GUEST EDITOR'S INTRODUCTION

Special Issue on Environmentally Sustainable Computing

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Welcome to the *IEEE Micro's* Special Issue on Environmentally Sustainable Computing. In the past decades, we have witnessed remarkable technological innovations. Orders-of-magnitude efficiency improvement in computing has engendered use cases that were not previously possible, stimulating novel applications domains, such as artificial intelligence (AI), extended reality, robotics, just to name a few. The significant investment in technology development has also enabled growth in other disciplines at an ever-faster pace. Computing technologies have accelerated scientific discovery, fueled significant economic growth, enabled humanity with a broader and more diverse spectrum of information and, at the same time, connect people of differing needs in the world together. Clearly, digital technologies have profound influence on the societal well-being of people, transforming all aspects of our lives.

As computing becomes increasingly pervasive, so does its impact on the environment. The information and communication technology industry is projected to account for 7%–20% of the global energy demand by 2030, resulting in profound carbon footprint implications.[1] While operational efficiency improvement continues to play an important role, the efficiency improvement potential of conventional approaches, from complementary metal–oxide–semiconductor (CMOS)-based integrated circuits and microprocessor architectures to datacenters at-scale and domain-specific specialization, is diminishing. Furthermore, advanced semiconductor manufacturing process is becoming more resource-intensive, demanding significant energy, water, and other natural resources for advanced lithography and wafer production. All in combination have led to the carbon bottle shift from operational to manufacturing carbon for computing at all scale. A recent study found that, in 2019, manufacturing carbon contributed to roughly half of cloud computing's carbon footprint, whereas manufacturing carbon accounted for over 70% of consumer electronics.[2] This creates new research exploration opportunities for sustainability-inspired systems beyond energy efficiency optimization.

One cannot optimize for the environmental sustainability of computing if it cannot be measured. Unlike performance or power consumption, quantifying carbon impact of digital technologies is a complex process. When the call of papers of this special issue was formulated, there existed no standard way to measure computing's carbon footprint, let alone design tools or carbon-centric metrics.

AS COMPUTING BECOMES INCREASINGLY PERVASIVE, SO DOES ITS IMPACT ON THE ENVIRONMENT.

A key step to reduce the environmental footprint of digital technologies is to enable the community with tools, metrics, and evaluation methodologies for assessing computing's environmental impact. Furthermore, technologies must be offered with environmental sustainability at the forefront—from manufacturing to product use to recycling. System design must adopt the circularity principle, such as e-waste reduction. The rise of pervasive computing puts particular emphasis on the importance of environmental design and deployment of digital technology.

What does an environmentally sustainable computing stack look like when environmental sustainability is placed as the first design and optimization principle? What new device technologies and novel computer architectures are promising alternatives for sustainability-optimized systems while considering performance, power, and cost at the same time? How can computing technologies assist us in achieving a more environmentally sustainable future for computing? What computing technologies can accelerate the discovery of new energy storage elements, crucial for the decarbonization of power grids? The *IEEE Micro* magazine explores cutting-edge research at the intersection of computing and environmental sustainability

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by featuring three articles in this Special Issue on Environmentally Sustainable Computing.

1) "Kaya for Computer Architects: Toward Sustainable Computer Systems" [A1]: This article takes an important step to understand the environmental impact of computer systems. Future directions are distilled based on the data-driven analysis for computer architects, with the key recommendation to design smaller chips, while reducing lifetime energy consumption is significant but of secondary importance.
2) "Sustainable AI Processing at the Edge" [A2]: This article explores the sustainability design space of hardware. The work considers the energy efficiency and sustainability implications from the use of mobile graphics processing units (GPUs) and edge-class field-programmable gate arrays to novel processing-in-memory using dynamic random-access memory and emerging racetrack memory. While GPUs offer higher energy efficiency, the embodied energy can make GPUs less sustainable than emerging memory technologies for AI processing at the edge.
3) "Data Centers on Wheels: Emissions From Computing Onboard Autonomous Vehicles" [A3]: This article characterizes greenhouse gas emissions of autonomous vehicles—an emerging yet less explored application domain. To curb the rising environmental impact of carbon emissions from computing onboard autonomous vehicles, this work introduces a probabilistic framework for the scenario-based analysis. Significantly higher hardware efficiency is needed for autonomous vehicles to keep its carbon impact in check.

THE THREE ARTICLES CAPTURE THE CROSS-CUTTING NATURE OF ENVIRONMENTALLY SUSTAINABLE COMPUTING FOR A DIVERSE COLLECTION OF APPLICATIONS.

The three articles capture the cross-cutting nature of environmentally sustainable computing for a diverse collection of applications. We envision significant cross-disciplinary efforts to build a circular technology development cycle by placing environmental sustainability at the design forefront. This is a crucial step in order to sustain and expand the benefits of a technologically rich society.

Finally, I would like to thank all the authors for contributing their research results to this special issue. In addition, I would like to thank all the reviewers for dedicating their valuable time to provide expert feedback to select and improve the quality of the articles in this special issue. Last but not least, I would like to acknowledge the dedication of Lizy Kurian John—editor-in-chief of *IEEE Micro*, which makes this Special Issue on Environmentally Sustainable Computing possible. I hope the research results in the articles inspire you with new research directions. It will take each of us to realize environmentally sustainable digital technologies in the decades to come.

APPENDIX: RELATED ARTICLES

[A1] L. Eeckhout, "Kaya for computer architects: Toward sustainable computer systems," *IEEE Micro*, vol. 43, no. 01, pp. 9–18, 2022, doi: 10.1109/MM.2022.3218034.

[A2] S. Ollivier et al., "Sustainable AI processing at the edge," *IEEE Micro*, vol. 43, no. 01, pp. 19–28, 2022, doi: 10.1109/MM.2022.3220399.

[A3] S. Sudhakar, V. Sze, and S. Karaman, "Data centers on wheels: Emissions from computing onboard autonomous vehicles," *IEEE Micro*, vol. 43, no. 01, pp. 29–39, 2022, doi: 10.1109/MM.2022.3219803.

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1. A. S. G. Andrae and T. Edler, "On global electricity usage of communication technology: Trends to 2030," *Challenges*, vol. 6, no. 1, pp. 117–157, 2015, doi: 10.3390/challe6010117.
2. U. Gupta et al., "Chasing carbon: The elusive environmental footprint of computing," *IEEE Micro*, vol. 42, no. 4, pp. 37– 47, Jul./Aug. 2022, doi: 10.1109/MM.2022.3163226.

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