Circular economy and electronic waste

Electronic waste is the fastest growing category of hazardous solid waste in the world. Addressing the problem will require international collaboration, economic incentives that protect labour, and management approaches that minimize adverse impacts on the environment and human health.

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The quantity of hazardous electronic waste (e-waste) circulating in the world is now estimated to be more than 6 kg per person, totalling 44.7 million metric tonnes in 2016[1]. Despite international policies designed to restrict transboundary movement of hazardous wastes, the problem of global e-waste is exacerbated by illegal trade and 'informal' rudimentary recycling[2]. Rudimentary processing of e-waste occurs in many parts of the world, especially in emerging market economy countries such as China, Ghana, India and Nigeria, and the process generates toxic residues and emissions to air, soil and water[3] (Fig. 1). The United Nation's Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (known as the Basel Convention) has been influential in framing the debate on e-waste management. For example, the first international recognition of e-waste as a high-priority waste stream was developed with the UN's guidance in 2002[4], and the Solving the E-waste Problem (StEP) initiative has been continuously hosted by the United Nations University (UNU). These policy milestones were established without conclusive scientific data about e-waste risks and without the necessary technical capacity to deal with the rapidly increasing pace of e-waste production. Implementing the policies were further complicated by several issues, including the transnational movement of e-waste, considerations for labour and employment, the desire to support humanitarian organizations donating used electronics to poorer countries, and concerns for environmental pollution and risks to human health[5].

It is increasingly clear that top-down regulatory approaches are not effective for international management of e-waste, which has high-value content amenable to inefficient and unsafe rudimentary recycling in emerging market economy countries. Engaging the private sector, including manufacturers, retailers and labour investors, is necessary to stimulate the development of innovative solutions that will bring the extensive informal sector of e-waste management under guidelines that protect environmental quality and human health, while employing workers whose source of livelihood depend on the flow of discarded e-waste. Here we describe the opportunities for developing new or right-scaling expensive innovations such as Apple's Daisy robot recycler[6], for artisanal e-waste processing in the informal sectors. We propose a strategy to encompass e-waste management into a global circular economy (CE) agenda: integrating technical innovation for e-waste processing and financial incentives through multi-agency collaboration to improve rudimentary e-waste management in regions where the waste piles up while labourers and environmental quality are adversely impacted by the toxic components of electronic products.

Fig. 1 | Approaches to electronic waste dismantling. a–e, There is a marked difference between formal e-waste dismantling, such as Apple's Daisy robot (**a**), and manual dismantling, such as that in the Agbogbloshie market sector in Accra, Ghana (**b**). Informal e-waste resource recovery leads to environmental pollution (**c**), while stockpiles of e-waste awaiting recycling in government-approved facilities on the outskirts of Beijing, China, continue to grow (**d**,**e**), requiring urgent solutions. Credit: photograph in panel **a** courtesy of Apple, Inc.; photographs in panels **b**–**e** taken on location by O.A.O.

Right-scaling technology

The cost of installing and operating the supply chain and equipment to effectively manage e-waste is prohibitive because of restrictive policies and regulations designed to protect environmental quality and human health. This hurdle has led to the proliferation of rudimentary approaches to processing e-waste with externalized costs associated with human health impacts and the degradation of environmental quality. For example, the mean concentration of lead in the blood of children living near an informal e-waste processing site in Guiyu, China, was reported to be 15.3 μg dl^{-1}, exceeding safe levels by a wide margin[2].

The informal rudimentary e-waste sector, consisting of small groups of collectors, transporters and recyclers emerged primarily in Asia and Africa to meet unfilled needs with consequential adverse impacts on the environment of communities in which they operate. However, recent improvements to informal e-waste management practices are driven by government interventions primarily in China and India. China's e-waste regulations have been effectively implemented and have expanded towards regulatory oversight[7]. India has proposed new approaches to increase the scope of formal e-waste collection by enforcing

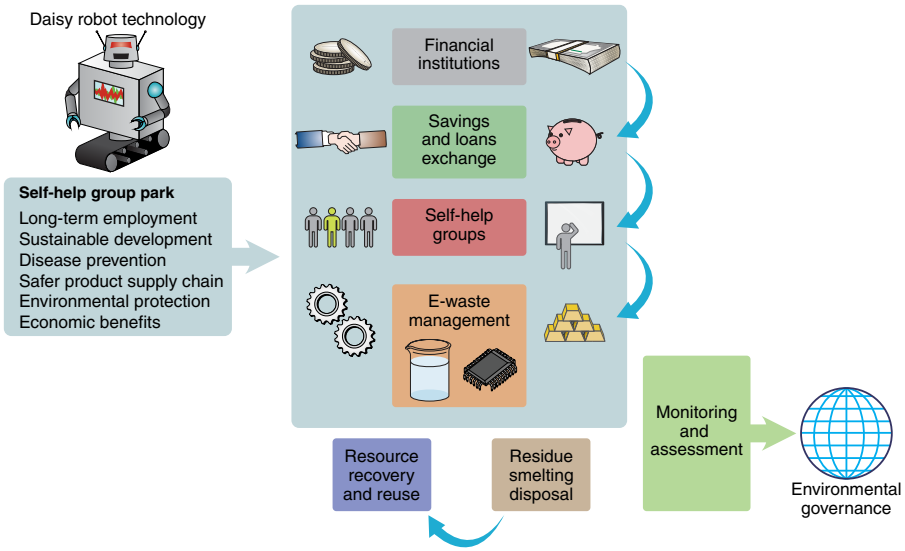

Fig. 2 | Illustration of a simplified self-help group park. The park could use Apple's Daisy robot, or similar technical assistance, and financial infrastructure as a model for supplementing a circular economy on e-waste management in developing countries. The motivation for establishing self-help groups (SHGs), depicted in the box under robotic technology, include benefits to labour, public health, environmental protection, economic productivity and boosts for sustainable development. In order to scale up to support e-waste management at the national level in developing countries these SHG parks need support either through the microfinancial systems of the banks offering initial financial provisions, or through corporate social responsibility funding by involving experienced institutions/organizations to promote the SHG formation — and this must be implemented under the umbrella of the environmental regulatory authority of the country. Closing the current gaps in the circular economy framework for electronic waste will also require continuous monitoring and assessment to support the shift from waste disposal to recycling and resource recovery.

e-waste management rules, promulgated in 2016[8]. Despite notable progress in these emerging market economy countries, a major gap exists between best available technology for e-waste management and resource recovery, for example the robot Daisy designed by Apple to dismantle an iPhone into component parts within a few minutes, and the actual technologies applied in the informal sector, which mostly consists of manual sorting, dismantling, material separation and burning. We argue that best environmental practices cannot be adopted widely if the best available technologies are not shared internationally or scaled to fit situations in different parts of the world. This is particularly the case for countries that import e-waste for the purposes of refurbishing, resale or scrap, without the essential infrastructure and policy environment to guarantee safety and efficiency of rudimentary recycling processes that are known to be widely practiced.

Policy developments

In the CE framework, extended producer responsibility (EPR) is essential to close the widening gap between the generation of e-waste and the recovery of scarce resources including rare earth metals[9]. Currently, EPR is subject to voluntary initiatives driven primarily by economic incentives. The rapid pace of technological innovation and miniaturization of electronic products indicates that the economic incentives for resource recovery as a justification for EPR may not be sustainable. Financing the infrastructure to ensure e-waste collection can be effective with mandatory EPR because of the need to manage various categories of e-waste, including products that do not contain precious materials that could have justified resource recovery according to economic calculations. Instead, e-waste that contains low-value but toxic components also need to be captured to avoid environmental pollution and exposures that damage population health[10].

The support of manufacturers for mandatory EPR will require designing policies that ensure a level playing field such that small manufacturers are not disproportionally burdened with the collection of used products from remote corners of the world where their brands are retailed, used and disposed. Instead, EPR should begin with a collective 'superfund' mechanism through which all electronic product manufacturers contribute financially, and manufacturers should be compensated for the adoption of green chemistry or eco-design principles that avoid the use of hazardous materials, which endanger environmental quality and human health anywhere in the life cycle of their products[4]. To be effective, the EPR superfund must also include end-of-life recovery of used products and reuse of recovered materials, whereby manufacturers contribute funds proportionate to the number of products sold, and an independent agency designs and implements strategies for the collecting, sorting and recycling of defunct electronic products worldwide. This CE model may be more attainable for large, easily marked and tracked electronic products for which technical knowledge of repairing or refurbishing them is not widely available to the workforce engaged in resource recovery in emerging market economies. For this category of e-waste, prevention of unsafe and unprincipled rudimentary recycling is a priority for integration into the proposed EPR superfund and CE framework.

Designing effective EPR for most high-volume electronic products, such as mobile phones, laptop computers and televisions, which dominate the e-waste stream, will require engaging local entrepreneurial stakeholders with minimally restrictive regulatory and policy instruments. Therefore, there is a need for alternative e-waste management models to formalize rudimentary e-waste processing, which needs to be integrated into CE models with new technological tools and regulatory policies designed to ensure that this sector functions safely without endangering the health of workers or shared environmental spaces.

The e-waste management town of Guiyu, China, is highlighted here as an example of how unsafe rudimentary processes were transformed through new environmental policies, but perhaps this model is still in need of technical innovation and EPR to be fully transformed into a CE framework for electronic products. Before 2015, Guiyu was the location of approximately 5,000 informal sector operations. Currently, most of these operations have combined to form 29 integrated formal companies located in a formal industrial park[7]. The high cost of participation in such industrial parks is prohibitive for most small artisanal operators, although many have joined with other small operators to register as an appropriately sized operation in the industrial park. The progress in environmental protection and improvement

of occupation conditions in Guiyu is notable, but inefficient manual labour still dominate operations, and the lack of technical and financial infrastructure for EPR prevents sustainable development of e-waste management CE in the region.

Economic incentives

Retrieval of defunct and dilapidated electronic products from consumers is a major stumbling block for proper e-waste management worldwide[11]. The rising popularity of web-based applications for e-waste collection is being pioneered in China, for example, through the Baidu and Recycling Brother (Huishouge) apps that connect consumers who would like to dispose of e-waste to the certified services of recycling and dismantling companies. The Baidu app was launched with the United Nations Development Programme (UNDP) Asia–Pacific Innovation Fund[12]. There is further interest in building an alliance of stakeholders including electronics manufacturers and financial institutions to build a comprehensive online e-waste management process. Such collaboration could integrate experiences from the informal recycler collectives at Chinese industrial parks with Indian microfinance economic incentives. The integration can lead to the establishment of self-help group (SHG) parks, implemented under the auspices of environmental regulatory authorities (Fig. 2).

Banks in India have provided initial capital investments for transforming and promoting sustainable rural development that is applicable to rudimentary e-waste management. For example, the National Bank for Agriculture and Rural Developments and the Small Industries Development Bank of India have collaborated to establish a SHG bank linkage scheme, which offer facilities for short-term lending to particular industrial sectors (micro, small and medium enterprises). These microfinancial strategies are regulated and supervised by the Reserve Bank of India; the banks also offer small-scale funding support to non-governmental organizations that promote SHG formation. Here we propose a similar scheme but scaled up to support e-waste management at national levels in emerging economies worldwide.

A second example of this approach is based on corporate social responsibility (CSR) funding for designated industrial sectors. Since 2014, the Indian Ministry of Corporate Affairs has implemented CSR, which mandates industries to spend 2% of their average net profit from the past three financial years on CSR activities[13]. This scheme could be adopted for transforming e-waste management in countries with economies in transition (Fig. 2). India already established SHGs for various forms of community development, to provide economic opportunities for the low-income workforce. For example, a solid waste collection and handling cooperative successfully transitioned from rudimentary procedures into a formal partnership with the municipality of Pune, India, to improve the efficiency and safety of solid waste management. Approximately 2,300 members are part of this cooperative, which continually provides formal collection and recycling services to about 400,000 households in Pune[14]. Initially, the local government provided subsidies for administrative and equipment-related costs. Recently, the cooperative purchased a storage site for waste recycling, and other basic equipment and resources, such as protection equipment, and provides monthly salaries for workers[14]. Further research is needed to assess how such cooperatives may be adapted for processing hazardous solid waste such as e-waste, which may contain toxic materials and potentially explosive components such as rechargeable batteries. Security of digital data and personal information on smartphones and computers is also a concern for e-waste management in such contexts.

Other examples in economies in transition include the World Bank's pilot project on e-waste management in Egypt and Ethiopia. The project is implemented in collaboration with the Egyptian government, and focuses on providing economic incentives with a collection strategy involving non-governmental organizations and the private sector in e-waste management[12]. Further research is also needed to compare these experiences for the purpose of revealing best practices that can be shared across many countries facing a deluge of e-waste, and trying to contribute to a sustainable CE at the global model without compromising employment opportunities locally.

Recommendations for integration

Rapid developments in electronic product design and social networking capabilities have made mobile devices globally ubiquitous. As the fastest growing category of solid hazardous waste produced and transported internationally, e-waste requires innovative management strategies that transcend national boundaries. The labour market situation in countries with economies in transition has produced various models for financial and technical support for e-waste management. Here, we make recommendations for integrating technical support and financial incentives to transform rudimentary e-waste recycling and resource recovery at various scales.

United Nations Sustainable Development Goals (SDGs) 8 and 12 provide a useful framework for exploring the various dimensions of collaborations needed to transform informal e-waste management[15]. Consistent with the principles of a CE, the SDGs encourage policies that may create employment through partnerships of public and private enterprises, diversification of high-value-added and labour-intensive sectors, protection of labour rights, and promotion of safe and secure working environments for workers, including minimizing impacts on the environment and human health[16]. The United Nations Environment Programme (UNEP) has declared that the information and communication technology sector, supported primarily by electronic products, offers many opportunities and challenges for sustainable development[15]. Electronic waste is a serious challenge for environmental management, while it is also considered as secondary resource material, which could fulfil the raw-material demand for the manufacturing of new products if justified by economic considerations.

United Nations agencies responsible for the integrity of labour markets, economic development, environmental protection and the monitoring of risk factors affecting human health can strengthen programmatic collaboration with national governments by providing advanced knowledge and expertise on electronic product life-cycle stewardship; by brokering financial assets to tackle emerging e-waste streams in many developing countries; and supporting web-based knowledge-sharing platforms on e-waste. In this regard, the UNDP Asia–Pacific Innovation Fund piloted an important initiative that was ultimately too limited to be scaled-up in China and too restricted to influence e-waste management practices in other countries with economies in transition[17]. We suggest that countries such as Ghana and Nigeria are ripe for translational strategies that implement locally tailored versions of UNDP 'app-based' initiatives with the assurance that such initiatives are designed to be sustainable through engagement and investments of local or regional financial institutions with local government support to provide security and infrastructural guarantees. Collaboration with other UN agencies including the World Health Organization, Environmental Programme, and International Labour Organization will be necessary to ensure cross-sectoral consistency of policies and actions to manage e-waste internationally.

International agreements such as the Basel Convention have established regional activity centres to ensure proper implementation of agreements and to monitor compliance. For example, the Mobile Phone Partnership Initiative and the Partnership for Action on Computing Equipment, known as MPPI and PACE, respectively[18,19], are intended to engage manufacturers and other stakeholders to promote the refurbish/reuse/recycle approach in order to avoid the end-of-life disposal of mobile phones into landfills where they might release toxic chemicals into groundwater or cause soil pollution. The MPPI is the Basel Convention's main mechanism for advising parties and signatories on matters associated with the framework for environmentally sound management of waste mobile phones. The programme's technical guidelines are: retrieval of used/end-of-life mobile phones from individuals and households, transnational movement of collected waste mobile phones, resale and reuse after refurbishment/repair of used mobile phones, material recovery and recycling of end-of-life mobile phones, and raising awareness of design-environment considerations. Lessons learned from such programmes can provide the basis for prospective public–private partnerships.

The Basel Convention is an international agreement, with 186 parties, for solving the challenges created by e-waste. The Secretariat of the Basel Convention is administered by UNEP, offering technical guidelines and strategies (technical and legal), and providing training and workshops on the appropriate management of e-waste. Therefore, the regional centres for the Basel Convention play an important role in the coordination of e-waste management pilot projects at the regional level, including South–South and North–South cooperation. Regional Basel Convention centres can develop technical guidelines and facilitate technology transfer to countries with economies in transition. Funding for these regional centres may be garnered through various mechanisms, such as contributions from the ministerial budgets of member countries (for example, ministries of finance, environment and labour), co-financing of specific projects with international agencies responsible for coordinating foreign aid (for example, the Global Environment Facility[20]), and revenues from user charges (for example, retail point-of-sale surcharges for prospective waste management).

Post-manufacturing resource recovery is labour-intensive and the profit margin can be so small that e-waste recyclers resort to drastic and unsafe measures that cause pollution. Many countries with economies in transition have not yet established formal e-waste collection and recycling systems due to the high cost of developing safe and effective procedures and facilities. Without government oversight, the informal e-waste sector in places such as the Agbogbloshie district in Accra, Ghana (Fig. 1), can become national embarrassments. Advancing e-waste recycling technologies and strengthening recycling infrastructure are necessary for countries such as Ghana and Nigeria to tackle the emerging issues created by the increasing size of the informal sector (Fig. 2). In such settings, e-waste processors can use internet-based applications for e-waste collection to centralize waste management operations. Financial incentives can be provided by programmes similar to Indian government initiatives for SHGs.

Technology transfer from regional to national scales can help transform informal sectors towards safer recycling practices. These are important topics for consideration by national governments with the responsibility to develop and implement local policies to encourage collaborative efforts in the informal e-waste management sector and support dissemination of best practices. Such cooperatives need to set clear goals, minimize environmental impacts and encourage consumers to send their e-waste only to formally recognized processors. In addition, to maintain the funding stream, the formal sector should be required to demonstrably increase the recycling rate by employing e-waste collectors to build social networks with consumers, so the overall collection system can work more efficiently. Finally, workshops and training sessions leading to operation licensing can improve accountability, while penalties for illegal conduct are strengthened. These are potential solutions for transforming the informal e-waste management sector into a profitable and safe component of the emerging global CE for the sustainable development of countries with economies in transition. ❐

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Competing interests

Oladele A. Ogunseitan co-chairs the Green Chemistry Advisory Board for Apple, Inc. (unpaid). Jinhui Li is executive director of the United Nations Basel Convention Regional Centre for Asia and the Pacific.