

# Enabling Carbon-aware Edge System Design

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## Abstract

Edge devices are often deployed at scale, yet their environmental impact, shaped by complex interactions between hardware choices, workload demands, and deployment context, has been overlooked by the mobile computing community. My work, *MicroGreen*, is the first design space exploration framework that enables edge system designers to move beyond cost and energy-efficiency to optimize end-to-end life cycle emissions. Leveraging on my prior work, *CarbonClarity*, which provides robust probabilistic embodied carbon modeling for integrated circuits, *MicroGreen*-guided heterogeneous design reduces total carbon emissions by 47.72% over a homogeneous baseline for visitor counter deployments across Central Park. Building on this foundation, I envision embedding carbon awareness directly into EDA toolchains, encompassing embodied carbon estimates and lower-carbon substitutions at design time, and to instantiate context-specific circuit designs from *MicroGreen*'s deployment-aware recommendations.

## CCS Concepts

• **Hardware** → PCB design and layout; Design databases for EDA; Impact on the environment; • **Computer systems organization** → Embedded hardware.

## Keywords

Sustainable Computing, Edge Computing, Internet of Things, EDA toolchain, heterogeneous deployment

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## 1 Introduction

Edge computing is experiencing rapid, large-scale expansion, spanning smart cities, critical infrastructure, and personal environments, with billions of devices deployed and growing exponentially. At this scale, the environmental consequences of edge system design decisions are enormous, yet sustainability remains significantly understudied by the mobile computing community. Building edge systems responsibly therefore demands that sustainability be treated as a first-class design objective.

Edge devices are often standalone once manufactured, making embodied carbon, emissions from manufacturing processors, PCBs,

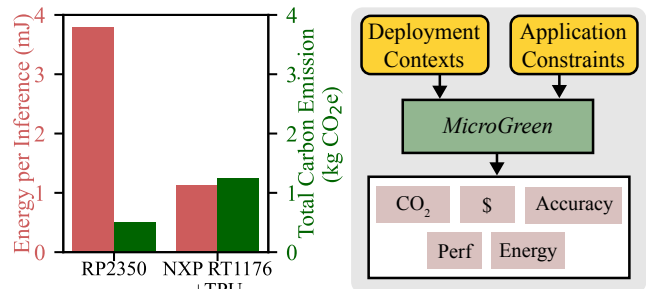


Figure 1: Left: Higher energy efficiency does not mean lower carbon emissions, as shown by two systems built using different MCUs, running keyword spotting at 1 inference per second under 900 W/m<sup>2</sup> solar radiation. The total carbon emissions here includes not just the MCU used but also energy harvesting devices and other necessary peripheral components. Right: *MicroGreen* incorporates ambient energy, usage frequency and deployment factors to estimate carbon across scenarios.

sensors, and batteries, the dominant factor, accounting for nearly 75% of their total lifecycle footprint [5]. This means the carbon emission of an edge device is largely decided at design time. Yet deployment conditions such as solar availability, duty cycle, and peripheral requirements vary widely across sites, making sustainability deeply context-dependent. Optimizing edge systems solely for energy efficiency is therefore a poor proxy for sustainability.

This gap motivates my research, *MicroGreen* [3]. By reasoning over the full lifecycle of edge devices, spanning hardware choices, workload demands, and deployment environment, *MicroGreen* reveals a counterintuitive insight: *energy efficiency does not equal carbon optimality*. As shown in Figure 1, the most energy-efficient processor can paradoxically carry higher total emissions. Manufacturing costs and peripheral requirements, such as larger solar panels for a power-hungry MCU, can dominate the total carbon budget. Designing sustainable edge systems therefore requires holistic reasoning that co-optimizes hardware selection, workload characteristics, and deployment environment. I further incorporate uncertainty estimation in carbon modeling to enable robust, carbon-aware design under real-world variability [2]. I demonstrate the effectiveness of this approach through visitor counter deployments across three Central Park entrances, each with distinct solar availability and visitor flow patterns; *MicroGreen*-guided heterogeneous design reduces total carbon emissions by 47.72% over a homogeneous baseline.

Yet realizing heterogeneous deployment in practice remains out of reach for most practitioners. Translating a context-specific system recommendation into a manufacturable, field-ready board requires manual effort across entirely disconnected tools, with no shared notion of carbon as a design dimension. I plan to address this gap by grounding *MicroGreen*'s carbon-aware reasoning directly into EDA toolchains. This spans component databases with



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annotated carbon emission information, automated schematic generation, and seamless integration with existing design workflows. Together, these advances aim to lower the barrier to sustainable edge system design, making carbon-aware heterogeneous deployment streamlined and accessible at scale.

## 2 MicroGreen and CarbonClarity

MicroGreen [3] is a design-time framework that takes application requirements (e.g. ML workload, inference rate, deployment lifetime) and environmental inputs (e.g. solar irradiance, location) and identifies Pareto-optimal device configurations across carbon, cost, and performance. It rests on three pillars: (1) **component-level embodied carbon modeling** using LCA databases and semiconductor carbon models [1, 2, 4, 9], decomposing each device into ICs, PCBs, capacitors, batteries, solar panels, etc.; (2) **workload-aware profiling** of eight COTS microcontrollers across six edge ML benchmarks; and (3) **environment-aware design space exploration** that integrates solar traces and power mode to model how ambient energy shifts total carbon over deployment lifetime.

A key enabler of *MicroGreen's* carbon-aware reasoning is robust embodied carbon estimation. To this end, I developed *CarbonClarity* [2], a probabilistic framework that models embodied carbon footprints as distributions rather than deterministic point estimates, capturing spatiotemporal variability in fabrication yield, energy per area, greenhouse gas emissions, and grid carbon intensity across technology nodes. I integrate *CarbonClarity's* uncertainty-aware SoC carbon estimates into *MicroGreen's* component-level modeling, ensuring Pareto-optimal recommendations account for both expected carbon costs and supply chain variability risk.

My evaluation of *MicroGreen* reveals that ambient energy availability, inference rate, and deployment lifetime jointly determine carbon-optimal design, yielding differences of over an order of magnitude. Neither energy efficiency nor cost reliably approximates sustainability. Designers must also strike a balance between local inference and data offloading, as remote processing can be more carbon-efficient for less capable processors.

Applying *MicroGreen* to three Central Park entrances with distinct solar availability and visitor flows, I demonstrate that heterogeneous location-aware deployment reduces total carbon by 47.72% over four years compared to a homogeneous baseline, while meeting all sensing and communication requirements.

## 3 Vision: Design Automation for Carbon-Aware Heterogeneous Systems

The 47.72% savings demonstrated above is practically inaccessible today: translating a context-specific *MicroGreen* recommendation into a manufacturable board requires manual effort across disconnected tools, none of which treat carbon as a design dimension. I envision two complementary efforts that close this gap.

**Carbon-aware component inventory and substitution.** A core barrier to carbon-aware design is the absence of any notion of carbon emissions within EDA tools. I propose automatically generating embodied carbon estimates for components in EDA tool inventories, drawing on *MicroGreen* [3]'s LCA methodology and *CarbonClarity* [2]'s uncertainty modeling to estimate component- and system-level emissions at design time based on application

requirements. This enables designers to inspect the estimated carbon footprint of their system as they build it. Extending the spirit of ecoEDA [8], the tool would also provide component substitution suggestions, lower-carbon alternatives that preserve electrical validity, directly within the design environment.

**Context-specific circuit design via hardware abstraction.** Beyond component-level substitution, I plan to leverage hardware description languages such as Polymorphic Blocks [6, 7] to define baseline edge system templates: abstract designs spanning processor, memory, wireless, sensing, and power subsystems. Given application constraints and deployment context, *MicroGreen* [3] selects the carbon-optimal configuration for each scenario and instantiates it as a concrete, context-specific circuit design. Rather than a single homogeneous board, a fleet deployment automatically yields a family of schematics, each tailored to its environment, without requiring designers to manually navigate the tradeoff space that *MicroGreen* already reasons about.

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