Workshop: Sustainability in Electronics Design

Project Report

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Abstract

Sustainability too often takes a back seat in engineering curricula, despite the mounting environmental challenges that demand we rethink how we design technology. To prepare the next generation of innovators, it is essential to embed environmental impact analysis at the very start of the engineering process. We introduce a workshop to equip undergraduate ECE and CS students with a solid understanding of embodied versus operational carbon, providing them with the tools to quantify a product's carbon footprint and appreciate how each design decision contributes to its overall impact.

At the heart of the course is a hands-on comparison activity: teams will build two paper circuits—one traced with copper tape, the other with conductive carbon ink. By calculating each material's embodied carbon and estimating operational carbon through simple power-consumption measurements, students will directly observe the trade-offs between performance and environmental cost. This exercise not only reinforces life-cycle assessment methods but also empowers students to make informed, sustainable choices in their future designs.

Contents

1. Introduction

1.1. Motivation

Sustainability in engineering is no longer a concern we can ignore, but rather a core imperative we need to address. The electronics sector alone is responsible for 2 - 4% of the global greenhouse gas emissions, a percentage that only continues to increase as technology becomes more ubiquitous and data-center demand expands [2]. Yet, most engineers receive little to no formal training in assessing or mitigating these impacts. In traditional curricula, topics such as embodied and operational carbon and life-cycle assessments (LCA) are at best treated as afterthoughts. As a result, engineering graduates enter industry or research without the tools or mindset to design truly sustainable systems from the outset.

This workshop's motivation is twofold. First, it addresses a clear educational gap: the absence of practical, quantitative sustainability training in undergraduate engineering programs. Second, it responds to an industry need: electronics companies are setting net-zero emissions targets, but meeting those goals requires engineers who understand both embodied and operational carbon pain points. By combining an interactive lecture, relevant examples, and a culminating circuit-construction LCA activity, we create a learning experience that is both theoretically rigorous and practical. Students will leave with a sustainability toolkit that they can immediately apply to any future electronics design challenge.

1.2. Objectives and Scope

The workshop has several pedagogical and technical objectives:

1. **Conceptual Understanding**: Introducing students to the components of carbon footprint - embodied and operational carbon - and familiarizing them with the Life Cycle Assessment as a formal methodology of quantifying a product's environmental impact.

2. **Application**: Students apply knowledge in a tangible material trade-off exercise by building two paper circuits, while calculating the embodied carbon by material usage and estimating the operational carbon using battery output.

3. **Systems Thinking**: Prompt students to consider how individual parts fit in with entire product life-cycles and identify sustainability trade-off strategies.

This workshop is intentionally scoped to provide an entry-level introduction to sustainable electronics design for undergraduate Computer Science, Computer Engineering, and Electrical Engineering students. However, the principles introduced in our workshop may apply to all engineers and beyond.

2. Workshop Focus

2.1. Operational vs. Embodied Carbon

Every electronic product's total greenhouse gas emissions are split into two distinct categories:

- **Embodied Carbon**: Emissions associated with raw-material extraction, component manufacturing, assembly, transportation, and end-of-life processing.
- **Operational Carbon**: Emissions incurred as the device consumes energy during its life.

These carbon values are measured in Carbon Dioxide Equivalent Units (CO_2e), which is the standard that expresses the combined impact of all greenhouse gases in terms of the equivalent mass of CO_2 so you can aggregate and compare diverse emissions on a common scale.

In the majority of consumer electronics, LCA studies show that embodied carbon accounts for the majority of lifetime CO_2e. Typically, production and material processing contribute 60-80% of total product emissions, with operational emissions contributing the remaining 20-40% [1]. For a typical laptop, 70-80% of total emissions are incurred primarily by semiconductor fabrication and PCB manufacturing [2]. By contrast, high-capacity systems such as data centers produce significant operational carbon emissions due to continuous electricity draw over multiple years [1].

The divergence in carbon emissions production underscores the need to treat both embodied and operational carbon as important design constraints. Optimizing only energy draw may leave savings, achievable through material or process modifications, on the table; however, focusing solely on low-cost materials may incur significant operational costs.

2.2. Life Cycle Assessment Basics

Life Cycle Assessment (LCA) is a standardized, formal, four-phase methodology for quantifying environmental impacts [3]. The four phases are as follows:

1. **Scope Definition**: Identify the purpose of the LCA and system boundaries.
2. **Inventory Analysis**: Compile relevant material and energy inputs and environmental outputs across life-cycle stages.
3. **Impact Assessment**: Define the significance of inventory data as impact indicators.
4. **Interpret**: Evaluate data and generate recommendations for improvements.

These phases are used to ensure transparency, consistency, and comparability across LCA studies. Despite such a methodological structure, LCAs consistently show non-obvious leverage points to guide engineers towards effective carbon-reduction strategies.

2.3. Engineering for One Planet Framework

Engineering for One Planet (EOP), launched by The Lemelson Foundation and Venturewell, provides a comprehensive, pedagogical model to incorporate sustainability into engineering education. EOP defines nine topic areas that are applicable across engineering disciplines and serve as a practical solution for organizing topics. Our workshop addresses each of these topics:

1. **Systems Thinking**: Students perform an end-to-end analysis of a device's environmental impact and reflect to consider how choices at one stage ripple through an entire electronics system.

2. **Environmental Literacy**: We introduce key topics such as embodied and operational carbon using clear definitions and real-world examples.

3. **Responsible Business and Economy**: Students learn to weigh environmental benefits against cost and complexity, simulating corporate trade-off analyses.

4. **Social Responsibility**: Our activities role-play as a sustainability-first electronics company, for students to consider the implications of material and design decisions.

5. **Environmental Impact Assessment**: The workshop teaches the formal four-phase LCA process and guides students through an LCA in our activity.

6. **Materials Selection**: In our hands-on activity, students will compare two different materials - copper tape and carbon paint - to evaluate the embodied carbon produced against their perceived performance.

7. **Design**: Students design circuits under emissions and performance constraints, considering different materials and applying circular-design principles for disassembly and recyclability.

8. **Critical Thinking**: Structured "pause and think" breaks to help students digest information and debriefs for students to consider practical, hypothetical questions.

9. **Communication and Teamwork**: Our culminating activity will be done in groups, for students to consider each other's sustainability priorities and engineering design choices.

3. Workshop Design and Methodology

3.1. Learning Objectives

By the end of our workshop, students will be able to:

1. Differentiate embodied carbon and operational carbon in electronics, and explain what contributes to each.
2. Apply a Life-Cycle Assessment to quantify the environmental output for an electronic device.
3. Quantify how material choices and energy use contribute to an electronic device's overall carbon output.
4. Evaluate sustainability and functionality by evaluating carbon-performance tradeoffs in sustainable electronics.
5. Integrate energy-saving strategies in both engineering practice and daily life to minimize carbon impact.

3.2. Target Audience and Prerequisite Knowledge

This workshop is designed for undergraduate students, specifically first- and second-year students in Computer Science, Computer Engineering, and Electrical Engineering programs. Participants would typically come into the workshop with foundational electronics knowledge and exposure to basic circuit assembly and analysis to benefit the most from the hands-on activity. Due to the time limit and introductory format of the course, this makes it ideal for students early in their degree program who have not yet encountered formal sustainability concepts, but can begin applying engineering knowledge with real-world design trade-off considerations.

Even though this course is still applicable to third-year, fourth-year, and even graduate students, having students consider sustainability early in their education helps to ensure that environmental thinking becomes second nature, shaping their design habits and decision frameworks from the beginning.

3.3. Instructional Framework

Our workshop is structured around an instructional framework that aligns the learning objectives with the activities and assessments, while following the EOP framework as closely as possible.

3.3.1. Structured Learning

We break our workshop into three brief and focused segments. The first two segments, titled "Carbon Footprint" and "Life Cycle Assessment," are lecture-based and provide students with the introduction needed to understand and apply such topics. In each section, we have embedded "Pause and Think" breaks for students to digest the information. At the end of each section, there is a more in-depth question for students to link these abstract concepts to practice. Our last section is the hands-on activity, which is based on applying the material learned throughout the workshop.

3.3.2. Assessment and Reflection

The embedded "Pause and Think" slides serve as a checkpoint for the instructor and students to ensure that everyone is on the same page. This continuous check helps to identify unclear spots in our curriculum and ensure everyone reaches the same level of understanding by the activity.

3.3.3. Hands-on Activity

To help students apply the information, we incorporated a hands-on activity that is a circuit-designing activity that combines abstract sustainability metrics into a design challenge. The direct experience of designing a usable circuit while having to calculate the embodied and operational carbon along the way solidifies the link between life-cycle thinking and real-world engineering choices.

3.4. Activity Description

The centerpiece of our workshop is a circuit-building activity that is designed to consider a real-life trade-off between carbon footprint and performance. We want students to:

1. See how material choice affects performance
2. Practice quantitative trade-offs with real materials
3. Consider how small design choices have big sustainability impacts

Students will work in teams to design, build, and analyze two paper circuits - one created using copper tape traces and one using conductive carbon-based ink - to explore the full life-cycle carbon impacts of using different materials. Each team will receive the following materials:

- A sheet of grid Cardstock

- A strip of copper tape
- A container of carbon ink
- One standard LED
- One D battery (9 V)
- A worksheet guide

Students must create two closed-loop circuits when the LED and battery are attached using the two provided materials, carbon paint and copper tape, that each accomplish the following:

1. The circuit must light up exactly 1 LED
2. The circuit path must cover at least 20 squares of distance
3. The circuit must fit within the board

3.4.1. Embodied Carbon

After constructing the circuit, students will record the number of squares each trace covers and use the provided carbon costs ($g/sq.$) to calculate the production costs of their boards.

$$C_{Production} = CircuitLength * CarbonCost$$

Additionally, students will choose one extra step of the embodied carbon process - material extraction, processing, or distribution - to calculate as well. We also provide a fixed disposal cost for the boards for students to calculate with. Then, adding the production and disposal costs, we can estimate the embodied carbon.

$$C_{Embodied} = C_{choice} + C_{production} + C_{disposal}$$

3.4.2. Operational Carbon

To estimate the operational carbon of the circuit, we use a simplified, standard equation for LCA studies for battery-powered electronics. It simply multiples the battery's stored energy by a grid-intensity emission factor to estimate the use-phase CO_2e.

$$C_{Operational} = 0.45 * V_{battery} * Q_{battery}$$

where,

- Electricity generation emits about $0.45kg$ of CO_2e per kWh, equivalent to $0.45g$ CO_2e per Wh.
- $V_{battery}$ is the voltage of the battery in volts (V).
- $Q_{battery}$ is its capacity in milliampere-hours (mAh).

4. Implementation and Timing

4.1. Section Flow and Timing

This workshop was split into several different sections to balance content instruction, student engagement, and hands-on work.

1. **Pre-Assessment** (2 minutes)

   Students fill out a pre-survey tailored to evaluate the students' current knowledge of sustainability and demographics.

2. **Welcome and Introduction** (5 minutes)

   Students are introduced to the workshop, motivation, and objectives.

3. **Carbon Footprint** (10 minutes)

   Introducing embodied and operational carbon definitions and presenting graphs that compare the carbon footprint percent splits for various electronics.

4. **Pause and Think** (3 minutes)

   Students reflect on the carbon percentage breakdowns that were introduced by the graphs in the previous section.

5. **Open Discussion** (3 minutes)

   "How do you consider the full life cycle of a product?" - Segues into the next section about LCA, where we introduce a formal mechanism of quantifying carbon costs and considering a product's life cycle holistically.

6. **Life Cycle Assessment** (10 minutes)

   Introduce the definition, steps, use cases, and online resources for a life cycle assessment.

7. **Pause and Think** (3 minutes)

   Students reflect on the true purpose of an LCA and any potential shortcomings that an LCA may not address.

8. **Material and Energy Tradeoffs** (12 minutes)

   Present how materials and energy may be traded off to create electronics that are sustainable but still meet performance requirements. Pose an open-ended question for students to consider: "How might you design for a device meant to run for 10 years versus one meant to last 1 year?"

9. **Circuit-Design Activity** (25 minutes)

   Introduce the activity, and have students perform it.

10. **Wrap-Up and Examples** (5 minutes)

    Present examples in industry where carbon cost and performance tradeoffs were considered.

11. **Post-Assessment** (2 minutes)

    Students fill out a post-survey

Total Time: 80 minutes

4.2. Assessments

To align the students' engagement with our presentation of the topic, we employed a multi-method assessment strategy to set benchmarks for the students. Both assessments include Likert scale questions as well as free-response questions.

4.2.1. Pre-Assessment

Purpose: Establish baseline familiarity with sustainability topics.

Our questions were designed to have the student consider their perspective on sustainability prior to the workshop. We wanted to know whether they typically consider sustainability when going about their lives as well as when using and purchasing electronics. Questions include:

1. I have a clear understanding of how the production, use, and disposal of electronics can impact the environment.

2. I consider the overall environmental impact of my personal consumption and lifestyle choices.

We also wanted to measure the students' outlook on sustainability and whether they feel their actions make an impact, as part of measuring common challenges with sustainability. We included questions such as:

1. I believe my everyday actions (e.g., recycling, conserving energy, choosing sustainable products) have a measurable impact on reducing environmental impact.

2. I'm confident in my ability to influence positive changes toward sustainability in my field.

Our final section included free-response questions to see how students articulate their perspective on sustainability.

1. In your own words, define what sustainability means to you.

2. In your opinion, what factors are most important when assessing how sustainable a product is?

4.2.2. Post-Assessment

Purpose: Measure changes in students' understanding of sustainability and gather feedback about the workshop

Questions in the post-assessment mirrored those of the pre-assessment because we wanted to see how our workshop had affected their understanding, perspective, and outlook on sustainability. As a result, our Likert scale questions remained the same to measure shifts in sentiment. We also included direct "quiz-style" questions to check students' understanding of the workshop material. For example, we incorporated questions such as:

1. What does LCA stand for?

2. True or False: LCAs evaluate environmental impacts from product inception to disposal.

Lastly, we included a section to measure the workshop's relevance and impact, with questions like:

1. How has your understanding of sustainability in technology evolved after participating in this workshop?

2. What is the most valuable insight you gained regarding the balance between performance and sustainability in technology design?

5. Discussion

We were able to do a few test runs of our workshop with various undergraduate students, so our initial results and perceptions are as follows.

5.1. Successes

Generally, sentiment towards our workshop was positive, as it was informative about sustainability and provided information that students don't learn in their standard engineering classes, but still think is relevant to know.

It seemed that we hit all our learning goals, and students were able to digest information and regurgitate it at the level we aimed for. Nearly all teams were successful in completing our activity, which helped to reinforce the material. Lastly, from our post-assessment, average scores for Likert scale questions all generally increased.

5.2. Challenges

It was difficult to get the timing of our workshop down perfectly, leading to some groups unable to finish the activity or having to rush the end of it, which resulted in a few errors or incomplete sections. We could have benefited from allocating more time for the activity or expanding the length of the workshop.

6. Recommendations and Future Work

6.1. Enhancing Activities

To fit within our time constraints, we couldn't implement some of the ideas we had in mind. To challenge students from a variety of technical backgrounds and make the activity more applicable to third- and fourth-year undergraduates, we wanted to implement different levels of difficulty. We initially start with a simple single-LED circuit, but allow the students to explore other concepts, such as circuits in parallel, control logic, or attaching sensors and switches. After the building phase, there will be a transition into the peer-teaching phase, where each team will deliver a short run-through of the circuit they've built. This format will reinforce technical concepts, as teaching demands a deeper understanding, while also allowing students to compare their performance metrics.

Finally, we considered adding a reflection exercise along with the post-assessment. This would allow students to reflect on decisions they made when building the circuit and consider how the current activity could influence their views on sustainability in the future.

6.2. Scaling

To improve the workshop's scalability, we would want to package our materials into a standardized kit to distribute to other departments. Each kit would include the materials students needed to perform our activity. This would save time during the workshop as well as create an option for students to take the activity home to do as well.

We want to consider expanding this into an entire full-quarter or full-semester course at the introductory level for students to take. This would ensure students get introduced to sustainability concepts early in their engineering curriculum, to have it ingrained in their work. We could then design full assignments, quizzes, and progress checks to ensure students can understand and apply this information.

Lastly, we want to expand beyond targeting this workshop for ECE and CS students. Sustainability topics are crucial to all engineering disciplines, and everyone, engineers and beyond, could benefit from the lessons of carbon footprint, life-cycle analysis, and performance-cost tradeoffs.

7. Conclusion

This workshop demonstrates that even a brief, targeted lesson on sustainability can substantially boost students' competence in sustainable design. By clearly defining learning objectives, presenting digestible information, and guiding students through a hands-on circuit design activity, participants were not only able to grasp sustainability concepts such as carbon footprint and Life Cycle Assessment, but also practice quantifying and applying them in real-time. Indications from our assessments showed growth in students' abilities to make data-driven design trade-offs.

Beyond the immediate outcomes, the workshop provides a clear and scalable model for integrating sustainability into core engineering education. With a few slight adjustments, future iterations of the workshop will deepen students' relationship with sustainability as engineers.

Most importantly, by engaging students early - before they develop habitual design practices - we lay the foundation for a generation of engineers who consider environmental impact in their projects before they finish them. The skills and mindsets developed through our workshop will empower engineers to champion sustainable innovation and put our planet first.

Bibliography

[1] Lotfi Belkhir and Ahmed Elmeligi. Assessing ict global emissions footprint: Trends to 2040 recommendations. *Journal of Cleaner Production*, 177:448–463, 2018.

[2] Charlotte Freitag, Mike Berners-Lee, Kelly Widdicks, Bran Knowles, Gordon Blair, and Adrian Friday. The climate impact of ict: A review of estimates, trends and regulations, 2021.

[3] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B.P. Weidema, and D.W. Pennington. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5):701–720, 2004.