Pervasive Sustainability

Matthew Louis Mauriello, *University of Delaware, Newark, DE, 19716, USA*
Mike Hazas, *Uppsala University, 75105, Uppsala, Sweden*

With each passing year, we continue to read and write statements such as "As the climate crisis accelerates, the imperative for sustainability has never been more urgent." Pervasive computing continues to be specially poised to contribute to this priority. As a field, we collectively develop new devices and services; we create tools for algorithmic data analysis and control; and not least, we study digital technologies and services in use, and assess their impacts. This introduction to the special issue briefly reflects on sustainability research in pervasive computing, makes connections to important related fields, and presents the issue's five articles, which represent the kind of diverse perspectives and approaches needed to address one of the biggest challenges of our time.

Welcome to this special issue of *IEEE Pervasive Computing,* dedicated to exploring "Pervasive Sustainability" or the intersection of pervasive computing and sustainability. In this issue, we present a collection of articles that contribute to understanding technology's possible roles in a more sustainable future. The rapid advancement of technologies offers promising avenues for mitigating our environmental impact, yet it also brings forth complex challenges and considerations. As we consider possible innovations in production, energy, and transportation, we must be mindful of their broader implications on society and the environment.

This issue brings together a diverse range of perspectives and insights, offering visions for a more sustainable future and identifying the research challenges that lie ahead. From enhancing user experiences in sustainable built environments to reimagining digital services for reduced resource consumption, the articles within provide valuable contributions to the ongoing dialogue on sustainability and computing.

We would like to give special recognition to Kayla-Jade Butkow, who served as student volunteer editor for this Special Issue. She went well beyond what we expected for such a role and contributed consistently throughout the lengthy review and editing process. In all, there were 11 submissions to this special issue, a testament to the sustained interest in the topic.

SOME RETROSPECTIVE AND REFLECTIONS

Fourteen years ago, *IEEE Pervasive Computing* published a special issue titled "Smart Energy Systems".[1] Including that issue, and since then, there have been over 25 publications in *IEEE Pervasive* alone, which are directly relevant to lowering energy demand, carbon emissions, or another topic related to environmental sustainability. Most recently, these have spanned topics, such as engaging with energy and sustainability in institutions[2]; contributing to the smart grid with minimal dedicated infrastructure in homes[3]; and critiquing AI for smart energy in the home.[4]

There has also been activity in two conference series: the International Conference on Pervasive Computing (often abbreviated as "Pervasive") and the International Conference on Ubiquitous Computing (Ubicomp). Ubicomp and Pervasive have historically shared an audience with the magazine you are reading now. The two conference series have merged, and in the past seven years have hosted the papers published in the *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* (IMWUT). Since IMWUT's launch in 2017, about 15 papers directly dealing with some aspect of environmental sustainability have been published there.

However, as we argued in a contribution to that first special issue,[5] research on energy at home (and by extension, pervasive sustainability more broadly),

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first has been going on for a long time, since at least the 1970s; and second is necessarily a multidisciplinary endeavor. Therefore, we encourage readers wanting more on this topic, to take on the challenge of engaging with literatures we might not otherwise encounter.

There has been a significant effort within the human–computer interaction community to engage with all aspects of sustainability, and much of that research is multidisciplinary, and informed by theories and methods outside of computer science and engineering. These have been published in proceedings of the ACM Conference on Human Factors in Computing Systems (CHI) and also the ACM Conference on Designing Interactive Systems. Looking further afield, it is important not to miss the International Conference on ICT for Sustainability (ICT4S), which draws on many disciplines, including life cycle assessment and design. The Workshop on Computing Within Limits (LIMITS) has been running for ten years, and includes viewpoints from futures studies and systems thinking. And within social sciences, *Energy Research and Social Science* and *Building Research and Information* are journals directly relevant to the pervasive computing audience working in sustainability. If you are looking to understand more about the energy and environmental impacts of computing systems themselves, the *Journal of Industrial Ecology* is a good place to start.

IN THIS ISSUE

We are pleased that the articles in this issue also come from different disciplines and viewpoints: distributed systems, embedded sensing, software engineering, design, and sociotechnical study of emerging practices.

In [A1], Toczé and Nadjm-Tehrani discuss the imperative to address the resource impact of edge computing beyond energy efficiency, highlighting the lack of research in this area. As edge computing gains traction for its promises of lower latency and reduced network load, ensuring its sustainability becomes crucial. The authors advocate embracing a sufficiency mindset to reduce absolute resource impact, and define acceptable service levels. They introduce an edge-sufficiency toolkit to facilitate this shift and demonstrate its application through a case study.

In [A2], Flores presents an innovative approach to environmental monitoring. By equipping these micromobility vehicles with sensors, they propose a comprehensive framework for collecting environmental data at a city scale, addressing existing challenges in coverage and accuracy. Facilitating analysis and organization of sensor data, the framework enables insights into the surrounding environment, paving the way for enhanced sustainability initiatives. This article sheds light on the potential of micromobility vehicles beyond transportation, positioning them as valuable tools in environmental stewardship.

In [A3], Remy et al. note that reducing energy demand in complex commercial premises presents formidable challenges. Yet, it is vital for organizations to meet climate and decarbonization goals. This article draws from extensive experience developing software systems to identify energy savings, and inform policy creation. A significant obstacle encountered is the lack of comprehensive business context, complicating efforts to optimize energy management. The authors share key insights, highlighting the diverse types of missing information and the importance of meaningfully linking disparate data sources. They propose ontologies as a solution to bridge stakeholder domains, offering valuable opportunities for advancing practice and operation in smart energy management.

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In [A4], Lu and Lopes focus on how computing technologies continue to pervade our lives, and the surge in e-waste underscores a pressing environmental concern. Despite our focus on user-centered design—prioritizing speed, usability, and usefulness in device development—we often overlook opportunities to enhance long-term sustainability. This article advocates for a shift in perspective, urging designers to consider users not only as consumers but also as caretakers, repairers, and recyclers of interactive devices. By expanding the roles attributed to users, we can foster a culture of responsibility and engagement toward sustainable computing practices. Drawing on examples of innovative interactive systems, the article demonstrates the potential of redefining user roles to support more sustainable futures for pervasive technology.

In [A5], Jensen et al. spotlight energy communities, which are emerging as innovative hubs where local actors drive green energy initiatives. These communities aim to harness pervasive energy

technologies to boost citizen participation for sustainable, democratic futures. However, the typical "one size fits all" design of these technologies often ignores local communities' unique cultural and social practices. This article draws on cutting-edge research and five design cases to reveal the complexities and nuances of developing technology for energy communities. The insights suggest a critical need for more adaptable design approaches that engage diverse communities.

CONCLUSION

We hope that this special issue serves to highlight and reinforce the care and attention to sustainability topics, long existing within our field. The challenges are immense: gathering, interpreting, and mobilizing relevant data; carefully designing systems and services and assessing their impacts; and working across disciplines to understand the far-reaching effects of digital technology. But the potential human and environmental costs of inaction on our part are even greater.

The guest editors would like to again thank Kayla-Jade Butkow, student volunteer editor for this special issue. We are also very thankful to the anonymous reviewers for their constructive feedback.

APPENDIX: RELATED ARTICLES

[A1] K. Toczé and S. Nadjm-Tehrani, "The necessary shift: Toward a sufficient edge computing," *IEEE Pervasive Comput.*, vol. 23, no. 2, pp. 7–16, Apr.–Jun. 2024.

[A2] H. Flores, "The role of micromobility in environmental monitoring: Reflections and opportunities on the use of pervasive sensing," *IEEE Pervasive Comput.*, vol. 23, no. 2, pp. 18–26, Apr.–Jun. 2024.

[A3] C. Remy, A. Tyler, P. Smith, O. Bates, and A. Friday, "Wasted energy? Illuminating energy data with ontologies," *IEEE Pervasive Comput.*, vol. 23, no. 2, pp. 27–36, Apr.–Jun. 2024.

[A4] J. Lu and P. Lopes, "Re-envisioning the role of a *user* in sustainable computing," *IEEE Pervasive Comput.*, vol. 23, no. 2, pp. 37–43, Apr.–Jun. 2024.

[A5] R. H. Jensen, V. V. Jensen, and R. C. Smith, "Energy communities: Pervasive technologies and collective futures," *IEEE Pervasive Comput.*, vol. 23, no. 2, pp. 44–54, Apr.–Jun. 2024.

REFERENCES

1. J. Paradiso, P. Dutta, H. Gellersen, and E. Schooler, "Guest editors' introduction: Smart energy systems," *IEEE Pervasive Comput.*, vol. 10, no. 1, pp. 11–12, Jan.–Mar 2011.
2. G. Mylonas, D. Amaxilatis, I. Chatzigiannakis, A. Anagnostopoulos, and F. Paganelli, "Enabling sustainability and energy awareness in schools based on IoT and real-world data," *IEEE Pervasive Comput.*, vol. 17, no. 4, pp. 53–63, Oct.–Dec. 2018.
3. S. Barker and D. Parsons, "Smart homes or real homes: Building a smarter grid with dumb houses," *IEEE Pervasive Comput.*, vol. 21, no. 2, pp. 100–104, Apr.–Jun. 2022.
4. T. Hargreaves and V. J. Pereira, "Provocative AI: Beyond calm interactions," *IEEE Pervasive Comput.*, vol. 22, no. 3, pp. 58–61, Jul.–Sep. 2023.
5. M. Hazas, A. Friday, and J. Scott, "Look back before leaping forward: Four decades of domestic energy inquiry," *IEEE Pervasive Comput.*, vol. 10, no. 1, pp. 13–19, Jan.–Mar. 2011.

MATTHEW LOUIS MAURIELLO is an assistant professor with the Department of Computer and Information Sciences, University of Delaware, Newark, DE, 19716, USA. His work applies user-centered design and computer science techniques (e.g., information visualization, machine learning) to challenges facing health, education, environmental, and computing systems. He is the corresponding author of this article. Contact him at mlm@udel.edu.

MIKE HAZAS is a professor of human–computer interaction at Uppsala University, Uppsala, 75105, Sweden. He is a multidisciplinary academician who works at the interface of human–computer interaction, embedded systems and studies of social practice. Hazas received his Ph.D. degree in mobile computing. Contact him at mike.hazas@it.uu.se.