Is TinyML Sustainable?
Assessing the Environmental Impacts of Machine Learning on Microcontrollers

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TinyML can support the SDGs but comes with costs. What is the net impact?
Is TinyML Sustainable?
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1. Applications of TinyML for Sustainability
2. Environmental Impact of an Individual MCU
3. Environmental Footprint of TinyML Systems
4. TinyML at Scale

Positive Effects of TinyML
Environmental Footprint
Net Impact at Scale
Applications of TinyML for Sustainability
TinyML Show and Tell

15:00  **Day Opening 5’**

15:05  **Selected Show and Tell Talks 2’**  
Speaker: Brian PLANCHER (Barnard College, Columbia University, USA)

15:10  **Smart Poultry Farm: TinyML-Based Disease Detection System Through Audio Signal 20’**  
Speaker: Segun ADEBAYO (Bowen University, Nigeria)

15:30  **Leveraging TinyML for Tracking Eidolon Helvum Movement Pattern and Forage Technique 20’**  
Speaker: Oluwatobi Halleluyah AwORINDE (Bowen University, Nigeria)

15:50  **Developing a "personal trainer" with TinyML 20’**  
Speaker: Ricardo CARMO (Federal University of Itajubá, Brazil)

16:10  **Sleep Apnea Detection System Using 20’**  
Speaker: Helen Neena GOVEAS (BITS Pilani, K K Birla Goa Campus, India)

16:30  **Rainfall estimation using Audio Monitoring and TinyML 20’**  
Speaker: Blessed GUDA (Carnegie Mellon University, Nigeria)

16:50  **Development of a TinyML Framework for Crop Disease Classification Tasks on Constrained Embedded Devices 20’**  
Speaker: Rehema Hemis MWAWADO (Sokoine University of Agriculture, Tanzania)

17:10  **Word recognition in Kichwa using audio and low-power devices: a machine learning approach for alert applications 20’**  
Speaker: Karina ORTEGA AVILÉS (Escuela Superior Politécnica del Litoral, Ecuador)

17:30  **DTMF Demodulation: A Brief Investigation of Machine Learning for Digital Signal Process 20’**  
Speaker: Umar Hadiza YUSUF (Carnegie Mellon University, Nigeria)

17:50  **Day Closing 10’**
Zero Hunger & Good Health and Well-Being (SDG #2 & #3)

Nuru, an ML app more accurate than humans at detecting plant diseases. Increased a farmer’s sales by 55% & yields by 146%.

Tiny drones can provide targeted pesticide applications that reduce use to 0.1% of conventional blanket spraying.

Using Edge Impulse, a system was prototyped to identify mosquitoes by wing beats sounds with 88.3% accuracy.
Life on Land & Below Water
(SDG #14 & #15)

Rainforest Connection uses recycled smartphones for solar-powered listening devices to warn of deforestation efforts.

RESOLVE’s AI camera transmits notifications of elephant detection and can run for more than 1.5 years on a single battery.

To prevent collisions with whales in busy waterways, Google deployed a TinyML model on hydrophones to alert ships.
Climate Action (SDG #13)

Ribbit Network is **crowdsourcing world’s largest greenhouse gas emissions dataset** through distributed intelligent sensors.

TinyML can help provide intelligence to **tiny robots like the Robobee** that can be used as artificial pollinators.

Smart HVAC systems show a **20-40% reduction in building energy usage.**
Environmental Impact of an Individual MCU
How might you be able to quantify the environmental impact of an MCU?

- End of Life
- Logistics
- Use
- Raw Materials
- Production: Other
- Production: Energy Consumption

https://www.st.com/content/st_com/en/about/sustainability/sustainable-technology.html
Energy Consumption During Production Dominates the Small Footprint

Reuse of old MCUs would greatly improve their sustainability!

<table>
<thead>
<tr>
<th>Total Impact</th>
<th>390g CO₂-eq</th>
<th>23L 23 bottles of water</th>
<th>120mg P-eq 0.2 washing cycles</th>
<th>823mg NMVOC 2.7km by car</th>
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| End of Life | <1% | <1% | <1% | <1% |
| Logistics   | 1%  | <1% | <1% | 1%  |
| Use         | 8%  | 6%  | 28% | 8%  |
| Raw Materials | 10% | 41% | 27% | 10% |
| Production: Other | 25% | 15% | 18% | 2%  |
| Production: Energy Consumption | 56% | 39% | 27% | 71% |
Environmental Footprint of TinyML Systems
Real TinyML Systems are more than just an MCU!

What else is in a TinyML System?

Sensors, Casing, Power Supply, and more!
Real TinyML Systems are more than just an MCU!

- Color, brightness, proximity and gesture sensor
- Digital microphone
- Motion, vibration and orientation sensor
- Temperature, humidity and pressure sensor
- Arm Cortex-M4 microcontroller and BLE module
## Building Representative Systems

<table>
<thead>
<tr>
<th>Cost Level</th>
<th>High Cost</th>
<th>Medium Cost</th>
<th>Low Cost</th>
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<tbody>
<tr>
<td>Application</td>
<td>Image Classification</td>
<td>Keyword Spotting</td>
<td></td>
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<tr>
<td>Size</td>
<td>Large</td>
<td>Compact</td>
<td>Compact</td>
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Building Representative Systems

Total Life Cycle Emissions (kg CO₂-eq)

- Power Supply (3 years)
- Sensing Module
- Transportation
- Casing, PCB, and User Interface
- Processing (e.g., MCU, Memory)
- ML Training
- Other (e.g., Product Use, End of Life)

TinyML
- High Cost
- Medium Cost
- Low Cost
TinyML Systems in Context

<table>
<thead>
<tr>
<th></th>
<th>16-inch MacBook Pro</th>
<th>Apple Watch Series 7</th>
<th>TinyML High-Cost</th>
<th>TinyML Medium-Cost</th>
<th>TinyML Low-Cost</th>
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<tbody>
<tr>
<td>Total Life Cycle Emissions (kg CO₂-eq)</td>
<td>349</td>
<td>34</td>
<td>7.1</td>
<td>3.4</td>
<td>0.9</td>
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5x to 38x Savings over a 3-year lifespan!
TinyML CO₂ Footprint Calculator

Embodied and Operational CO₂ Footprint

For more information on the usage of this TinyML CO₂ Footprint Calculator, please see our paper and documentation at github.com/harvard-edge/TinyML-Footprint.
TinyML at Scale
TinyML Market Forecast

Source: ABI Research: TinyML
How many TinyML Devices are there?

There are around $250$bn MCUs deployed today and around $15$bn IoT devices.

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**IoT Device Growth**

<table>
<thead>
<tr>
<th></th>
<th>~15 Billion</th>
<th>&gt;50 Billion</th>
<th>&gt;100 billion</th>
<th>&gt;250 Billion</th>
<th>&gt;1 Trillion</th>
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<tr>
<td>Linear</td>
<td>2023</td>
<td>2041</td>
<td>2067</td>
<td>2144</td>
<td>2531</td>
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<tr>
<td>Exponential</td>
<td>2023</td>
<td>2032</td>
<td>2036</td>
<td>2043</td>
<td>2053</td>
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</table>

What if we scale to 250bn devices?

If our devices have longer lifespans this data starts to look even better!
Limitations and Areas for Future Study

What about the net impact of factors **beyond carbon**?

What about **Jevons’ Paradox**?

What about the **human costs**?

How can **emerging technologies** help?
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