Sustainability for Semiconductors

ELISE HARRINGTON, SAIRAJ DHOPLE, XIAOJIA WANG, JUNGWON CHOI, AND STEVEN KOESTER

The CHIPS and Science Act of 2022 allocates $52 billion to support incentives and research and development for semiconductor manufacturing. The private sector is also making substantial new investments in the sector. Intel, for example, is planning a $20 billion investment in chip factories in Ohio. Together, policymakers and the private sector should take advantage of this moment to embed sustainability in all aspects of the US semiconductor industry.

It's long been clear that chip manufacturing can cause significant pollution and hazards to human health. Semiconductor manufacturing in California in the 1980s and '90s has been linked to harmful chemical pollutants in drinking water. Santa Clara County alone, home to Silicon Valley, has 23 federal Superfund sites—areas recognized as highly contaminated and earmarked for cleanup. And chips are formidable consumers of energy themselves: since 2010, the energy use from semiconductor-based products or devices has doubled every three years as they have proliferated across computing and electrification. The expected growth in renewable energy generation and electrification will only continue this trend, with the demand for semiconductor-based devices expected to increase precipitously by 2050: 23-fold for wind and 68-fold for electric vehicles.

Thus the CHIPS and Science Act presents a once-in-a-lifetime opportunity to center sustainability in ongoing R&D and investment and mitigate the myriad environmental impacts of chips before they become even more ubiquitous. Manufacturers need alternative methods of designing and producing chips and devices, as well as new approaches to recycling and reuse. However, appropriate expectations and goals must be defined now.

Sustainability is often categorized as an environmental issue, but it could have significant spillover effects that advance other goals. Current policy discussions about chips frequently revolve around geopolitical concerns, national security, and supply chain risks, as these affect the price and accessibility of technologies that use semiconductor-based chips. But focusing on sustainability in semiconductor R&D could also reinforce national security goals. Researching ways to repair and recycle chips and related components, for example, can result in designs that avoid dependence on foreign suppliers or scarce resources, increasing the security of domestic supply chains. Likewise, leading the world in repairable, low-impact chips could turn out to be a competitive advantage.

A sustainability framework for the semiconductor industry

A first step in making chips more sustainable is agreeing on what would constitute success. Right now, there is limited consensus on what sustainability means in the semiconductor industry and what actions different stakeholders should take to achieve it.

To support the development of a standard for regulating the detrimental effects of chip manufacturing, scholars have proposed seven primary indicators of environmental impact spanning the component life cycle. These indicators are greenhouse gas emissions, including carbon emissions from electricity use and perfluorochemicals; use of nonrenewable materials such as minerals and metals; water quality issues such as algal blooms; water consumption; toxic impacts on ecosystems; summer smog; and local electrical consumption. Although each of these indicators varies in geographic impact and the semiconductor life cycle stage, each one can affect other parts of the supply chain.

Another related challenge is determining what the sustainability targets should be. Because different stages of production and use prioritize different processes, metrics, and outcomes, it's difficult to build consensus. For example, fabrication facilities may focus on reducing water and energy consumption and greenhouse gas emissions, while semiconductor packaging producers prioritize limiting hazardous content of packaging materials. Device manufacturers currently have little motivation to align sustainability goals across their supply chain.

Beyond developing standards and targets for mitigating the negative impacts of semiconductor-based chip production, industry and nonprofit stakeholders must coordinate to achieve overall sustainability. Approaches that emphasize circularity will bolster the resilience of the semiconductor industry. Circularity aims to reduce inputs, waste, and environmental impacts, such as emissions, by considering the life cycle of a product—from design to maintenance and repair to reuse, refurbishing, and recycling. But circularity is not synonymous with sustainability. Synchronizing circularity and sustainability to curb consumption and environmental degradation offers potential avenues for achieving innovation and development decoupled from resource extraction. Linking innovative design approaches with broader goals of circularity can assist in creating a resilient semiconductor industry by addressing supply chain problems, electronic waste, human health, and environmental impacts in a more holistic way. Building truly circular approaches will require coordination from materials to design to disposal and the crafting of new standards for the reuse of chips on secondary markets, providing further impetus for cross-sector partnership and communication.

For semiconductor materials R&D, two priorities offer potential sustainability benefits that reach well beyond the sector. The first is reducing the material inputs that are needed by increasing the efficiency of how the materials are used. The second priority is innovating new materials that are recyclable or biodegradable. Paying more attention to materials could drive widespread change across both the semiconductor and the power sectors. The US Department of Energy recently produced a semiconductor "deep dive assessment" as part of the first-ever clean energy supply chain evaluation. By integrating information on resource forecasting, sustainability of manufacturing, recycling and reuse, and planning for the end of life of semiconductor devices, this assessment provides an example of the type of cross-sectoral analysis required to support sustainability.

The report also foreshadows that a business-as-usual approach on the part of policy and business may limit the growth of the industry. New applications such as artificial intelligence are currently spurring rapid growth, but high energy demand and water use, vulnerabilities in the production of silicon wafers, an essential component of semiconductors, and the availability of the required skilled workforce may all become limiting factors. Focusing explicitly on sustainability could move the industry out ahead of these challenges.

Centering sustainability and its benefits in chip design will require extensive cooperation between government and industry along the supply chain. There is, however, historical precedent for such coordination. In the 1980s, Japan's leadership in the semiconductor industry and the declining share of US global chip production spurred a new industry-government partnership. SEMATECH, a consortium of American chip manufacturers, received $870 million through the Defense Advanced Research Projects Agency from 1988 to 1996. By leveraging these investments, SEMATECH had a significant influence on chip manufacturing in the 1990s. Subsequent iterations extended the consortium to international partners and established the International Technology Roadmap for Semiconductors (today known as the International Roadmap for Devices and Systems).

Although not without its critics, SEMATECH demonstrated the role of coordinated, strategic R&D planning in a sector of critical interest across government and industry partners. A small portion of the consortium's funding targeted research on reducing water consumption, an example of sustainability-related research and innovation. Integrating sustainability into semiconductor R&D will mean repurposing prior funding models like SEMATECH's and working across the design, development, and deployment stages.

If done successfully, making chips more sustainable could be massively beneficial to the electricity sector and beyond. Embedding issues of resource extraction, use, pollution, and waste into the supply chain could support American leadership in new areas of chips innovation. But failing to take advantage of this opportunity would also reverberate far beyond the single industry, making it more difficult to address other vital national and global challenges, including climate change and environmental justice.

Elise Harrington *is an assistant professor in the Science, Technology, and Environmental Policy area at the University of Minnesota's Humphrey School of Public Affairs.* ***Sairaj Dhople*** *is the Robert and Sydney Anderson Associate Professor in the Department of Electrical and Computer Engineering at the University of Minnesota.* ***Xiaojia Wang*** *is an associate professor in the Department of Mechanical Engineering at the University of Minnesota.* ***Jungwon Choi*** *is an assistant professor in the Department of Electrical and Computer Engineering at the University of Minnesota.* ***Steven Koester*** *is the Russell J. Penrose Professor in Nanotechnology in the Department of Electrical and Computer Engineering at the University of Minnesota and the director of the Minnesota Nano Center.*