A Brief Exploration of Human-Computer Interaction, XR Technology and Global E-waste

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As computing moves beyond screens and keyboards, human-computer interaction (HCI) plays a central role in shaping how we experience and navigate digital environments. Carroll (1997), professor of Information Sciences and Technology writes, “Human-computer interaction (HCI) is the area of intersection between psychology and the social sciences, on the one hand, and computer science and technology, on the other. HCI researchers analyse and design-specific user-interface technologies (e.g. three-dimensional pointing devices, interactive video). They study and improve the processes of technology development (e.g. usability evaluation, design rationale). They develop and evaluate new applications of technology (e.g. computer conferencing, software design environments)…HCI is a science of design. It seeks to understand and support human beings interacting with and through technology. Much of the structure of this interaction derives from the technology, and many of the interventions must be made through the design of technology. HCI is not merely applied psychology; it has guided and developed the basic science as much as it has taken direction from it. It illustrates possibilities of psychology as a design science.” (pp. 501-502).

In the 1970s and 1980s, as HCI was emerging, developers often prioritized machine functionality over user experience, overlooking the importance of designing computers around human needs “…the notion that computer systems and software should be designed and developed with explicit consideration of the needs, abilities and preferences of their ultimate users was not taken seriously. Most writings about computing from the mid-1970s are stunningly dismissive of usability and rather patronizing of users” (p. 502). However, through much iterative research, by the 1990s, the field of HCI shifted its foundation to be human-centered and had become well integrated in computer science. Carroll (1997) continues, “After only a decade, the computer industry and the discipline of computer science were transformed. The case had been made for a user-centered system development process, a process in which usability was a primary goal. People began to distinguish sharply between technology-driven exploratory development, which is now accompanied by explicit disclaimers about usability, and real system development, in which empirically verified usability is the final arbiter…A 1988 Association for Computing Machinery (ACM) task force enumerated HCI as one of nine core areas of the computer science discipline (Denning et al., 1989).” (p. 506)

HCI provides the theoretical and practical foundation for the information that shapes modern User Interface (UI) and User Experience (UX) (Sharma & Tiwari, 2021). As XR technology becomes more widespread, and as technology evolves in general, maintaining HCI research as a societal priority is crucial for understanding and addressing its impacts on human life (Marcus, 2015).

Brief History of Extended Reality (XR)

Extended Reality (XR) technology is transforming how people interact with physical and virtual spaces, shifting experiences from observing to fully participating. XR is a broad term that includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). While AR blends virtual elements with real-world objects in real time, VR immerses users in a simulated environment that can be realistic or imaginary with full movement control and navigation (Ro et al., 2018; Suh and Prophet, 2018; Chuah, 2018). Both technologies are often combined to create MR, a more immersive experience. The development of Extended Reality (XR) started two centuries ago through essential technological breakthroughs (Hillmann, 2021; Vohra, 2025). Charles Wheatstone invented the stereoscope in 1838 which displayed different images to each eye creating a three-dimensional image with a sense of depth. This established the foundation for modern VR displays. In 1957, Morton Heilig from the field of cinematography developed the Sensorama which combined 3D film with stereo sound, aromas and motion and created simulated real-world experiences. The first motion-tracking VR headset emerged from Philco engineers in 1961 and in 1968, Harvard professor Ivan Sutherland, developed the Sword of Damocles, a head-mounted display which tracked head movements. Myron Krueger introduced VIDEOPLACE in 1975 which displayed users' silhouettes on a screen for interactive activities while Fake Space Labs launched the Binocular-Omni-Orientational Monitor (BOOM), a complex system that encompassed a broad virtual moving environment, a stereoscopic display system and mechanical arm tracking in the late 1980s (Vohra, 2025).

During the 1980s and 1990s, Jaron Lanier's VPL research released the first commercial VR devices including DataGlove and EyePhone and Boeing researchers, Tom Caudell and David Mizell, introduced the term Augmented Reality by adding computer graphics to real-world assembly views. The University of Illinois in Chicago developed the CAVE (CAVE Automatic Virtual Environment) for scientific visualization through VR in 1992. The post-2000 period brought Palmer Luckey's Oculus Rift to market until Facebook acquired it in 2014. What follows then is Microsoft's HoloLens release in 2016 and the introduction of IKEA Place as an AR application in 2017 (Vohra, 2025).

According to Hillmann (2021), “One could say that the modern area of XR was defined in the decade between 2010 and 2020. These 10 years saw the iterations of VR headsets, from mobile phone–based Google Cardboard variations to high-end enterprise solutions, driven foremost by HTC Vive and Oculus and the evolution of handheld AR with the two main developer frameworks, ARKit by Apple and ARCore by Google, plus the pioneering HMDs Magic Leap and Microsoft's HoloLens." (p.21).

Cognitive and Behavioral Research, Clinical Interventions, Education and XR

Today, XR sits at the intersection of information technology and the cognitive, clinical, and educational sciences. XR has long captured public interest, and its development is a major focus for leading technology companies. It has the potential to provide behavioral insights, transform clinical treatments, and enhance learning and education (Draschkow et al., 2023). According to experts, immersive tools can help patients manage pain while providing benefits for their mental and physical health (Freeman et al., 2017; Maples-Keller et al., 2017; Osumi et al., 2017). XR has been effective in treating patients with PTSD and schizophrenia and in reducing anxiety symptoms (Freeman, 2008; Freeman et al., 2008, 2018; Rothbaum et al., 1995, 2000, 2001). A recent example of VR's clinical impact is the development of automated therapy for treating agoraphobia and alleviating distress in patients with psychosis (Freeman et al., 2022). Studies also show VR rehabilitation may be able to boost patient motivation and support the multimodal sensorimotor reintegration of a phantom limb, which can in turn produce a strong pain-relieving effect (Osumi et al., 2017). The controlled safe environment of XR enables patients to confront and overcome their avoidance behaviors through realistic scenarios that would otherwise be nearly impossible to achieve in conventional laboratory settings or clinical environments or real-world locations.

In training and education, XR can enable active learning and knowledge building (Winn, 1993). Experts say driving and flight simulators were among the earliest XR use cases (Aginsky et al., 1997; Van Veen et al., 1998). Since then, XR has gained a growing role in education

(Rojas-Sánchez et al., 2023), with its high levels of immersion and interactivity (Martín-Gutiérrez et al., 2017; Radianti et al., 2020) shown to improve knowledge acquisition (Chavez & Bayona, 2018). Draschkow et al. (2021) also notes that XR can also be used to address inequalities in educational attainment by increasing accessibility (https://oxr.eng.ox.ac.uk/blog/edtechphase1/) and addressing racial biases in medicine (Roswell et al., 2020).

Electronic Waste, E-waste, or Waste Electrical and Electronic Equipment (WEEE)

The potential educational and health benefits of XR sound promising, however, it does raise concerns about the environmental cost of producing new electronic hardware while electronic waste and climate change remain urgent global issues (Baldé et al., 2024; Fawole et al., 2023). The 2024 Global E-waste Monitor, published by UNITAR and the ITU reports that in 2022, the world generated 62 million metric tons of e-waste (about 17.2 lbs per person) which was an 82% increase since 2010. If current trends continue, that figure could climb to 82 million metric tons by 2030. Yet, only 22.3% of this waste was formally collected and recycled in 2022, and projections suggest the rate may drop to 20 percent by the end of the decade. This represents an estimated US $62 billion in lost recoverable resources each year. Because of rapid technological advances, higher consumption, limited repair options, shorter product lifecycles, increasing electronification, and insufficient e-waste management infrastructure, e-waste is outpacing traditional recycling efforts “by a factor of almost 5” (p. 10). This report also states that millions of tons of critical minerals needed for clean energy technologies are being discarded annually. In 2022, an estimated 12 million tons of metals were lost. Without major policy shifts, infrastructure improvements or coordinated global action, the gap between e-waste generation and recycling will continue to grow, threatening both environmental sustainability and the security of essential resource supplies (Baldé et al., 2024; Widmer et al., 2005).

Chapter 10 of the Global e-waste monitor 2024 did present four scenarios for e-waste management by 2030, each reflecting different levels of policy action, infrastructure development, and global cooperation as shown in Figures 1 - 4.


Chapter 10. Improvement Outlook from 2022 to 2030

The quantities of e-waste formally documented as collected and managed in an environmentally sound manner are projected to increase at the same pace as observed in the time series between 2010 to 2022, reaching 16 billion kg by 2030. This implies a further decline in the global e-waste collection rate to only 20 per cent of the e-waste generated, because the substantially higher rate of e-waste generation will outpace any improvements in e-waste management. Therefore:

- A rising share of e-waste (24 billion kg) will be managed outside formal systems by the informal sector in low- and middle-income countries. This shift is anticipated because of the faster growth in formally undocumented collection and recycling of e-waste in countries without regulated e-waste management systems. The environmental impact will be 46 thousand kg of mercury released and 149 billion kg of CO_2-equivalent emissions contributing to global warming.
- E-waste collected and recycled outside formal systems in upper-middle-income and high-income countries is expected to increase to 22 billion kg.
- As a result, approximately 25 billion kg of metal resources are projected to be viably recovered by various means, including formal (environmentally sound) collection and recycling, mixing with scrap metal, residual waste and the involvement of the informal sector. The amount of metals lost (non-viable to recover) is estimated to be 17 billion kg.
- The overall economic assessment for this scenario is that the cost of e-waste management is projected to **grow to USD 40 billion by 2030**.

Benefits
- Viable recovery of metals: USD 42 billion.
- Value of avoided greenhouse gas emissions: USD 26 billion.

Costs
- The primary costs consist of USD 93 billion in externalized costs to the population and the environment, stemming from lead and mercury emissions, plastic leakages and contributions to global warming as a result of non-compliant activities, particularly in cases where hazardous substances are not properly managed (such as in the informal sector, e-waste in residual waste and e-waste mixed with scrap metal).
- Additional costs are associated with the treatment of e-waste, amounting to USD 15 billion, primarily comprising compliant e-waste recycling costs. Costs incurred by the informal sector, scrap metal and residual waste management are comparatively lower, as such processes are considerably cheaper to manage.

Scenario 1: Business as Usual by 2030

KEY E-WASTE STATISTICS
16 billion kg | 20%
e-waste projected to be formally collected and managed by 2030.

METALS
25 billion kg
metal resources are viably recovered.
17 billion kg
metal resources are lost.

ENVIRONMENTAL IMPACT
46 thousand kg
emissions of mercury released.
149 billion kg
CO_2.eq. contributing to global warming.
11 thousand kg
mercury emissions avoided.
105 billion kg
CO_2-eq. emissions avoided.

OVERALL ECONOMIC IMPACT OF E-WASTE MANAGEMENT
Benefits
26 billion USD
value of avoided greenhouse emissions.
42 billion USD
value in viable recovery of metals.
Benefits
Costs
Costs
15 billion USD
value of compliant recycling costs.
93 billion USD
value of externalized costs to the population and the environment.
-40 billion USD
projected annual economic monetary impact of e-waste management globally.

Source: The Global E-waste Monitor 2024

The Global E-waste Monitor 2024 58

Fig. 1

Scenario 2: Progressive by 2030

KEY E-WASTE STATISTICS

31 billion kg | 38%
e-waste projected to be formally collected and managed by 2030.

METALS

28 billion kg
metal resources are viably recovered.

14 billion kg
metal resources are lost.

ENVIRONMENTAL IMPACT

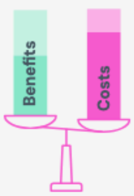
36 thousand kg
of mercury emissions released.

21 thousand kg
emissions of mercury avoided.

116 billion kg
CO_2-eq. emissions released.

155 billion kg
CO_2-eq. emissions avoided.

OVERALL ECONOMIC IMPACT OF E-WASTE MANAGEMENT



-4 billion USD
projected annual economic monetary impact of e-waste management globally.

Benefits

39 billion USD
value of avoided greenhouse emissions.

52 billion USD
value in viable recovery of metals.

Costs

20 billion USD
value of compliant recycling costs.

75 billion USD
value of externalized costs to the population and the environment.

Source: The Global E-waste Monitor 2024

In this scenario, global action takes the form of voluntary collection schemes in regions where no legislation is currently in force. In regions that currently have legislation and decent e-waste management infrastructure, formal collection rates increase to 85 per cent. The dismantling and final treatment of waste printed circuit boards is expected to be optimized, to extract more value.

Countries with unregulated e-waste management will launch voluntary collection schemes, essentially starting from scratch, with the aim of collecting 10 per cent of the total e-waste generated. Countries that already have (drafted) legislation for e-waste collection but do not have an established e-waste management infrastructure will start strengthening their enforcement efforts so as to substantially increase collection rates, to 15 per cent. Countries with established e-waste management infrastructure will boost their collection rates by improving enforcement and implementing more accessible return systems covering a wider range of products. This means that the majority of EU and high-income countries (except those in which collection rates are currently below 40 per cent) will achieve the EU collection target of 85 per cent. At the same time, the resource efficiency of environmentally sound e-waste management increases such that there will be lower losses of printed circuit boards thanks to higher specific dismantling, and the implementation and optimization of waste management technologies using artificial intelligence, automation and advanced robotics play a growing role in waste treatment processes. Therefore:

- The global e-waste collection and recycling rate will increase to 38 per cent.
- Most changes will occur in upper-middle- and high-income countries optimizing their collection rates and printed circuit board dismantling rates.
- As a consequence, in middle- and high-income countries, the amount of e-waste being collected and recycled outside formal channels will fall to 14 billion kg and the amount disposed of as residual waste to 13 billion kg. Resources will still be lost, however, and there will still be an environmental impact.
- The amount of e-waste collected and recycled outside formal systems in low- and lower-middle-income countries is expected to stay the same, at 24 billion kg. It will be managed mainly by the informal sector and will continue to have a serious negative environmental and social impact.
- There will nonetheless be some improvement in terms of environmental impact: the release of 21 thousand kg of mercury, the emission of 116 billion kg of CO_2 equivalents and the generation of 1.4 trillion kg of waste from ore extraction will be avoided.
- As a result, approximately 28 billion kg of metal resources are projected to be brought back into the economy as secondary resources (viable recovery) by various means, including formal (environmentally sound) collection and recycling, mixing with scrap metal, residual waste and the involvement of the informal sector.
- The amount of metals lost (non-viable to recover) will be reduced to an estimated 43 billion kg.
- The overall economic assessment for this scenario is that the cost of e-waste management will be close to net zero (-USD 4 billion).

Benefits

- Viable recovery of metals as secondary resources: USD 52 billion.
- Value of avoided greenhouse gas emissions: USD 39 billion.

Costs

- The primary costs consist of USD 75 billion in externalized costs to the population and the environment, stemming from lead and mercury emissions, plastic leakages and contributions to global warming from the release of refrigerants.
- The costs associated with the treatment of e-waste increase to USD 20 billion, primarily comprising compliant e-waste recycling costs. The costs incurred by the informal sector, scrap metal and residual waste management are comparatively lower, as they are considerably cheaper to manage.

Fig. 2

In scenario 3, global action takes the form of effective voluntary collection schemes, while governments focus on enhancing source separation of e-waste in regular waste management systems. Efforts will be made to formalize the informal sector, and formal collection schemes will be established to collect a portion of imported used EEE items in low- and middle-income countries. As in the progressive scenario, the dismantling and final treatment of waste printed circuit boards is expected to be optimized, to extract more value.

Under this more ambitious scenario, all countries that currently lack formal e-waste management systems will actively participate in the collection and management of more e-waste, building on the voluntary actions already carried out. They will gradually engage with the informal sector and formalize its working conditions, providing safety measures and training in more efficient and environmentally sound treatment. They will guarantee acceptance of the materials collected in the informal sector by formalized environmentally sound final treatment processes in low- and middle-income countries. Furthermore, high-income countries lacking specific e-waste legislation will commence source separation, bolstered by the establishment of effective collection schemes.

National governments with existing recycling systems will place higher priority on further increasing collection rates through targeted interventions, such as implementing eased return systems and setting appropriate and ambitious collection rates. There will also be a focus on collecting imported used EEE in low- and middle-income countries after they became waste. Therefore:

- The global e-waste collection rate will increase to 44 per cent, with 37 billion kg of e-waste managed in an environmentally sound manner.
- A total of 12 billion kg of e-waste will eventually be diverted from residual waste and less e-waste will be managed outside the formal e-waste management system in upper-middle- and high-income countries.
- Better efforts in low- and middle-income countries will lead to a modest decrease in the amount of e-waste managed by the informal sector, to 21 billion kg.
- The impact on the environment will be further improved, and approximately 29 billion kg of metal resources are projected to be viably recovered by various means, including formal (environmentally sound) collection and recycling, mixing with scrap metal, residual waste and the involvement of the informal sector. The amount of metals lost (non-viable) will be reduced to an estimated 13 billion kg.
- The overall economic assessment for this scenario is that e-waste management will be net positive.

Benefits

- Viable recovery of metals: USD 54 billion.
- Value of avoided greenhouse gas emissions: USD 43 billion.

Costs

- The primary costs consist of USD 66 billion in externalized costs to the population and the environment, stemming from lead and mercury emissions, plastic leakages and contributions to global warming arising from non-compliant activities, particularly in cases where hazardous substances are not properly managed (such as in the informal sector, e-waste in residual waste and e-waste mixed with scrap metal).
- The costs associated with the treatment of e-waste increase to USD 21 billion, primarily comprising compliant e-waste recycling costs. Costs incurred by the informal sector, scrap metal and residual waste management are comparatively lower, as they are considerably cheaper to manage.

Scenario 3: Ambitious by 2030

KEY E-WASTE STATISTICS

37 billion kg | 44%
e-waste projected to be formally collected and managed by 2030.

METALS

29 billion kg
metal resources are viably recovered.

13 billion kg
metal resources are lost.

ENVIRONMENTAL IMPACT

32 thousand kg of mercury emissions released.

25 thousand kg emissions of mercury avoided.

103 billion kg CO_2-eq. emissions released.

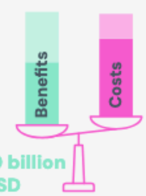
171 billion kg CO_2-eq. emissions avoided.

OVERALL ECONOMIC IMPACT OF E-WASTE MANAGEMENT

Benefits

43 billion USD
value of avoided greenhouse emissions.

54 billion USD
value in viable recovery of metals.



Costs

21 billion USD
value of compliant recycling costs.

66 billion USD
value of externalized costs to the population and the environment.

10 billion USD
projected annual economic monetary impact of e-waste management globally.

Source: The Global E-waste Monitor 2024

Fig. 3

In scenario 4, high- and upper-middle-income countries with legislation will attain a formal collection rate of 85 per cent. All other countries with legislation will collect and formally manage 40 percent of their e-waste, as will countries without legislation. Furthermore, collaborative efforts between low-income and high-income countries will lead to the treatment of more imported used EEE goods. Similar to the progressive scenario, the dismantling and final treatment of waste printed circuit boards will be optimized, to extract more value.

There will be significant cooperation between the formal and informal sectors, focused on substantially improving and formalizing the work of the latter. This will include prioritizing source separation of e-waste in countries lacking specific e-waste legislation and establishing effective collection schemes. The separately collected e-waste is then transferred to environmentally sound e-waste recyclers. National governments with existing recycling systems will prioritize increasing collection rates through targeted interventions and setting appropriate collection rates. Under this scenario, all imported used EEE will be collected at end of life in low- and middle-income countries. Large investments in e-waste management capacity will drive demand for recycled materials, resulting in higher prices for both informal recyclers and formal waste managers.

Consequently, the global e-waste collection rate will further increase to 60 per cent, with 54 billion kg of e-waste being managed in an environmentally sound manner. In this scenario most gains are realized in low- and middle-income countries, as follows:

- The amount of e-waste managed outside the formal sector in lower-middle- and low-income countries (the informal sector) will fall to 13 billion kg.
- The amounts disposed of in mixed residual waste and/or treated outside compliant schemes in high- and upper-middle-income countries will fall slightly, to 10 billion kg.
- Consequently, an estimated 30 billion kg of metal resources will be viably recovered globally. The amount of metals lost (non-viable to recover) will be reduced to an estimated 12 billion kg.
- The main gains for society are improvements in terms of releases into the environment, as 34 thousand kg of mercury emissions and 209 billion kg of CO_2-equivalent emissions will be avoided. This will essentially be due to significant improvements in working conditions in the informal sector.
- The overall economic assessment for this scenario is that e-waste management will be net positive globally, at 38 billion USD, mainly thanks to monetized mitigated greenhouse gas emissions. However, in low- and middle-income countries, the result could be still negative. Realistically, the revenue gained will not be used to pay the externalized costs.

Benefits

- Viable recovery of metals: USD 57 billion.
- Value of avoided greenhouse gas emissions: USD 52 billion.

Costs

- The primary costs consist of USD 47 billion in externalized costs to the population and the environment, stemming from lead and mercury emissions, plastic leakages and contributions to global warming arising from non-compliant activities, particularly in cases where hazardous substances are not properly managed (such as in the informal sector, e-waste in residual waste and e-waste mixed with scrap metal).
- The costs associated with the treatment of e-waste increase to USD 24 billion, primarily comprising compliant e-waste recycling costs. Costs incurred by the informal sector, scrap metal and residual waste management are comparatively lower, as they are considerably cheaper to manage.

Scenario 4: Aspirational by 2030

KEY E-WASTE STATISTICS

54 billion kg | 60%
e-waste projected to be formally collected and managed by 2030.

METALS

30 billion kg
metal resources are viably recovered.

12 billion kg
metal resources are lost.

ENVIRONMENTAL IMPACT

23 thousand kg
of mercury emissions released.

34 thousand kg
emissions of mercury avoided.

73 billion kg
CO_2-eq. emissions released.

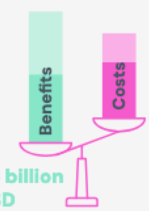
209 billion kg
CO_2-eq emissions avoided.

OVERALL ECONOMIC IMPACT OF E-WASTE MANAGEMENT

Benefits

52 billion USD
value of avoided greenhouse emissions.

57 billion USD
value in viable recovery of metals.



Costs

24 billion USD
value of compliant recycling costs.

47 billion USD
value of externalized costs to the population and the environment.

38 billion USD
projected annual economic monetary impact of e-waste management globally.

Source: The Global E-waste Monitor 2024

Fig. 4

Discussion

HCI serves as the research and design framework for developing XR technologies, shaping how people interact with immersive systems in education, healthcare, manufacturing, and entertainment. As XR devices become more common, their usability and accessibility directly influence adoption rates and upgrade cycles. These same design decisions also determine the environmental footprint of XR hardware, affecting both material selection and the ability to repair and recycle devices (Amoah et al., 2025). The Global e-waste monitor tracks the lifecycle endpoint of these devices, measuring how much XR-related hardware is formally collected, recycled, or lost. Data from the e-waste monitor reveals the scale of resource recovery opportunities and environmental risks associated with the growing volume of electronics, including XR headsets, sensors, and wearable controllers (Amoah et al., 2025; Widmer et al., 2005). By continuing to integrate HCI's research focus on user needs and environmental sustainability with XR's immersive capabilities and the Global e-waste monitor's data-driven insights, policymakers should feel empowered and motivated to enforce regulations that help researchers and designers create XR technologies that are not only engaging and accessible but also environmentally responsible (Fawole et al., 2023; Sharma et al., 2023; Widmer et al., 2005).

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