Closing the sustainability gap in materials education

Carol A. Handwerker

As materials scientists and engineers, we have the responsibility and ability to make sustainability a reality by creating and implementing sustainable materials and processes. It is, after all, the materialization of our needs and wants that have led to the current situation. However, we need to have the will to do it, know what to do, and how to do it. We must learn what sustainable options are possible, learn to choose among the options based on societal, environmental, and economic concerns, and learn how to work with others to make decisions that change the status quo. This leads to the questions: what community is prepared to act with us and how can we educate people to make a difference? As discussed in this article, the answer is the microelectronics industry. There is a growing recognition that microelectronics both cause and prevent societal and environmental problems. It is there, in the context of these problems and the growing importance and proliferation of microelectronics in our everyday lives, that we can forge partnerships to simultaneously solve sustainability issues and teach materials science and engineering students to become leaders in sustainable electronics.

We are facing an existential sustainability crisis: we are destroying our environment and accelerating climate change, and this is driven by our choices and behavior: massive emissions of greenhouse gases, depletion of limited resources (e.g., water and some materials), use of toxic and environmentally persistent chemicals, and the release of environmental pollutants.[1–3] The current situation can be characterized as a "Tragedy of the Commons." A "commons" is a shared resource that multiple people and communities use and depend upon for their livelihoods; a commons can be degraded and even destroyed by people's overuse or improper use, hence, creating a "tragedy."[4] In our modern society, the production and use of products at a massive scale ("market resources") lead to the erosion of ecosystems, human health, and the environment ("nonmarket resources").[5] Sustainability is the opposite of the Tragedy of the Commons, where a society meets "the needs of the present without compromising the ability of future generations to meet their own needs" as defined by the United Nations Brundtland Commission.[6] The question is how to replace the "tragedy" we are living in by changing the path we are on.

As materials scientists and engineers, we have the responsibility and ability to make sustainability a reality by creating and implementing sustainable materials and processes. It is, after all, the materialization of our needs and wants that have led to the tragedy. But we need to have the will to do it, know what to do, and how to do it: learn what sustainable options are possible, learn to choose among the options based on societal, environmental, and economic concerns, and learn how to work with others to make decisions that change the status quo. That we are falling short is evident almost everywhere we look, from how we use our talents to what we are teaching our students to do and become. To understand the roles that we as materials scientists and engineers play in creating this situation, it is useful to consider the "Tragedy of the Commons" in combination with the well-known technology transition/system failure, known as the "Valley of Death."[7] By exploring these two paradigms and their root causes, we can create a path forward by incorporating sustainability core concepts in materials science and engineering (MSE) education and research and creating a community of practice to design and use them to make a positive difference in the world.

The National Research Council (NRC) Study on Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems[7] described the concept of the "Valley of Death" as an "icon for the difficulty of successfully commercializing or implementing *proven technologies*," but it is much more. This concept describes a failure somewhere along the development pathway and one-way transition of a technology from, for example, a university

Carol A. Handwerker, School of Materials Engineering, School of Environmental & Ecological Engineering, Purdue University, West Lafayette, USA; carolh@purdue.edu

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or federal R&D laboratory to a company that commercializes the technology that, in turn, is bought by ready, willing, and able customers. The root causes for the Valley of Death are many and varied, but a key to "bridging the Valley of Death" is having "a culture that fosters innovation, rapid development, and the accelerated deployment of materials technologies."[7]

Such a culture is not how I would characterize the way those of us who are educators train MSE technical experts in our domain-specific university programs. In MSE, there is first a focus on specific technical learning outcomes at the core: processing–structure–property relationships of materials while ensuring base competency in math, physics, and chemistry and honing skills in critical thinking and discovery. We teach classes to achieve such outcomes, some in sequence, some in parallel that define a classically trained and educated materials scientist/engineer. Once such base concepts are learned, there can be special project courses as well as a selection of more advanced, technical electives, sometimes with a component of sustainability, for further enrichment based on a student's personal interests and future career choices. Students demonstrate their ability to integrate the knowledge and skills they have learned in the first three years in senior capstone research projects, often sponsored by industry, but rarely including sustainability. With such skills, students get good jobs and MSE departments with their heads/chairs and faculty meet their obligations, with some curriculum changes over time, while remaining true to the Accreditation Board for Engineering and Technology (ABET) technical core. ABET is a US-based nonprofit that provides engineering accreditation for the United States and 39 countries that do not have their own nationally accepted accreditation body. Similar regional and national accreditation organizations exist globally, such as the European Network for Accreditation of Engineering Education and the Asean Federation of Engineering Organisations. ABET operates through more than 2200 volunteers from professional societies, industry, academia, and government who serve as domain-specific program evaluators, commissioners, board members, and advisors to ensure the quality of engineering education. Here, the focus is on ABET, and what we can do within its framework. For engineering, the goal of ABET is "with ABET accreditation, *students, employers, and the society we serve* can be confident that a program meets the quality standards that produce graduates prepared to enter a global workforce."[8] Our programs have created a "social contract,"[9] an implicit agreement between students and faculty at ABET-accredited universities to cooperate for the benefit of students and for benefits to employers and society. For many students and employers, their expectations are satisfied and there is no "Valley of Death": the proven technical products of an MSE education, that is, MSE graduates, are developed and used as intended.

So, what creates a Valley of Death with respect to sustainability? We produce graduates well equipped by their typical MSE education for technical jobs, but give them little, if any, systematic training or experience in applying the MSE core concepts to design and accelerate the use of new sustainable materials and processes to benefit society. So where do we go from here?

Thankfully, there has been a dramatic change in ABET since 2019 that recognizes our *responsibility* for designing sustainability into the solutions we create. Before 2019, sustainability was listed as one of many "realistic constraints" for engineering design in Outcome (c) "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability." As of 2019, ABET introduced two new student outcomes covering the three pillars of sustainability across all engineering disciplines: (1) "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors;" and (2) "an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts."[8] However, these have not yet been integrated widely into core MSE curricula (undergraduate or graduate).

To make progress, we need to create strong partnerships, the first with environmental engineering (EnvE) programs to gain the needed expertise and tools and the second with other stakeholders for whom sustainability is becoming a key part of the "social contract." In particular, companies are recognizing increasingly that they should and can do better by incorporating sustainable engineering practices into their work with a combination of positive environmental, economic, and societal outcomes. Much like MSE programs, students in ABET-accredited EnvE programs become environmental-domain engineers, learning how to examine local-to-global-scale resource utilization, commodity production, prevention and remediation of waste streams, and life-cycle and ecosystem impacts. They are offered and take jobs in compliance, pollution reduction, and mitigation, thereby fulfilling their "social contract." However, they are missing the technical domain knowledge needed to fix the root cause during early-stage R&D when new sustainable materials and processes can be designed. At the moment, MSE and EnvE have no common language and few issues in common. As a society, we need people who bridge the two domains in knowledge and action. **Figure 1** shows a continuum of core concepts that bridge the technical disciplines of MSE and ecology, modified from Bakshi,[10] for MSE. On the left are the MSE core concepts. Starting where the two circles begin to intersect are topics that quantify impacts and guide engineers to understand the implications of their choices. "Industrial symbiosis" and "techno-economic-ecological synergy," where the circles intersect, describe a holistic, quantitative, transparent analysis of systems, their strengths and weaknesses, and where innovation is needed to make a difference. Covering the topics in a holistic way in the left circle for MSE students and researchers and in the

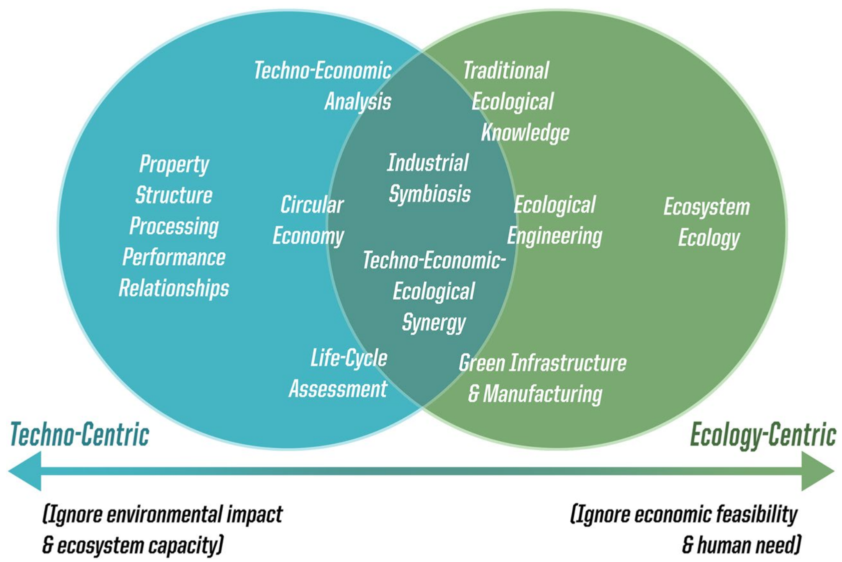

Figure 1. Bridging materials science and engineering (MSE) techno-centric and ecology-centric concepts to create a sustainability core for MSE education, as modified from Bakshi.[10]

right circle for EnvE students and researchers is a necessary step in bridging the sustainability gap in new materials and process design and accelerating technology transfer in ways that help society and the planet. However, it is not sufficient to cause change.

Our Commons requires authentic partnerships to create a culture of accelerating the design and technology transfer of new, sustainable materials and processes—industry partners who need and will use them; R&D funding agencies and national laboratories who see the need for both research itself and a sustainability-focused education for engineering students; universities and their MSE and EnvE faculty who are willing to work together with materials scientists and engineers at companies to create innovative curricula and R&D programs to put them to use; professional societies such as the Materials Research Society, ABET, the American Society for Engineering Education, and The Minerals, Metals, & Materials Society, to support cross-disciplinary sustainability research and education; and last, but not least, engineering students who will enthusiastically join our new Commons with sustainability as a core value. I believe that students will join if and only if we create a Commons where students have "the capacity to initiate actions and deliberately influence the course of events" in terms of sustainability that they become agents for change.[11] It is up to us, however, to make this vision a reality.

The global semiconductor and microelectronics industry needs a Sustainable Electronics Commons now. Electronics companies and their leaders have committed to significant reductions in greenhouse gas emissions, sustainable materials and processes, net-zero manufacturing, and energy-efficient computing in recognition of an existential sustainability crisis of its own making. Data centers use approximately 1–1.5% of total global energy, with total energy use for data storage and transmission use increasing as demand increases.[12] Artificial intelligence (AI) systems produce energy savings in some applications, but require energy-intensive training and operation, and are experiencing exponential growth in their application. Water, energy, and materials use in electronics manufacturing is high, with more than 1000 steps required to create an integrated circuit. Most of those steps and their impacts are set by current technologies, with pervasive innovation needed to eliminate toxic chemicals and environmental pollutants and to reduce materials use. Companies are stepping up. For example, Intel has committed to net-zero greenhouse gas emissions in manufacturing by 2040, and is driving sustainability practices throughout its supply chain.[13] SEMI has formed the new Semiconductor Climate Consortium, with more than 60 companies across the electronics value chain partnering to accelerate the ecosystem's reduction of greenhouse gas emissions and create sustainable materials and processes.[14] For this groundswell of activity to lead to a new generation of sustainable electronics, companies and their leaders must have and engage employees in R&D to create innovative sustainable materials and technologies and make different decisions than in the past. This leads to a question of what sustainability knowledge, skills, and abilities are needed for their new employees. The Roadmap for Microelectronics and Advanced Packaging Technologies (MAPT) Committee—funded by the US National Institute of Standards and Technology (NIST) and led by the Semiconductor Research Corporation—is working with industry, university, and nonprofit partners to determine (1) the serious challenges that the world faces in energy consumption and sustainability caused by MAPT while exploiting the benefits that microelectronics bring to society and (2) the MAPT workforce needs in the United States by sector, region, and the knowledge, skills, and abilities (KSAs) needed, including sustainability, from community college through PhD degrees. What makes this a critical point for sustainability education is the crosscutting roadmap team that is examining the intersection of R&D workforce needs and sustainability-related KSAs and how to fill the gap.[15]

The next step is having funding and funding agencies in place. The CHIPS and Science Act is infusing USD$11 billion through the US Department of Commerce and NIST and USD$200 million through the National Science Foundation (NSF) to create a sustainable semiconductor and microelectronics R&D ecosystem that promotes innovation, commercialization, and workforce development, while also potentially addressing many of the sustainability challenges previously listed.[16] Other countries and regions, such as India, Japan, and the EU, have similar "CHIPS" legislation. The US Department of Commerce has formed the Industrial Advisory Committee to provide advice to the Secretary of Commerce "on the science and technology needs of the nation's domestic microelectronics industry, the national strategy on microelectronics research, the research and development programs and other advanced microelectronics activities funded through CHIPS for America, and opportunities for new public–private partnerships."[17] This is one place that semiconductor and microelectronics R&D are being identified and prioritized that can be leveraged to combat accelerating climate change, resource use and depletion, continued use of toxic and environmentally persistent chemicals, and release of environmental pollutants.[18]

The microelectronics industry and government are organizing and beginning to act, and the rest of us need to join them. The timeline for CHIPS Act program implementation creates a time pressure for us to act. We do not have to start from scratch. Under the auspices of the ASEE, The Lemelson Foundation, and funded by NSF, the ASEE Engineering for One Planet (EOP) Framework is based on a "curated list of core and advanced sustainability-focused student learning outcomes" integrated across all ABET learning outcomes, and is being implemented by a community of practice with hundreds of faculty members.[19] The EOP team has identified specific sustainability learning outcomes for materials. What the framework needs for microelectronics as a key component in the Sustainable Electronics Commons is to form partnerships to apply these and other sustainability concepts to collectively solve the many problems that we face.

The next step is to bring together industry, government, universities, national laboratories, and professional societies to discuss how we can create a Sustainable Electronics Commons with a "culture that fosters innovation, rapid development, and the accelerated deployment of materials technologies." The MRS Focus on Sustainability Subcommittee has agreed to lead one such effort and recruit others to the endeavor, starting with a brainstorming session in the spring 2023. This is just one "first step," but many such "first steps" must be taken by those of us who believe in this path forward. Coming together as a community will take hard work on all sides, particularly of leaders who are committed to creating a Sustainable Electronics Commons. We are fortunate that Elinor Ostrom (2009 Nobel Prize in Economic Sciences) identified a framework for forming complex, sustainable communities such as the one envisioned here that not only avoids the "Tragedy of the Commons," but also thrives.[20] As you have read in this article, many organizations and approaches have laid the groundwork. The time to act is now and your participation and leadership are needed, wherever and whenever you see an opportunity.

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Publisher's note

Carol A. Handwerker is the Reinhardt Schuhmann, Jr. Professor of Materials Engineering and Professor of Environmental and Ecological Engineering at Purdue University. Her research areas include developing innovative interconnect technologies for microelectronics and sustainable thin-film solar cells, improving Pb-free solders interconnects for high performance systems, and integrating sustainability in new materials design. Before joining Purdue in 2005, she was at the National Institute of Standards and Technology (NIST) for 21 years, co-leading Advanced Packaging and serving as the Chief of the NIST Metallurgy Division. Handwerker can be reached by email at carolh@purdue.edu.