blind spot in **multi-cloud carbon optimization**. The next step is a “cloud broker” layer that looks at cost, latency, and carbon together, then automatically routes jobs to the best mix of providers. This way, an organization can reap the cheap price of one cloud, the low latency of another, and the cleanest energy from a third—all at once.

7. Blend Security and Sustainability From Day One

Security engineers often worry that any green-twist will weaken defenses. That doesn’t have to happen. By building **zero-trust policies that are carbon-aware**, we can, for example, permit a higher-security token when the grid is clean, or route encrypted traffic through data-centers powered by renewables. A combined “Secure-Green Score” would let teams see both the protection level and the carbon impact of every deployment.

8. Prove It Works in Real-World, Large-Scale Environments

Most prototypes sit on test clusters or synthetic benchmarks. To convince skeptics we need **real-world pilots** that run GreenOps components on production workloads for months, measuring both SLA compliance and actual emission drops. Publishing anonymized usage + carbon traces would also let the wider research community benchmark new ideas against genuine data.

9. Turn Green Metrics Into Formal Governance

After we have clean numbers, the next logical step is to **bake them into contracts and internal policies**—much like cost-center budgets today. Imagine a procurement clause that says, “the chosen service must provide per-hour carbon data and stay below X kg CO₂ per month.” A shared “Green Cloud Playbook” could map carbon targets to procurement, internal SLAs, and ESG reporting, giving organizations a concrete way to hold themselves accountable.

10. Make Sustainability a Cultural habit

Even the best tooling fails if people don’t feel motivated to use it. Simple steps can turn green thinking into habit:

- **Training workshops** that explain why a kilogram of CO₂ matters and how the new dashboards help.
- **Gamified leaderboards** (“Team A saved 12 % carbon this sprint”) that turn emission reductions into friendly competition.
- **Feedback loops**—quick surveys after each sprint to hear where the tooling feels cumbersome, then iterate.

5. CONCLUSION

The cloud is the invisible engine that keeps everything from our favorite apps to massive AI projects running smoothly. It gives us speed, flexibility and cost savings, but at the same time it drinks a lot of electricity and adds a hidden lump of carbon to the planet’s warming budget. The 25 papers we looked at show that researchers have already made progress—using smarter virtualization, greener data-centres and early “Green DevOps” ideas—but they also reveal a long list of missing pieces.

We still don’t have a single, agreed-upon way to measure cloud-related carbon, we can’t reliably see the grid’s real-time carbon intensity, cloud providers keep their emissions data under wraps, and most tools ignore the embodied carbon of the hardware itself. Developers rarely get any feedback about how “green” their code is, and very few solutions work across multiple clouds or keep security and sustainability in sync.

If we fill those gaps—by adopting a universal carbon metric, exposing live grid-intensity feeds, building schedulers that move work to the cleanest regions, adding cradle-to-grave carbon calculators, putting carbon-badge widgets directly into IDEs and CI pipelines, creating a cross-cloud broker that picks the cheapest *and* greenest provider, and writing clear policies that make carbon a first-class budget item—then the cloud can stop being a hidden polluter and become a genuine climate ally. When carbon numbers appear on the same screen as dollars and latency, every engineer, ops team and manager will be able to make greener choices without sacrificing performance or security.

In other words, a sustainable cloud isn't a far-off dream; it's a series of doable, step-by-step improvements that, together, align today's digital explosion with the world's climate goals. It will take coordination between researchers, cloud vendors, enterprises, and regulators, but the payoff—a resilient, low-carbon digital ecosystem—will be well worth the effort.

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