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Original Research

# Disentangling the worldwide web of e-waste and climate change co-benefits

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ABSTRACT

The benefits of consumer electronic products have transformed every societal sector worldwide. However, the adverse impacts of electronic waste (e-waste) disproportionately affect low-income communities and marginalized ecosystems in nations with economies in transition. The embodied carbon footprint of new electronic products, especially information and communications technology (ICT) devices, is an important source of greenhouse gas (GHG) emissions, accounting for 67% ± 15% of total lifetime emissions, instigated by mineral mining, manufacturing, and supply chain transportation. We estimate that between 2014 and 2020, embodied GHG emissions from selected e-waste generated from ICT devices increased by 53%, with 580 million metric tons (MMT) of $CO_2$e emitted in 2020. Without specific interventions, emissions from this source will increase to ~852 MMT of $CO_2$e annually by 2030. Increasing the useful lifespan expectancy of electronic devices by 50%–100% can mitigate up to half of the total GHG emissions. Such outcomes will require coordination of eco-design and source reduction, repair, refurbishment, and reuse. These strategies can be a key to efforts towards climate neutrality for the electronics industry, which is currently among the top eight sectors accounting for more than 50% of the global carbon footprint.


## 1. Introduction

The international commitment to achieve the Paris Agreement's aim of limiting average global temperature increases to 1.5 °C is facing an unlikely outcome based on the current trajectory of greenhouse gas emissions unless there are unprecedented cutbacks in all sectors of the global economy (Höhne et al., 2021; IPCC, 2021). The electronics industry is notorious for its heavy footprint of energy intensity and carbon emissions (Chen & Ogunseitan, 2021; Gomes et al., 2021; I et al., 2020). However, the environmental impacts of digital technologies have been investigated largely about the toxic impact of electronic waste (e-waste), and other interconnected impacts are poorly understood at the regional or global level. Estimates of the contribution of digital technologies to climate change suggest a range of 1.4%–5.9% of global GHG emissions, of which ~31% is contributed by digital devices such as smartphones, desktops, displays, and netbooks (GEC, 2021). Moreover, the global supply chain of the electronics industry is among the top eight sectors accounting for more than 50% of the global carbon footprint (WEF, 2021). The upward trend of global demand for ICT devices is driven in part by planned obsolescence, the incremental introduction of technical innovations, and restrictive policies and regulations regarding options to repair and refurbish (Chen & Ogunseitan, 2021; Ogunseitan et al., 2009). Toxic materials are inevitable components of new electronic products and render e-waste management hazardous, thereby causing major health problems for informal waste management laborers including women and children in countries where most (~83%) of obsolete electronics are informally dismantled (WHO, 2021).

Recent estimates indicate that ~53.6 MMT, an average of 7.3 kg per capita, of e-waste were generated in 2019 worldwide, a 21% (9.2 MMT) increase since 2014. The quantity of e-waste is predicted to increase to 74.7 MMT by 2030. Only 17.4% of e-waste is presently documented as formally recycled. Europe and the Americas generate more e-waste per capita than other regions, with 16.2 and 13.3 $kg^{-1}$, respectively, while Asia and Africa generate the least,

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with 5.6 and 2.5 kg per capita, respectively. The e-waste collection and recycling rate in Asia (11.7%) is higher than that in the Americas (9.4%), whereas Europe shows the highest rate of collection and recycling 42.5% (Forti et al., 2020).

Research to develop strategies for reducing GHG emissions from the ICT sector has focused on improving energy efficiency during the useful life of products, and there is a paucity of studies focusing on embodied GHG emissions of ICT equipment (Belkhir & Elmeligi, 2018; Malmodin et al., 2010; Malmodin & Lundén, 2018; Teehan & Kandlikar, 2013; Zhou et al., 2019). The rapid reduction of equipments' useful lifespan due to the rapid pace of technological innovation drives the accumulation of e-waste. From 2013 to 2020, the useful lifespan of average electronic devices such as desktops, laptops, and smartphones decreased by 41%, 22%, and 30%, respectively (see Table S1, which is in the Electronic Supplementary Material (ESM) in the online version of this paper). Electronic product repair, reuse, and recycle (3re) are crucial for e-waste source reduction and the integration of the electronics industry into a circular economy framework (Awasthi et al., 2019). However, extending the useful lifespan of electronic products may stifle access to innovative technology, and the concomitant reduction in e-waste generation may not directly lead to a reduction in exposure of workers to hazardous components of e-waste or the levels of precious or critical materials such as gold which attracts the postconsumer labor market. A co-benefit of extended product lifespan, e-waste source reduction, and material resource recovery is the concomitant reduction in the embodied greenhouse gas (GHG) emissions associated with the manufacturing of brand-new electronic products (Dickson, 2021; Gomes et al., 2021; Pauliuk et al., 2021; Singh et al., 2018, 2019, 2021; Society, 2020). Here, we present a quantitative model of the relationship between the increased useful lifespan of digital devices for the reduction of e-waste and the mitigation of climate change. The scenario analysis accounts for source reduction and prevention strategies that might limit the average global temperature increase to 1.5 °C. Our estimate shows that the total cumulative GHG emissions savings from 2021 to 2030 are from 2.5 billion to 3.7 billion tons of $CO_2$e from source reduction depending upon the product useful lifespan extensions of 50%–100% of e-waste generated by ICT devices.

## 2. Materials and methods

### 2.1. Modeling trends in e-waste generation and $CO_2$ emission

Electronic product repair, reuse, and recycle (3re) are crucial for effective source reduction of e-waste. Strategies for increasing the lifetime of products capture ambitious goals of reducing the amount of e-waste generated and reusing products with resilient hardware and upgradable software to keep them amenable to functional innovations. The increased product lifetime is considered one type of source reduction (EPA, 2016). For our analysis, we adopted data from 1003 authorized release life cycle analysis reports of different manufacturers (see Tables S2–S11 in the ESM) to model the impacts of electronic product repair on the amount of reduction in e-waste generation and $CO_2$ emission based on the following formula:

$$\mathrm{Pr} = \mathrm{Pe} \cdot \mathrm{Rc} \tag{1}$$

where Pr is the $CO_2$ emissions prevented by 3re (kg), Pe is the embodied $CO_2$ emissions (kg), and Rc is the rate of "displacement" of a new purchase.

We assume that extending the lifetime of an electronic product such as a mobile phone is equivalent to reducing the production of the same product that would otherwise replace those devices, because an increase in the useful life expectancy of a device would lead to fewer replacements. Implicit in this assumption is that longer-life hardware continues to provide satisfactory performance and accommodates software updates such that consumers do not seek other new supplementary devices. For example, purchasing a new iPad because the iPhone still works but does not have the capacity for new apps could defeat the goal of reducing e-waste generation in the long term. Another caveat is that in order to extend the product lifetime, the consumer may need to accommodate maintenance and improvement activities that could have implications for greenhouse gas (GHG) and other environmental impacts that we do not include in our model. We assumed further that the consumption of materials during repair and gains by upgrade to "energy efficient" device would be insignificant.

A 50% increase in the average useful lifetime of a device is considered equivalent to a reduction in the manufacture of a third of the full device. This proportion is based on assuming that for every 100 devices retired under current conditions, only 67 devices would be retired in the alternative scenario, where the lifetime of devices has been extended. This can be expressed by the following formula (EPA, 2016):

$$\mathrm{Rp} = \mathrm{Lc}/\mathrm{Li} \tag{2}$$

where Rp is the total percent of retired devices after the extension of a useful lifetime, Lc is the current lifetime of the device, and Li is the increased lifetime of the device. This can be expressed in a simple ratio of a current lifetime to an increased lifetime of $1/1.5 = 0.67$. This is approximately equivalent to increasing the average life of smartphones to 4.5 years, from the current 3 years average before end-of-life.

### 2.2. Data source

The data of e-waste generation are adapted from http://ewastemonitor.info/, which is a collaborative product of the Global E-waste Statistics Partnership, formed by United Nations University, the International Telecommunication Union, and the International Solid Waste Association, in close collaboration with the United Nations (UN) Environment Program. E-waste of ICT device data were estimated from the Global E-waste Monitor 2020. Here, the ICT devices refer to screens and monitors and small IT and telecommunication equipment categories of electrical and electronic equipment, (Table S12 in the ESM). The combined value of both categories of e-waste is about 21.3% (12.5% + 8.8%) of the total e-waste generated in 2019 (Forti et al., 2020). Life cycle analysis outcomes data were adopted from 1003 authorized release reports (containing total $CO_2$ emissions in kg of the entire lifespan of the product including the share of manufacturing, transport, use, and end-of-life) of different manufacturers (Tables S2–S11 in the ESM). The data of toxic elements were based on a comprehensive literature review analysis of the hazardous elements in the media (air, water, and soil) of the e-waste recycling sites, especially in the countries where most of the e-waste is recycled both formally or informally (Tables S13–S23 in the ESM).

### 2.3. Population at risk of exposure to e-waste toxins

In the recognized 22 e-waste recycling centers in 15 countries (WHO, 2021), we estimated the population at risk of exposure for each site by collecting the city population from countries' census databases. The number of people who were directly or indirectly coming into contact with the toxic chemicals in the exposed sites was calculated based on the number of people who live or are involved in informal recycling. The number of people who live in informal settlements or are involved in informal recycling is estimated to be about 24% of the total population, as reported by the United Nations (UN, 2020). For the age distribution at sites, we applied age distribution estimates from the U.S. Census Bureau (2019) for each site to the population (United States Bureau Census, 2020) We divided each site's estimated population into 17 age groups based on these distributions to enable our calculations.

### 2.4. Limitation and uncertainty

We recognize that aside from the data of embodied $CO_2$ emissions and the weight of the products which are generated by a Monte Carlo simulation ($10^5$ iterations) to obtain final estimates of mean and standard deviation (see Table S24 in the ESM), the results are presented as point estimates without uncertainty. The life cycle analysis (LCA) of a product is a complicated process and LCA data for any given device that belong to different manufactures can be analyzed in numerous ways depending on its purpose and requirements. The comparison between devices and their outcomes related to GHG emissions could vary depending on energy sources used for manufacturing the goods in different countries and based on the legislation of the particular countries. The LCA analysis is also prone to the choice of the LCA framework, the material extraction and manufacturing processes, the interpretation process of completeness, and the sensitivity and consistency of the LCA study. In this case, the data of embodied $CO_2$ emissions and the weight of the products are simulated by a Monte Carlo simulation ($10^5$ iterations) to obtain final estimates of mean and standard deviation. Oracle's Crystal Ball as a Microsoft Excel add-in component was utilized to perform the uncertainty analysis (additional data are presented in Tables S25–S30 in the ESM).

## 3. Results

### 3.1. Co-benefits of e-waste source reduction

In Table 1 we show the results of the numerical model programmed to estimate emission reductions associated with reduction of electronic devices entering the e-waste stream according to source reduction scenarios: (1) total embodied greenhouse emissions in $CO_2$-equivalent, (2) variable lifespan of electronic devices, and (3) average weight of devices. The scenario modeling of each device was based on 1003 authorized release life cycle analysis data of different manufacturers (see Tables S2–S11 in the ESM). Estimates of $CO_2$-equivalent GHG emissions are based on the estimated quantities of e-waste from ICT devices from 2014 to 2030 are shown in Fig. 1. The results are based on embodied $CO_2$ emissions attributed to the manufacturing and transportation of electronic devices excluding the emissions from the use and end-of-life management. Data presented in Fig. 1(a) show the proportionate quantity of waste from selected ICT electronics during the time span 2014 to 2030. Between 2014 and 2020, the amount of e-waste from ICT devices increased by ~25%, with 11.8 MMT of waste generated in 2020, further increasing to ~15.9 MMT by 2030. Flat display televisions contributed the largest quantity of waste by weight (33%) and mobile phones contributed the smallest quantity (~1%) of the total estimated weight. The quantity of waste cathode ray tubes (CRT) devices including televisions and computer monitors decreased considerably due to their replacement with flat liquid crystal display and light-emitting diode displays (Singh et al., 2016a; 2016b) (see Tables S31 and S32 in the ESM).

The data presented in Fig. 1(b) show that between 2014 and 2020, embodied GHG emissions from selected electronic devices increased by ~53%, with 580 MMT of $CO_2$e emitted in 2020. The business as usual (BAU) scenario shows that emissions are expected to increase to ~582 MMT of $CO_2$e annually by 2030, worldwide. The category of flat display televisions is associated with the highest emissions with ~41% of total cumulative emissions followed by laptops and tablets, flat display computer monitors, desktops, mobile phones, computer accessories, printers, and game consoles with ~18%, 17%, 10%, 5%, 4%, 3%, and 2%, of $CO_2$e emissions, respectively.

The data presented in Fig. 2 show the outcome of source-reduction modeling of the relative quantities of waste reduction and GHG mitigation scenarios associated with extending the useful life of electronic devices. The results show expectedly that the declining lifetime of the ICT devices is significantly associated with increases in the quantities of e-waste (Fig. 2(a)). For example, about 19–28 MMT of e-waste would have been prevented through a 50%–100% increase in the useful lifetime of ICT devices in the time period between 2015 and 2020. For future scenarios between 2021–2025 and 2026–2030, ~21 to 32 MMT and 25 to 38 MMT of e-waste could be prevented, respectively, if the lifetime of ICT devices extends from 50% to 100%. The BAU scenarios show that the cumulative amount of e-waste generated from 2015 to 2020, 2021–2025, and 2026–2030, were ~57, 64, and 74 MMT, respectively.

The data presented in Fig. 2(b) show the outcomes of the scenarios for GHG emissions through e-waste source reduction. In

**Table 1**
Estimated data of electronic devices for source reduction scenarios including total embodied greenhouse emissions in $CO_2$ equivalent, lifespan, product weight, and prevention by scenario-based modeling (see Tables S2–S11 in the ESM).

| Electronic devices | Total embodied $CO_2$ kg/device | Lifespan (year) | Product weight (kg) | Total embodied $CO_2$ (kg/kg device) | $CO_2$ prevention by increased lifespan 50% (kg/kg device) | $CO_2$ prevention by increased lifespan 100% | Waste prevention by increased lifespan 50% (kg/device) | Waste prevention by increased lifespan 100% (kg/device) |
|---|---|---|---|---|---|---|---|---|
| Desktop | 372.8 | 4.0 | 6.7 | 55.3 | 18.2 | 27.6 | 2.22 | 3.4 |
| Display | 393.6 | 5.8 | 6.4 | 61.5 | 20.3 | 30.7 | 2.11 | 3.2 |
| Laptop | 283.4 | 4.0 | 1.9 | 145.5 | 48.0 | 72.7 | 0.64 | 1.0 |
| Mobile phone | 50.5 | 2.5 | 0.2 | 333.5 | 110.1 | 166.8 | 0.05 | 0.1 |
| Notebook | 22.7 | 2.5 | 0.1 | 203.5 | 67.2 | 101.7 | 0.04 | 0.05 |
| Tablet | 116.1 | 2.3 | 0.7 | 171.4 | 56.5 | 85.7 | 0.22 | 0.3 |
| Digital camera | 25.8 | 10.0 | 0.5 | 50.4 | 16.6 | 25.2 | 0.17 | 0.3 |
| Printer | 100.7 | 4.4 | 12.5 | 8.1 | 2.7 | 4.0 | 4.11 | 6.2 |
| Games console | 140.7 | 4.0 | 3.2 | 44.0 | 14.5 | 22.0 | 1.06 | 1.6 |
| PC accessory | 27.0 | 4.0 | 0.8 | 33.7 | 11.1 | 16.9 | 0.26 | 0.4 |

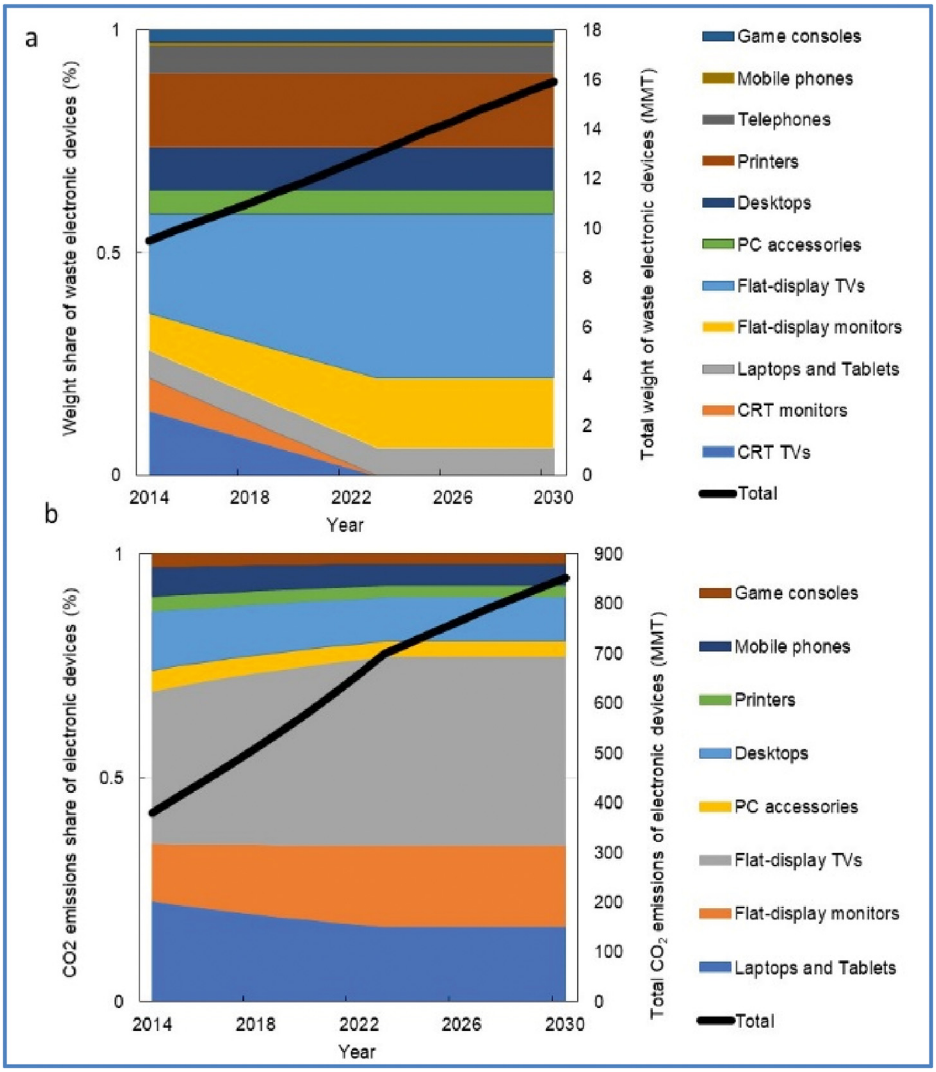


**Fig. 1.** Estimated quantity of greenhouse gas emissions and e-waste generation of ICT devices worldwide. (a) Weight percent share of individual e-waste device and the total amount of waste from selected electronics, (b) total and share percent of embodied greenhouse gas emissions in each e-waste of ICT device (Note: greenhouse gas emissions of CRT monitors and televisions are not calculated in this study due to their replacement by the new flat display.). The emissions from telephones devices are also excluded due to the lack of embodied carbon footprint data (Note: it should be noted that there could be an incremental error (±10%) for future emissions due to the uncertainty in the reported data, see Tables S31−S35 in the ESM).

2014, the total contribution of embodied GHG emissions from selected electronic devices was ~380 MMT of $CO_2$e. This quantity increased to a cumulative total 2962 MMT in 5 years from 2015 to 2020 and our modelling results indicate an expected increase to 3444 MMT from 2021 to 2025, and 4051 MMT from 2025 to 2030, in the BAU scenarios. We note that these quantities could be avoided if the current lifetime of the gadgets can be extended through the implementation of strategies for repair, reuse, and recycle. For example, ~978 to 1481 MMT of $CO_2$e emissions would have been avoided if the useful life of electronic devices were extended from 50% to 100%. In futuristic scenarios, if the current useful life of devices last more than 50%−100%, 1136 to 1722 MMT of $CO_2$e of GHG emissions can be avoided by 2025, and ~1337 to 2026 MMT of $CO_2$e of GHG emissions avoided by 2030 (Fig. 2(b)). Strategies that address the rapidly declining useful life of digital devices, therefore, offer the best prospect for reductions in e-waste and GHG emissions.

The data presented in Fig. 3 show the global embodied GHG emissions from selected e-waste generated from ICT devices with the top 20 countries' GHG emissions modelled from 2020 to 2030, and their mitigation scenarios based on source reduction of e-waste by extension of the useful lifetime of the ICT devices. The results show that ~580 MMT of embodied $CO_2$e of GHG emissions was associated with ICT devices in 2020. The results of BAU scenario modelling show an increase to ~7495 MMT of embodied $CO_2$e of GHG emissions from 2021 to 2030. China would contribute the highest quantity of embodied GHG emissions from 2021 to 2030, representing ~19% of total global emissions, followed by the United States, India, Japan, and Brazil, which accounted for about 13%, 6%, 5%, and 4% of total global emissions, respectively. At the regional level, Asia would contribute the most about 46% of total global emissions, followed by the Americas (25%), Europe (23%), Africa (5%), and Oceania (1%). The quantity of $CO_2$ emissions from wasted ICT devices in 2020 was equivalent to removing about 8.5% of total GHG emissions in the USA annually (EPA, 2021). The mitigation scenarios based on source reduction by the extension of the useful life of electronics on individual country shows that ~647 to 708 MMT of $CO_2$ emissions from 2021 to 2030, could be avoided by the

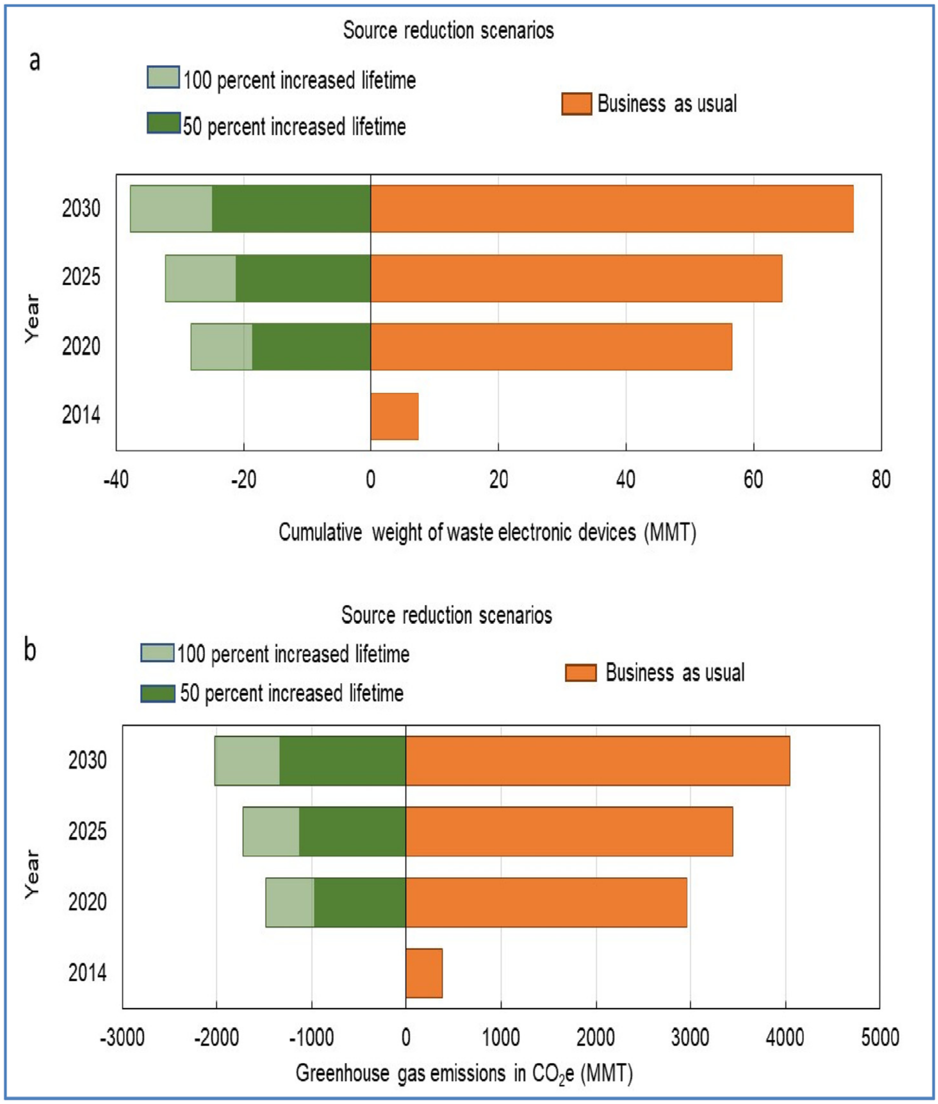


**Fig. 2.** Source reduction scenarios based on the lifetime extension of electronic devices. (a) Source reduction scenarios for the cumulative weight of waste electronic devices in 2014, 2015–2020, 2021–2025, and 2026–2030 with business as usual (BAU) and an increase of 50%–100% of electronics lifetime. (b) Source reduction scenarios for cumulative embodied GHG emissions of e-waste of ICT devices in 2014, 2015–2020, 2021–2025, and 2026–2030 with business as usual (BAU) and increased of 50%–100% of electronics lifetime. Note: it should be noted that there could be an incremental error (±10%) for future emissions due to uncertainty in the reported data.

50%–100% of useful lifetime extension of selected electronics in China. In the USA, the equivalent quantity is ~319–484 MMT of emissions reduction from 2021 to 2030. The 3re practice is the most common strategy for reverse logistics and resource conservation. Increasing the useful lifetime of electronic products reduces the amount of waste generated over time, and it is a type of source reduction with potential impacts on technological innovation and the economic profit margin of manufacturers (EPA, 2016).

### 3.2. Toxic pollutants

Estimates of the population at risk of exposure to toxic e-waste show that ~30 million people are vulnerable in 32 cities that are listed as e-waste recycling centers in 15 countries (see Table S36 in the ESM). Of the exposed population, ~5.8 million were younger than 18 years of age and about 6.1 million were women of child-bearing age (15–49 years of age). Estimates of the concentration of the hazardous metals in the media (air, water, and soil) at the recognized sites of e-waste dismantling show a significantly higher quantity than permissible standards set by the USA EPA, WHO, and European Union Air Quality Standards (Table 2).

### 3.3. Mining and planetary health

To manufacture consumer electronic products, mined minerals are essential, and these potentially include "conflict minerals" typically noted as the three T's tin, tungsten, and tantalum (coltan). Cobalt and gold are also essential for manufacturing ICT devices such as smartphones, tablets, and computers (Sovacool et al., 2020). The concern along the supply chains of these minerals, most apparent in the Democratic Republic of Congo, is the use of child labor and the intensive use of water and energy for the mining process. These requirements place additional strain on communities in terms of human rights abuses, and on strategies including the use of Blockchain platforms for overseeing the responsible sourcing of these minerals, including rare earth minerals, which are expected to be increasingly in short supply in certain countries dominating the remaining reserves (Church & Wuennenberg,

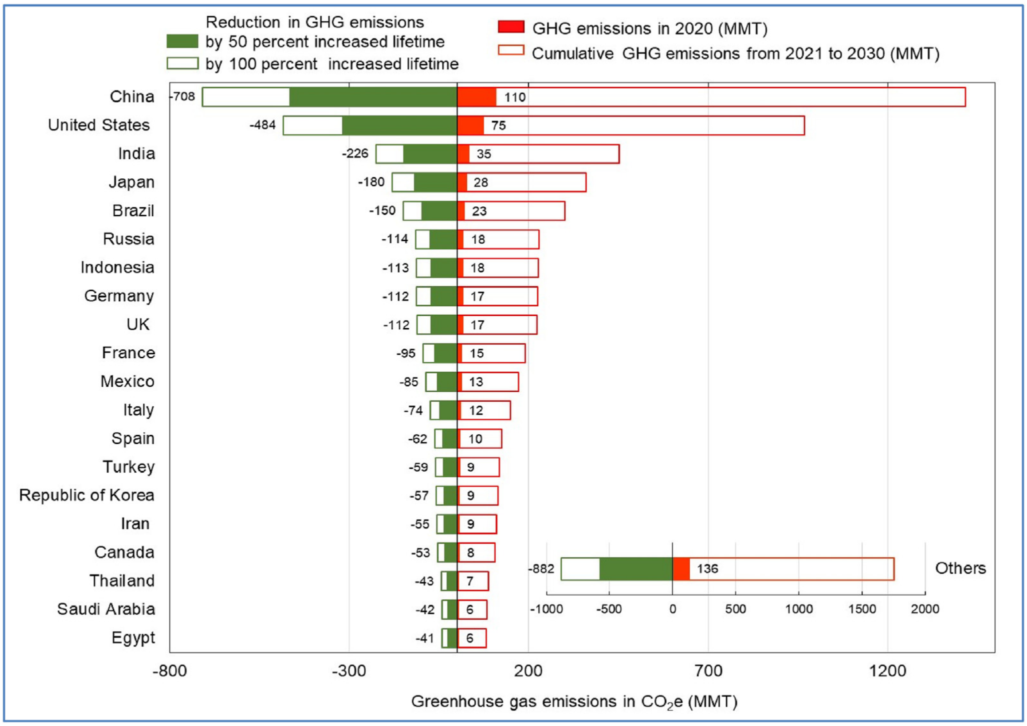


**Fig. 3.** The total amount of embodied $CO_2$ emissions to end-of-life selected electronic devices worldwide, top 20 contributor countries are presented separately and the remaining countries' quantity is presented together as others. The outcomes include GHG emissions of 2020 and a cumulative amount from 2021 to 2030, with the mitigation scenarios as business as usual (BAU) and an increase of 50%–100% of electronics lifetime. Note: it should be noted that there could be an incremental error (±10%) for future emissions due to uncertainty in the reported data (see Table S35 in the ESM).

**Table 2**
The concentration of toxic metals at the recognized sites of e-waste dismantling. Additional data see Tables S13–S23 in the ESM.

| Toxic metal | Soil concentration (mg/kg) | | | |
|---|---|---|---|---|
| | Mean | Max | USEPA standards | Sample size |
| As | 101.9 | 173.8 | 0.7 | 1216 |
| Cd | 141.7 | 241.0 | 7.1 | 2187 |
| Cr | 74.0 | 165.6 | 6.3 | 1900 |
| Pb | 687.3 | 1941.2 | 400 | 2205 |
| Hg | 59.7 | 115.8 | 1.1 | 888 |
| | Water concentration (mg/L) | | | |
| | Mean | Max | WHO standards | Sample size |
| As | 0.14 | 0.16 | 0.01 | 118 |
| Cd | 0.62 | 1.58 | 0.003 | 609 |
| Cr | 3.39 | 8.92 | 0.05 | 392 |
| Pb | 0.53 | 0.82 | 0.01 | 428 |
| Hg | 0.02 | 0.04 | 0.006 | 132 |
| | Air concentration (μg/m$^3$) | | | |
| | Mean | European Union Air Quality Standards | | |
| Cd | 0.0054 | 0.005 | | |
| Cr | 0.5839 | 0.200 | | |
| Ni | 0.0086 | 0.020 | | |
| Pb | 0.2712 | 0.500 | | |
| As | 0.0081 | 0.006 | | |

2019). The current recycling rates for these metals are extremely low: for lithium-ion batteries specifically, the recycling of cobalt and lithium is less than 5% at their end of useful life. Source reduction of e-waste can contribute to strategies to improve the security of natural resources through the circular economy and planetary health frameworks (Church & Wuennenberg, 2019).

## 4. Discussions and suggestions

### 4.1. Emergence of a fragmented regulatory framework

Right-to-repair guidelines for consumer electronic products have recently been announced by the European Commission, and UK has already introduced similar rules that legally require manufacturers to provide repair manuals and make spare parts available to people buying a limited range of electronic goods including washing machines and washer-dryers, fridges, dishwashers, and electronic displays (including televisions) (EC, 2021; UK, 2021a). The USA is also anticipating passing a similar rule on the repair of farming equipment (O'Reilly, 2021). However, for electronic devices, especially smartphones, tablets, and laptops, a right-to-repair policy is still under public discussion in many countries such as Australia (Productivity Commission, 2021).

In the USA, most of the 50 states proposed a "right to repair" guideline in 2021 but only one state, Massachusetts, passed a law in 2013 (The General Court of the Commonwealth of Massachusetts, 2021). The Massachusetts right-to-repair law requires vehicle manufacturers to provide diagnostic and repair information to owners and independent repair facilities for any car made in 2015 or later. The term "right to repair" was first used in Massachusetts law. The right to repair defines a consumer's ability to repair faulty goods, or access repair services, at a competitive price either by a manufacturer, a third party, or a self-repair option through available repair manuals and original spare parts. Typically, manufacturers do not impose any such restrictions on consumers concerning the repair of goods they supply, instead, third parties or consumers are intentionally prevented from being able to repair the manufacturers' goods due to a lack of access to original necessary parts, apparatuses, or analytical software/manuals (Productivity Commission, 2021). For these reasons, the existing rules and regulations amount to few limited rights to repair electronic products in many countries. Subsequently, these regulatory hurdles result in early obsolescence—planned obsolescence by the design of the electronic products and the uncompetitive repair market.

The European Union (EU) and UK right-to-repair guidelines were approved in March 2021 and July 2021, respectively. To be compatible with the EU regulation, the UK followed quite similar legislation in its own version of right-to-repair guidelines, as was agreed by the UK and the EU member states before Brexit (Harrabin, 2021). The UK's new energy standard for washing machines and fridges related to right-to-repair legislation is expected to save ~75 British pounds (~US $103) per consumer a year in energy bills and will reduce the 1.5 MMT of electrical waste generated each year (UK, 2021b). Whereas the EU's guidelines could directly save 20 Billion euro on energy costs per year beginning in 2030 onwards and could result in nearly 50 MMT of $CO_2$ emissions savings (Harrabin, 2021). The main aim of these new guidelines is likely to extend the lifespan of the products by up to 10 years, while also reducing a significant amount of energy consumption of electronic goods which likely leads to mitigation of greenhouse gas (GHG) and reducing the generation of e-waste in a progressive circular economy.

The focus of right-to-repair guidelines varies according to countries' existing rules and regulations. For example, the discussion in the USA has focused on access to spare parts, software, and information required by consumers and independent repairers. Electronics manufacturers claim that these issues directly contradict intellectual property rights. However, The USA Federal Trade Commission took a different approach than the European Union (EU), where the right to repair is associated with product design (both for repairability and durability) under the eco-design directives, and as a resource management strategy under the European Commission's circular economy action plans (Productivity Commission, 2021).

### 4.2. Toward a global right-to-repair framework

The fragmentation of right-to-repair policies and guidelines for electronics at the national and regional levels have obvious limitations in the context of the global scope of electronics manufacturing, international trade in new and used electronic products, and the transboundary movement of e-waste. A global forum to develop internationally applicable guidelines is essential, and these can be guided by considering the strengths and weaknesses of the existing frameworks.

Securing consumers' right to repair purchased products can extend the lifespan of the current configuration of products by up to 10 years while also reducing energy consumption and GHG emissions (UK, 2021b). The extended useful lifespan of electronic products will also slow down the generation of e-waste and promote resource reuse. However, the right-to-repair guidelines in the EU and UK apply to a limited range of electronic products including washing machines and washer-dryers, fridges, dishwashers, and electronic displays (including televisions). The EU's new circular economy action plan is expected to eventually include smartphones and laptops. These smaller electronic products are of particular concern because they are particularly affected by early obsolescence and they represent a major portion of internationally-trafficked e-waste.

Additional concerns about the current national and regional right-to-repair guidelines include product liability and safety considerations that may occur if in an attempt to repair, consumers tamper with the electric circuity of devices. In this sense, the guidelines do not legally bind manufacturers in the same way that extended product responsibility laws attempt. It is also unclear if the cost of spare parts will continue to be affordable to support sustainable implementation of the guidelines. Moreover, electronic devices may become more expensive if they are designed to last longer, thereby limiting access and widening the digital divide.

In summary, alarm over the rapid accumulation of e-waste has been sounding for more than two decades, but there is no end in sight for the trend. Reversing the trend requires strategies for source reduction, including extending the useful lifetime of the electronic products, which will directly address the quantity issue, in addition to co-benefits in supporting initiatives to reduce GHG emissions to mitigate climate change, discourage child labor in mining operations, and reduce toxic impacts on the health of workers engaged in waste management. The current 3re initiatives are hampered by incoherent policies and regulations. There is an opportunity to develop an international consensus on a legal framework to support 3re and align with other initiatives focusing on counterfeit products and spare parts, and copyright infringement.

## Author contributions

Singh N. and Ogunseitan O. A. designed the research, Singh N. performed research and analyzed data, and Singh N. and Ogunseitan O. A. wrote the paper. Ogunseitan O. A. supervised the research work.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Ogunseitan O. A. is co-chair of Apple, Inc.'s Green Chemistry Advisory Board (unpaid), and he is co-principal investigator for Microsoft Corporation awards administered by the University of California, Irvine.

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## Electronic Supplementary Material

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