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Commentary

Bending the curve of the electronics revolution toward a circular economy of e-waste

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Advocacy for a fully circular economy of electronic products has intensified in response to relentless demand for materials and the toxic legacy of electronic waste (e-waste). Convergence of innovation in resource recovery, regulatory policies, and consumer participation is needed to bend the curve of the electronics revolution toward a circular economy.

E-waste economy: Spiraling out of control

The electronics revolution has transformed public and private sectors of societies worldwide. More than two-thirds of the world's population currently access the internet and conduct routine occupational and recreational activities with the aid of personal electronic devices, with notable regional variation ranging from a high of ~98% internet penetration rate in Northern Europe to a low of 8% in Eritrea and less than 1% in North Korea. The global market size of consumer electronic devices ballooned to US$724.48 billion in 2021, attributable in part to the global societal lockdown response to the COVID-19 pandemic, which forced social networking, schooling, and most commercial transactions to depend on electronic device-enabled virtual platforms. The relentless production of new consumer electronic devices is expected to continue as projections of the market size will reach US$1.13 trillion by 2030, representing a compounded annual growth rate of 5.1%.[1] Since electronic products have become ubiquitous and indispensable in all sectors of society including healthcare, transportation, entertainment, social networks, and retailing, disruption of the supply chain of electronic components such as semiconductor microchips, lithium-ion batteries, and rare earth elements reverberates across all sectors of society. There are two sustainability challenges associated with this electronic revolution.

The first challenge is the introduction of a growing threat to human health and environmental quality due to toxic chemicals contained in defunct and discarded electronic waste (e-waste).[2] For more than two decades, evidence has accumulated to support the suspicion that e-waste is the fastest growing category of hazardous waste globally, with 53.6 Mt of e-waste generated in 2019 and projected to more than double (110 Mt) by 2050.[3] The average per capita generation of e-waste (7.3 kg) masks a wide disparity in the regional sources of the waste and the regions where its adverse impacts are experienced. The fate of 83% of e-waste generated globally is unknown and likely discarded, traded within and between countries, or managed by unlicensed laborers to recover materials through processes that do not comply with best practices for protecting human health and the environment. There is evidence that in 2019, at least 5.1 Mt of e-waste was moved across international borders, and about two-thirds of this amount were not controlled or monitored through international regulations. Differences in e-waste collection in economically affluent countries in the Northern Hemisphere illustrate the need to harmonize policies and best practices including engagement of consumers and manufacturers (Figure 1). In 2019, the average rates of locally generated e-waste collection in Africa (1%), Americas (9%), Oceania (9%), Asia (12%), and Europe (43%) support arguments for an international convention designed specifically for e-waste. The low e-waste collection rates in regions where labor is cheap reflects the challenge of inadequate monitoring and data reporting in underground economies and the undocumented importation of e-waste for resale and unsafe processing that compromises the health of laborers and pollutes their environment.[3]

The second reason that the current electronic revolution is not sustainable is its intense demand for natural minerals required to produce new electronic devices, responsible for harms to both environmental and human health. In many cases, the required raw materials, like cobalt, are mined from primary natural reserves. For example, the Democratic Republic of Congo has the largest productive deposit of cobalt in the world, but the atrocities incurred through the employment of child labor in artisanal mining has become a notorious case study for environmental injustice. In 2021, a US district judge controversially dismissed a lawsuit brought by International Rights Advocates on behalf of 14 families in the Democratic Republic of Congo against Apple, Dell, Google (Alphabet), Microsoft, and Tesla over the deaths, disability, and illness of children laboring to mine cobalt that is essential for the manufacture of electronic devices. The urgency of the international scramble for cobalt and other essential metals and minerals has now extended to the deep ocean and polymetallic nodules that contain cobalt and rare earth elements. Alarms have been raised and lawsuits have been filed by various constituencies noting the potential adverse impacts of deep-sea mining. But the economic incentives are perhaps too attractive for small island states and large corporations

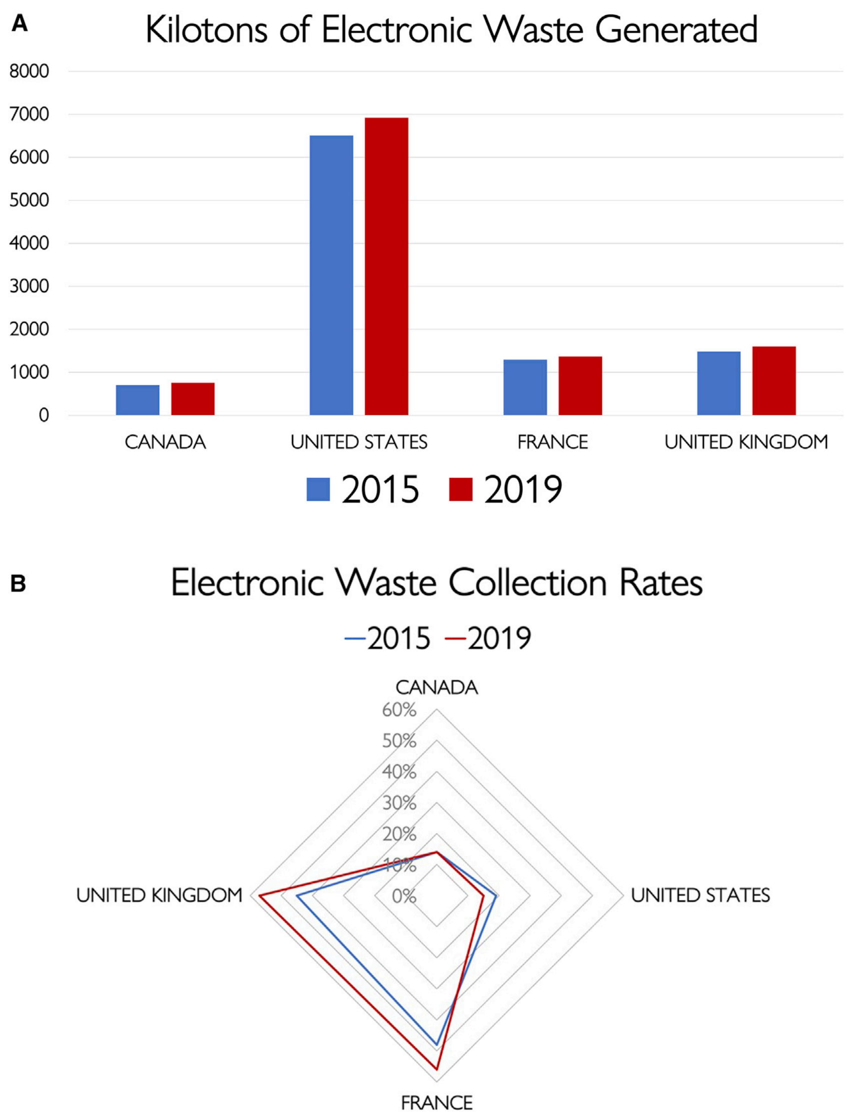

Figure 1. Electronic waste production and recovery for selected affluent countries
(A and B) Wide range of electronic waste production and collection rates across countries and regions reflect gaps in regulatory policies and consumer participation in addressing the e-waste problem. (A) In the four affluent countries featured, e-waste generation increased between 2015 and 2019. In these countries, the average per capita generation of e-waste in 2019 was 21.5 kg, nearly three times the global average. (B) Collection of e-waste generated vary widely among the featured countries, with, e.g., collection in the US decreasing from 19% in 2015 to 15% in 2019. The plotted data are from the Global E-waste Statistics Partnership established through collaboration of the International Telecommunication Union (ITU), United Nations University – Sustainable Cycles (UNU-SCYCLE) and the International Solid Waste Association (ISWA) and managed through the new Sustainable Cycles (SCYCLE) program under the United Nations Institute for Training and Research (UNITAR).[4]

using the loopholes in the administrative and functional structures of the International Seabed Authority, which is empowered by the United Nations (UN) Convention on the Law of the Sea. From the perspective of planetary health, the potential problems associated with deep-sea mining are more serious because scientific knowledge of the deep-sea ecosystem is sparse in comparison to terrestrial ecosystems, for which a there is a widespread body of literature that documents irreparable damage. Mining, in its current guise, does not present a sustainable path toward supporting the electronics revolution.

The increasing trends in mining natural resources to produce new electronic devices with short periods of useful life and the increasing trends in e-waste accumulation are in opposition to circularizing the economy of the electronic industry. E-waste recycling is the clear solution to these challenges, but current processes fall short of a sustainable system. The toxic chemical constituents of e-waste pose particular risks for population health because the toxicity is commingled with precious and semi-precious materials, which attract artisanal miners who labor under conditions that expose people and ecosystems to pollutants that cause various diseases and degradation of environmental quality. In 2021 the World Health Organization released a landmark report noting that globally, less than 20% of electronic products are collected for resource recovery, and more than 18 million children and 12.9 million women labor to recover small amounts of valuable metals from e-waste under conditions that endanger their lives and the quality of the environment through exposure to toxic metals and organic chemicals.[5] The recycling of metals such as cobalt from e-waste is not currently viable commercially, representing a big gap in the circular economy of electronics.[6] The ongoing COVID-19 pandemic further revealed major weaknesses in the global supply chain of materials and components on which the electronics industry depends. Current levels of product recovery and e-waste management are inadequate and cannot effectively correct the linear take-make-waste trends. At best, they lead to spirals away from a fully circular economy (Figure 2). The spirals need course correction to mitigate the disastrous impacts of e-waste.

Spiraling into a sustainable circular economy

Beyond documenting its unsustainable environmental footprint and human health impacts, research activities across a wide range of disciplines continue to reveal opportunities to curb the outward spiraling economy of the electronics industry into a closed circular economy. The challenge will require coordination of innovative strategies across the life cycle of electronics, most importantly investments in the infrastructure to recover used electronics products before they become discarded e-waste and implementing the technical knowledge available for recovering valuable components

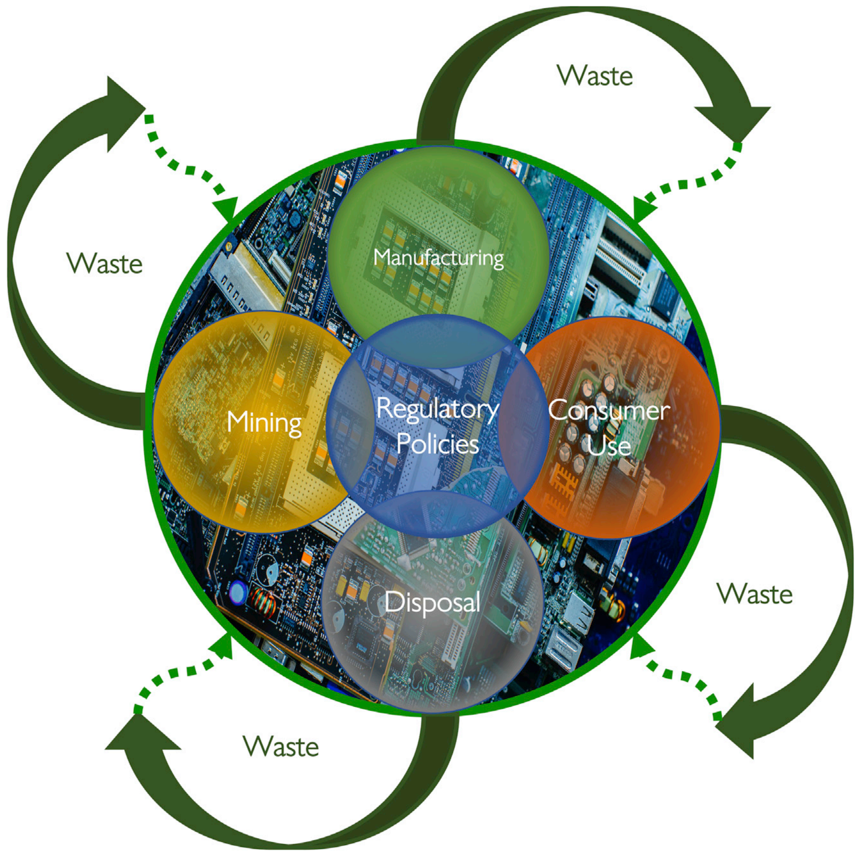

Figure 2. Bending e-waste into a circular economy
A fully circular economy of electronic products demands drastic reduction or elimination of wastes generated throughout the materials life cycle of the products from mining to manufacturing, consumer use, and disposal at end of useful life. Currently, wastes from these sectors are externalized in the economy and in need of solutions to favor internalization of material recovery and reuse. Coordination of regulatory policies at the local, national, regional, and international levels is necessary to avoid gaps that undermine the integrity of the circular economy.[7]

and materials from used and defunct electronics.

Bending the curve in end-of-life product recovery

The first gap in recovering reusable and recyclable materials from used electronics is to take back the products from consumers. Numerous studies have shown that this is a major snag in the circular economy of e-waste worldwide, although the current situation varies across countries. For instance, the information presented in Figure 1 shows striking differences in e-waste production and recovery in four economically prosperous countries with similar technical and social infrastructure. In North America, represented by Canada and the United States, less than 20% of e-waste generated annually is collected. Moreover, the trend of e-waste collection stagnated or declined between 2015 and 2019, a situation that was probably worsened by the societal lockdown forced by the COVID-19 pandemic. Alternatively, in Europe, represented by France and England, more than 50% of e-waste was collected from consumers in 2019, representing an increasing trend over the previous 5 years. The differences are due in part to differences in regional and national policies and levels of consumer education about the topic. International harmonization of policy best practices is essential to initiatives that can bend the curve toward increased collection of e-waste.

Bending the curve in product disassembly

The second gap in the path to the circular economy of electronics relates to the technology needed to disassemble electronic devices, collect reusable components, and recover or recycle materials that may circle back to electronics manufacturing or be re-purposed for manufacturing in other industries as inspired by the industrial ecology framework. Apple corporation's creation of a robot to disassemble the iPhone in a few minutes is a wonderful demonstrative invention. The robot is also an example of a solution that is difficult to scale up to the level that can accommodate the scope and magnitude of the problem in terms of the variety shapes and sizes of electronic devices and the number of individual devices that continue to enter the e-waste stream. Apple's Daisy robot is quick and expensive, and it is very unlikely to be deployed in its current configuration for use in many parts of the world where e-waste from phones is accumulating rapidly, particularly in the Southern Hemisphere. The lack of uniformity and interchangeability of electronic components is also a major impediment for disassembly for reuse. Charging cords, connection cables, rechargeable batteries, screens, digital memory units, and cameras vary widely between models of the same manufacturer and even more so among manufacturers. In an attempt to reduce the magnitude of e-waste, the European Parliament approved a law in July 2022 to require all manufacturers of portable electronics to adopt the USB-C charging port and cord on phones and other small devices sold in the European Union effective 2024.[8] Some manufacturers argued that the law may stifle innovation, but its benefits may include acceleration of the development of cordless charging technology, which will also contribute to the reduction of wasted electronic paraphernalia.

Bending the curve in material resource recovery

The third gap in the circular economy electronics is the recovery of potentially valuable resources from defunct products. Research to mine e-waste has focused on the recovery of precious and valuable metals such as gold and copper. The technology to mine e-waste for these metals borrowed from centuries-old technology developed for mining natural ores. Thus, the problems associated with e-waste mining are similar to the problems associated with mining ores in terms of environmental pollution with toxic waste. The legacy e-waste is associated with a broad range of notorious toxic chemicals including cadmium, lead, mercury, nickel, brominated chemicals used for flame retardation, and complex residues, which are poorly characterized with respect to potential toxic impacts on human health and environmental quality. Therefore, the proliferation of artisanal e-waste mining in under-resourced communities in Africa and Asia has led to rampant environmental pollution and diseases. Research to close the gap is needed to add to the focus on gold and copper to include the recovery of increasingly rare and geopolitically sensitive resources such as cobalt, lithium, and rare earth elements. Without investments in the collection and dismantling of e-waste to concentrate the recovery of valuable and precious materials, sustainable economic viability of e-waste mining at an effective scale is unlikely.

Bending the curve in regulatory policies

The fourth gap in closing the circular economy of electronics is the inadequate coverage of regulatory policies to encourage best practices at the national, regional, and international levels. Few countries have adopted legislation or implemented comprehensive policies to regulate e-waste generation and management. US President Biden issued an executive order in March 2022 to encourage recovery and recycling of metals such as cobalt, which represents a good start. Attempts to regulate international exportation and importation of e-waste through conventions such as the Basel Convention on the Transboundary Movement and Disposal of Hazardous Waste are neither universally ratified nor easy to enforce.[9] Therefore, expansion and harmonization of policies to regulate e-waste management within and across countries is necessary to plug loopholes that allow the detrimental effects of e-waste to have more adverse impacts in regions in which manual labor is cheap in comparison to regions that produce large amounts of e-waste but in which labor is expensive and local environmental policies prevent the establishment of factories designed for safe and efficient e-waste processing. Voluntary incentives aimed at consumers to purchase environmentally responsible electronics typically increase the cost of products and are prone to exacerbate the inequitable distribution and impacts of e-waste toxicity. Similarly voluntary incentives for manufacturers including the green electronic standards, adoption of safer material alternatives, and manufacturer take-back programs are spotty in their implementation and undervalued relative to incentives to sell new products with upgraded features and the uncertainties associated with consumers' willingness to pay premium costs.[10] Bending the curve of toward circularity of e-waste will require a new convention with participation of manufacturers and cooperation across UN agencies such as the International Labor Organization, the United Nations Environment Program, the United Nations Industrial Development Organization, and the World Health Organization. Models for such a convention already exist in the UN's political declaration to address antimicrobial resistance and the Minamata Convention on Mercury, which cuts across several societal sectors. The e-waste challenge has grown sufficiently to warrant such concerted efforts.

Bending the curve in public education

The fifth and final gap in circularizing the economy of electronics industry is the role of manufacturers and government agencies in educating the general public about environmental stewardship. Consumers worldwide are the beneficiaries of the electronics revolution, which has also made electronics manufacturers among the most profitable corporations in the world. The societal lockdown resulting from recent threats to public health including the COVID-19 pandemic and monkeypox outbreak have reinforced the necessity of constant access to remote information, data, and social networks, all of which are enabled by electronic devices. It is doubtful that the side effects of the electronic revolution in terms of e-waste toxicity and resource scarcity can be treated effectively without engaging consumer participation at a level higher than current experience. The gaps in consumer education about e-waste collection and recycling can be reduced through public education campaigns organized by government agencies. Manufacturers of electronic products must play a role in consumer engagement beyond advertising new device hardware and software upgrades to consumers. Unfortunately, the existing examples of consumer participation in product recovery and recycling programs such as lead-acid batteries have turned out to be unsustainable.[11] Cultivating electronic waste stewards among consumers who are already passionate about transnational issues,[12] including child labor, toxic pollution, climate change, and pandemic prevention, is likely to disseminate information about the need to bend the curve of the electronics revolution toward a more circular economy of electronic products.

Revising the electronics revolution

At its center, the electronics revolution is characterized by ingenious and entrepreneurial activities that continue to drive technical innovation that regularly introduces new devices with increasingly clever functions to consumers eager to remain at the cutting edge of social networking, work performance, and creativity. The revolution has also been characterized by convoluted spirals of adverse impacts on people and the planet. Progress in materials science and engineering research promises solutions that rely on the invention of less toxic, recyclable, and sustainable electronic products.[13] It is important that such solutions scale to the level that can transform the entire electronic industry through coordination with new ways of thinking about international regulatory policies and consumer behavior and preferences.[14] The learning curve has been steep toward grasping the various dimensions of the electronics revolution's impacts on society. The strategic implementation and coordination of solutions in the five areas addressed in this article will bend the curve toward a desirable circular economy of electronic products and an end to e-waste.

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O.A.O. serves as an unpaid co-chair of Apple Corporation's Green Chemistry Advisory Board. He is a recipient of research grants from Microsoft Corporation.

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