FUTURE E-WASTE SCENARIOS

Keshav Parajuly, Ruediger Kuehr, Abhishek Kumar Awasthi, Colin Fitzpatrick, Josh Lepawsky, Elisabeth Smith, Rolf Widmer, Xianlai Zeng

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step solving the e-waste problem

FUTURE E-WASTE SCENARIOS

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The Solving the E-waste Problem (StEP) Initiative is a network of e-waste experts and a multi-stakeholder platform for designing strategies that address all dimensions of electronics in an increasingly digitized world. The independent Initiative applies an integrated and science-rooted approach to create salient solutions to global e-waste challenges throughout the entire lifecycle of electronics.

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The International Environmental Technology Centre (IETC) is a branch of the United Nations Environment Programme (UNEP), located in Osaka, Japan, and works with the collection and dissemination of information on environmentally sound technologies with a focus on waste management.

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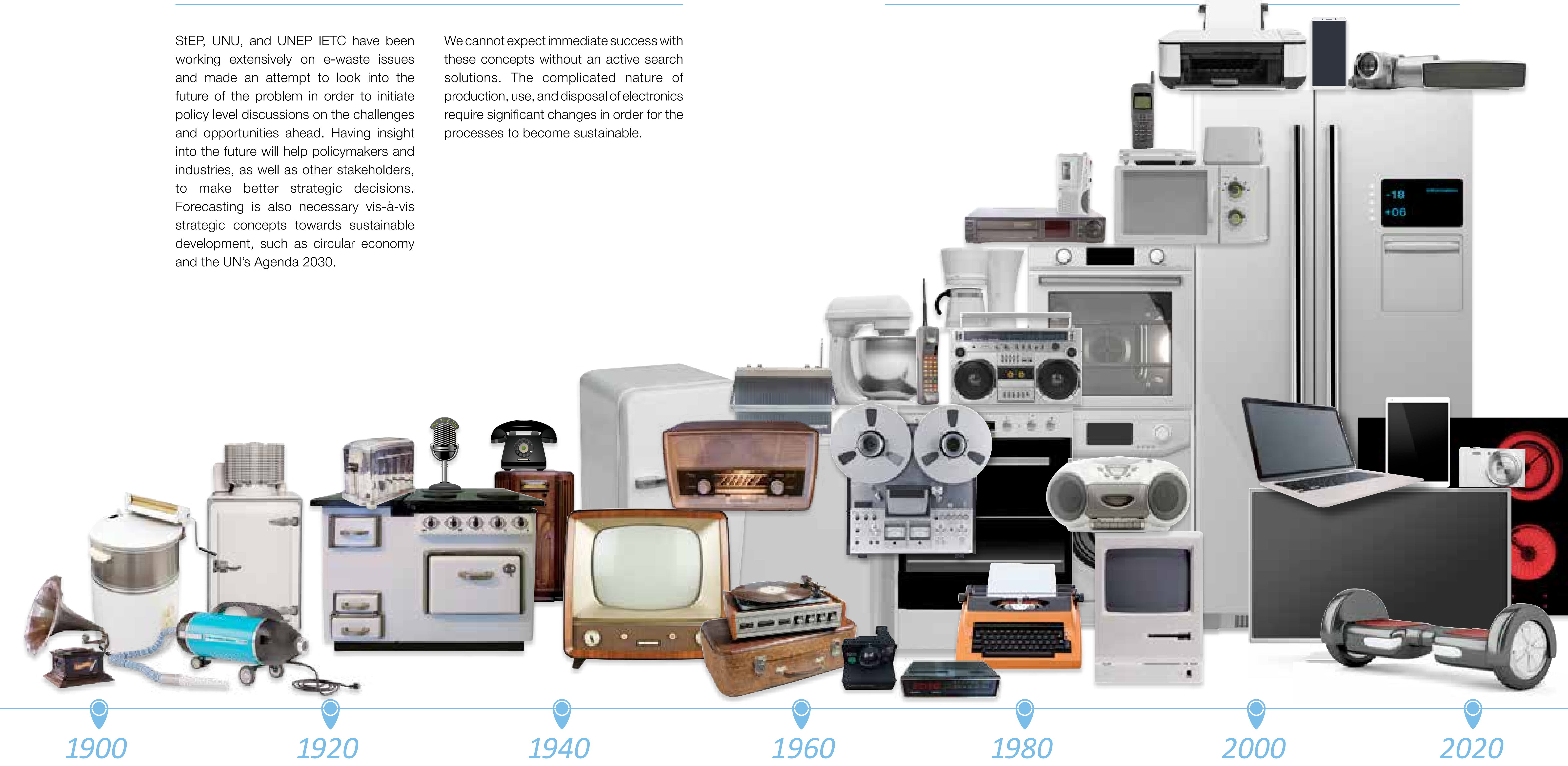
1. BACKGROUND

StEP, UNU, and UNEP IETC have been working extensively on e-waste issues and made an attempt to look into the future of the problem in order to initiate policy level discussions on the challenges and opportunities ahead. Having insight into the future will help policymakers and industries, as well as other stakeholders, to make better strategic decisions. Forecasting is also necessary vis-à-vis strategic concepts towards sustainable development, such as circular economy and the UN's Agenda 2030.

We cannot expect immediate success with these concepts without an active search solutions. The complicated nature of production, use, and disposal of electronics require significant changes in order for the processes to become sustainable.

FIGURE 1 *Technological advancement and evolution of e-products over the last century has been unpredictable*



1.1 E-WASTE

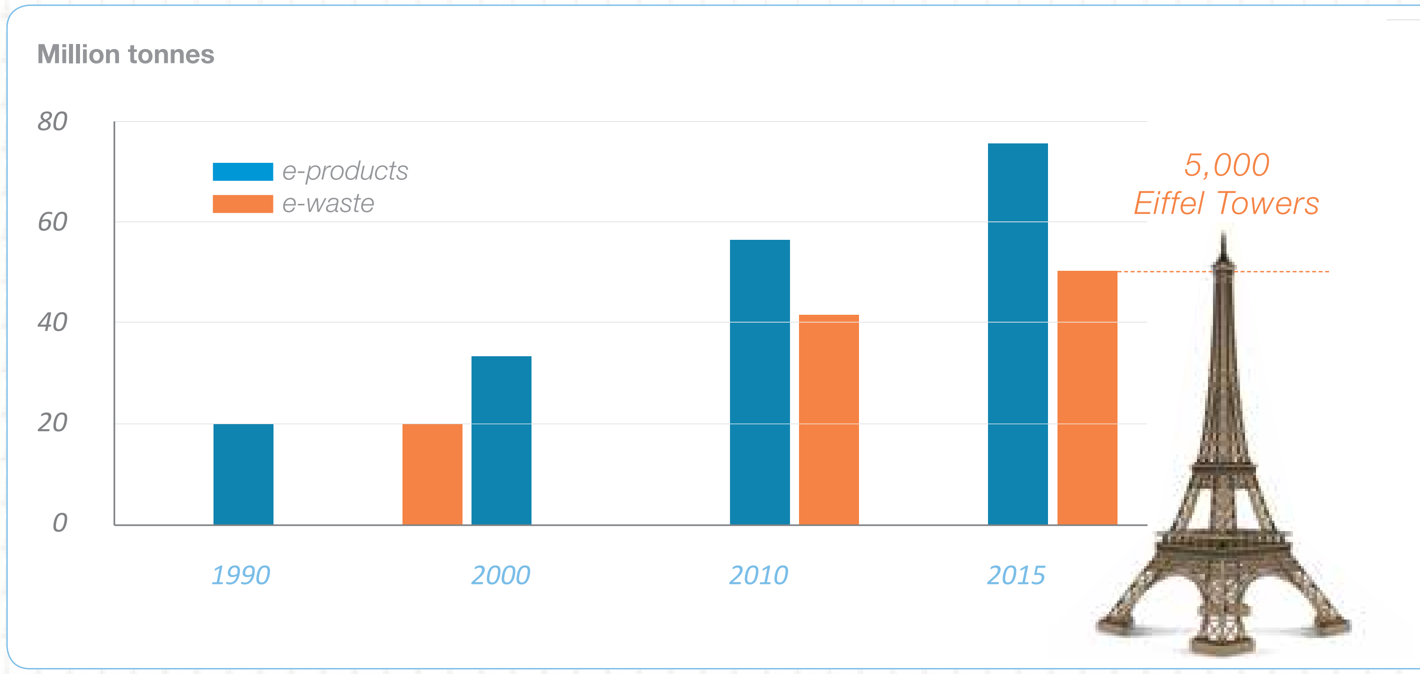
Electrical and electronic products (e-products) are defined as any household or business item with circuitry, or electrical components with power or battery supply[1]. This includes products from basic kitchen appliances to computers to cellphones. Besides everyday household use, e-products are also becoming increasingly integrated in transport, energy supply, health, and security systems, making them a major part of modern society. These gadgets make lives more convenient and work more efficient.

Nevertheless, all e-products come with a life expectancy, and once they stop functioning or new technology makes them obsolete, they must be discarded. Electronic waste (e-waste) is a term used for all types of e-products, and their parts, that have been discarded as waste without the intention of reuse[1].

Around 50 million metric tons of e-waste is generated globally per year, with an average of more than 6 kg per person[2]. Not surprisingly, this distribution is uneven: richer countries produce more. Norway, for example, produces 28.5 kg per person per year, compared to an average of less than 2 kg in African countries.

Often referred to as the fastest growing solid waste stream, the growth of e-waste is not surprising given the rising demand and use of e-products. The management of e-waste, however, has proven to be unbelievably challenging. Even industrialized nations with well-established waste management systems are struggling with the complex nature of e-waste. And for less-developed countries with little to no policies or infrastructure, e-waste has added challenges to the already existing waste-management crisis.

FIGURE 2 *The amount of e-waste generated every year is equivalent to the weight of 5,000 Eiffel Towers*[2,3]



1.2 OBJECTIVES

This paper maps several dimensions of the e-waste problem and provides a snapshot into future challenges. It looks into what we can anticipate in terms of how the use of e-products and management of e-waste could evolve. The goal is to initiate public discussions on these unforeseen challenges and opportunities, in order for the political agendas of governments and businesses to address such issues early on.

This is done based on **a)** a comprehensive understanding of the elements linked to the e-waste problem and **b)** an outlook of the problem given possible future scenarios. Given the unpredictable nature of technological development, it is impossible to precisely quantify the future of e-waste. However, based on the global trends of growth and regulatory initiatives, tentative projections can be drawn at a macro level. This paper uses a qualitative approach and intuitive logics to conceptualize future scenarios. It is meant to be a thought-provoking exercise for all actors in the e-waste arena including researchers, policy makers, businesses, e-waste managers, non-profit organizations, and everyday consumers of e-products.

2. E-WASTE ELEMENTS

Several elements are linked to the global e-waste problem and must not be addressed in isolation. A comprehensive understanding of these elements is therefore necessary to speculate about the future of the e-waste problem and to find possible solutions.

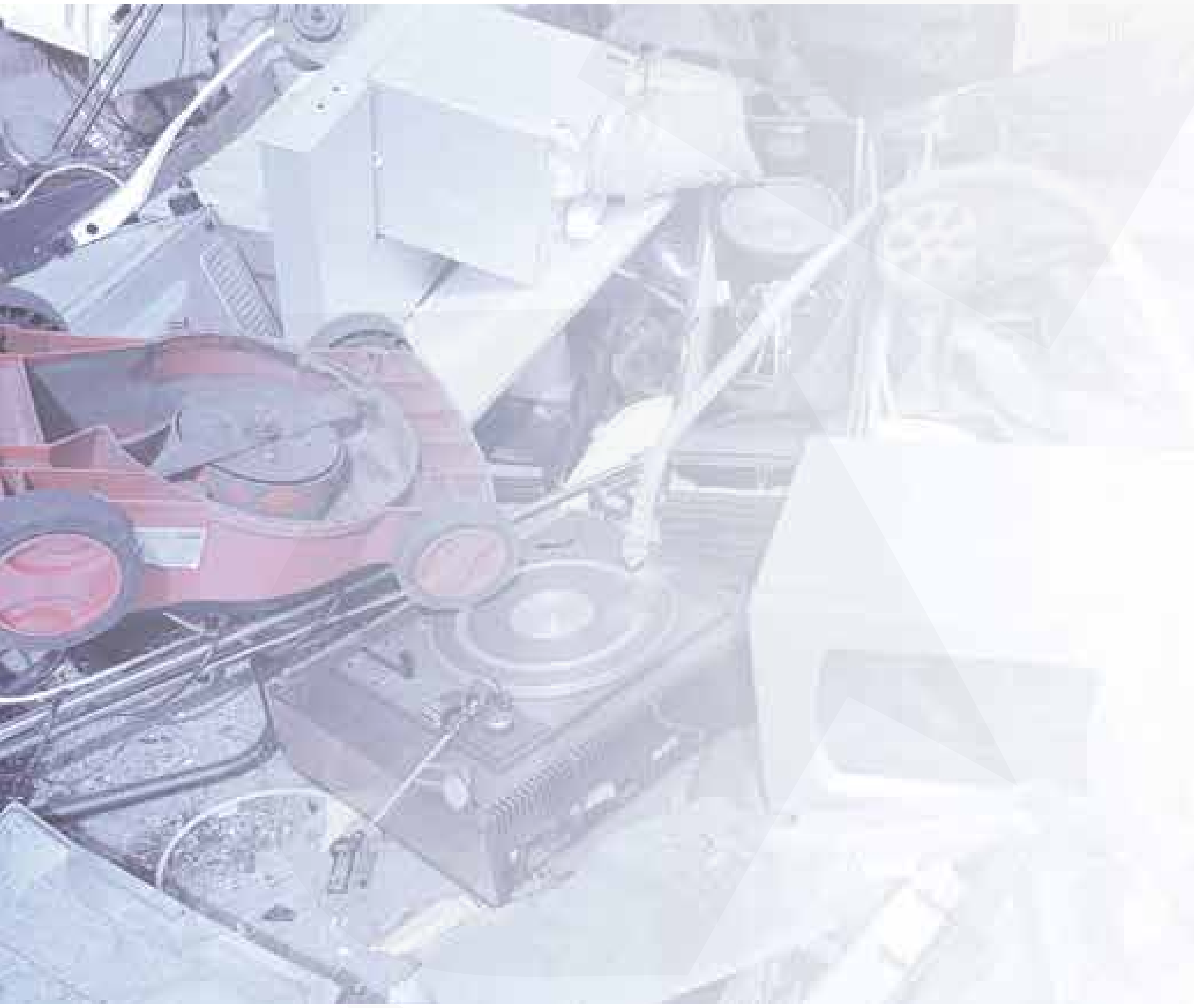
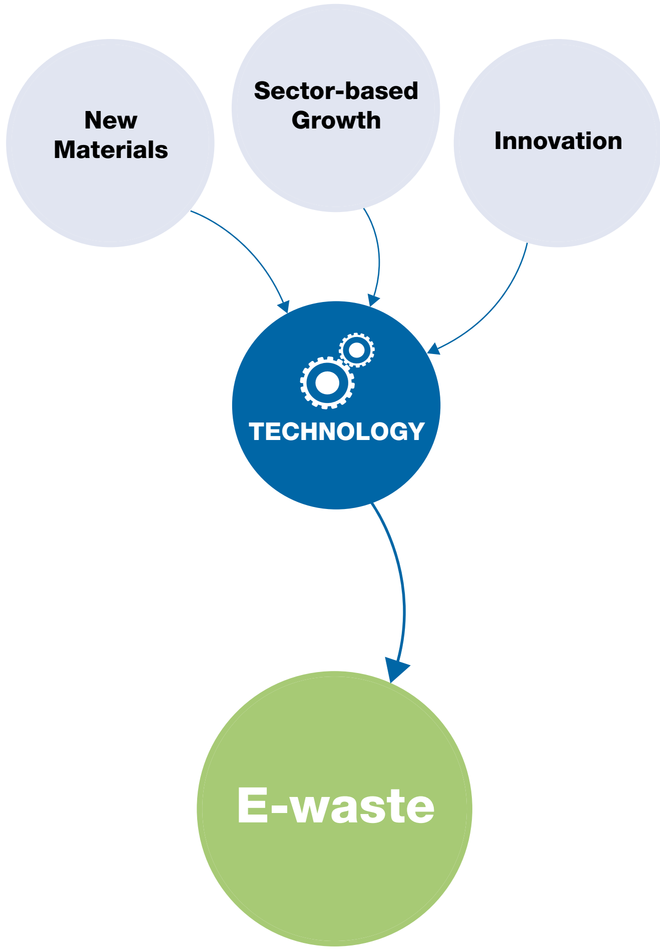


FIGURE 3 *Elements of the e-waste problem*

2.1 TECHNOLOGY

Aside from stand-alone equipment in households and businesses, e-products are increasingly used in buildings (lightning, temperature control, security system, etc.) and transport systems (displays, connectivity, etc.). Use of technologies such as wearables, including for medical monitoring and electronics integrated in clothing (known as e-textile), is also increasing, which results in so-called "cross-over products." Moreover, the growing use of clean technology means increasing demand for e-products such as photovoltaic panels and large batteries. Digitization may contribute to lowering product use in the future with virtual services (streaming, cloud computing, and purchasing services instead of products), requiring less hardware (in particular ICT equipment) to be used in households. Nevertheless, with the total number of users set to increase, the total use of e-products, and thus e-waste quantities, has only one direction: up.

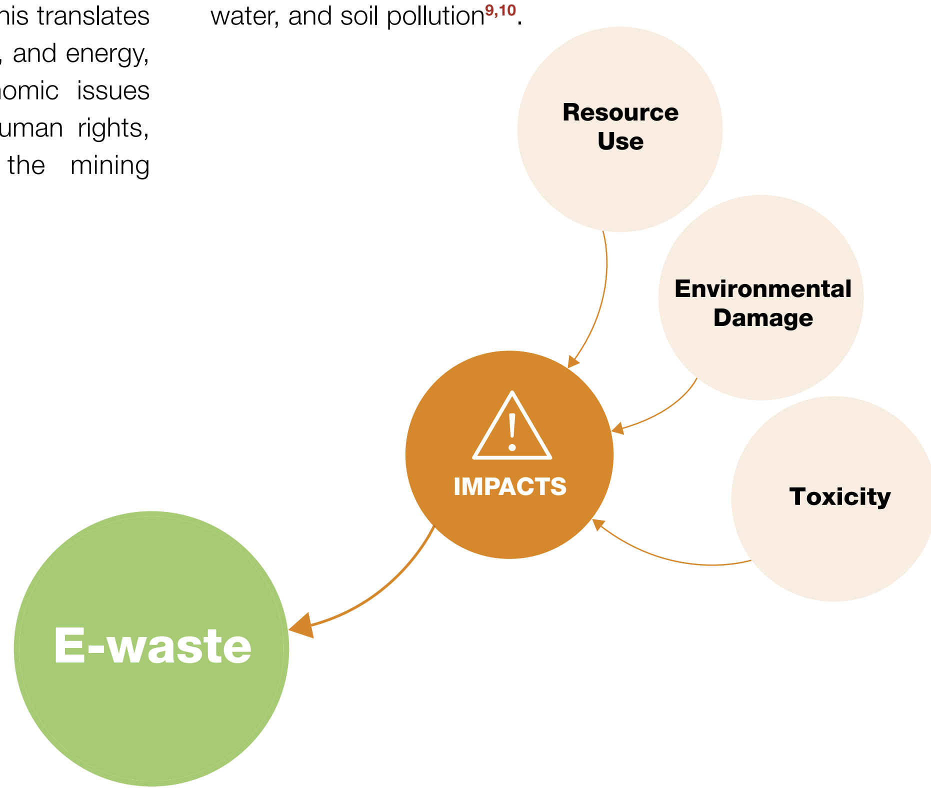
As products continue to miniaturize and become sophisticated, several materials in the form of metals, alloys, and polymers are needed to achieve multiple functionalities and quality. For example, more than 70 stable metals (out of 83) from the periodic table can be found in a modern smartphone[4]. On the other hand, product lifespans are shortening. E-products come to their end-of-life (EoL) due to technological advancement (that renders the current gadget obsolete), planned obsolescence, inability to repair, or software compatibility issues. For energy-intense appliances, the availability of more energy-efficient technology encourages replacement of old items, which also contributes to e-waste generation.



2.2 IMPACTS

The environmental impacts of the first e-products (mainly energy-intensive household appliances) with longer lifetimes were mostly linked to the 'use' phase of the products. But as e-products become more advanced, and use an increasing number of resources, the environmental impacts are now shifting from 'use' to the 'production' and 'material extraction' stages. Given the challenges of resource extraction, manufacturing and EoL resource recovery, the energy use is no longer the most crucial factor in the lifecycle of modern products such as smartphones[5]. Generally, the lifecycle impact of bulk metals per unit is smaller than that of special metals (e.g. gold, palladium, and cobalt)[6]. The mining of critical resources often requires more effort than for bulk metals. This translates into use of more land, water, and energy, as well as other socioecnomic issues including health hazards, human rights, and conflicts linked to the mining process[7].

The toxicants used in manufacturing (as intermediate inputs) can also leave a long trail of toxicity. For example, fluorinated greenhouse gases, used in manufacturing of LCD flat-panel displays, involves chemicals with atmospheric lifetimes beyond 3,000 years and thousands of times more global warming potential than CO_2[8]. Manufacturing of chips and semiconductors uses a variety of chemicals, including volatile organic compounds. In the lack of guiding policies and proper processing infra-structure, rudimentary e-waste recycling practices can lead to serious damage. The infamous e-waste 'recycling' sites in Agbogbloshie, Ghana and Guiyu, China are extreme examples of improper e-waste recycling that result in severe air, water, and soil pollution[9,10].



2.3 MANAGEMENT

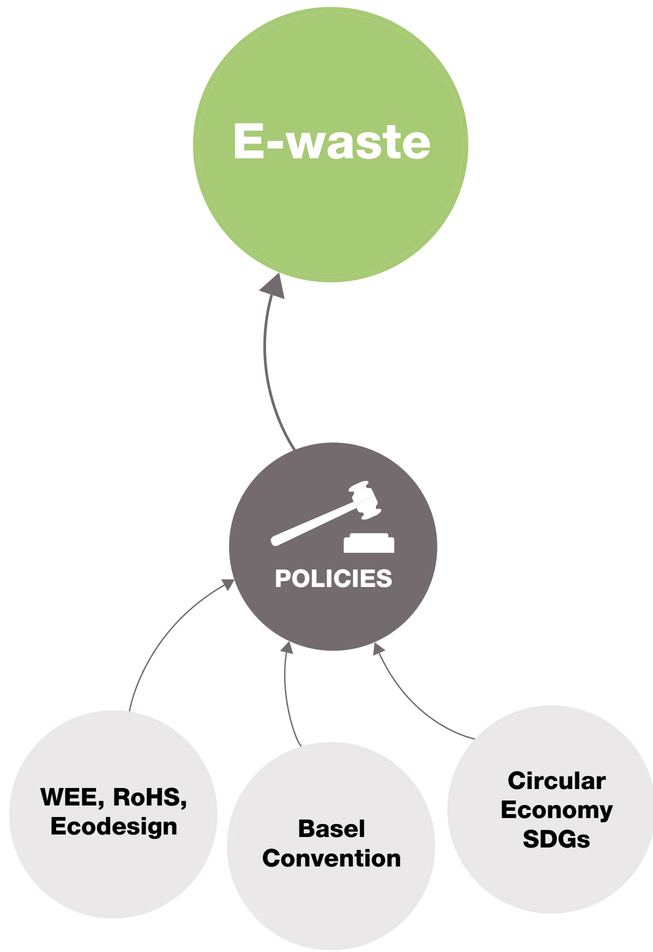
Many industrialized countries have established e-waste management systems based on the principle of Extended Producer Responsibility. The EoL management and material recovery involves three main steps: collection, pre-processing, and end processing. In general, base metals such as copper, steel, and aluminum are recovered efficiently because of the available recycling infrastructure, but critical resources, including rare earth elements do not have very high recycling rates[11]. While technically possible, it is not economically feasible to recover all resources in e-waste. This is mainly due to the low concentration of these elements in e-products, complex product design, and higher cost of recycling compared to lower potential revenue from the recovered resources. Although concepts such as 'design for recycling' to address these challenges have been around for more than two decades, their implementation in e-products' design is not fully materialized.

The issue of e-waste management is even more pressing for less industrialized countries that lack proper waste management infrastructure. Informal recyclers, who operate in subpar working conditions, are the major player in many developing countries. Rudimentary techniques for material recovery, mainly used by informal recyclers, are not effective because **a)** such processes lead to loss of valuable resources and **b)** they target valuables but do not necessarily take care of less valuable fractions such as plastics. More importantly, it leads to localized environmental pollution and health-hazards. Unfortunately, the e-waste challenge is partly being exported from industrialized countries to less developed regions[12,13]. This is linked to the low e-waste collection rate under the official management system (European countries, for instance, collect 35% of their generated e-waste whereas the collection rate of the USA is only 22%[2]). Pollution outsourcing from developed to less developed countries is not only prohibited, but also inefficient in terms of resource recovery.

2.4 POLICIES

The European Waste Electrical and Electronic Equipment (WEEE) Directive was the first comprehensive legislation to exclusively cover e-products with technical details on collection targets for e-waste and its subsequent recycling[14]. Based on the principle of Extended Producer Responsibility, the 2003 WEEE Directive mandates that producers be in charge of their respective e-waste. Linked with the WEEE Directive, Restriction of Hazardous Substances Directive (2003) prohibits the use of select chemicals in the manufacturing of e-products.

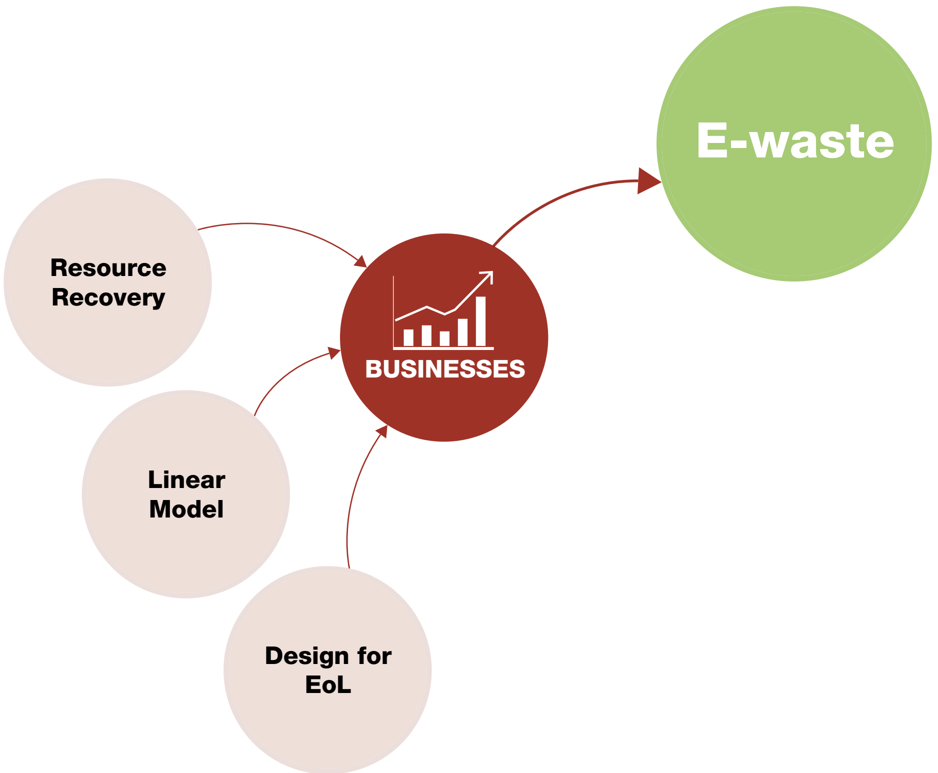
On a broader level, the European Commission's 'Flagship' Resource-Efficient Europe Initiative (2011) and Action Plan for the Circular Economy (2015) address the challenges of, among others, resource use in e-products. And finally, the UN's global Agenda 2030 has a goal (SDG 12) to Ensure Sustainable Production and Consumption, which targets sound management of wastes, 'substantial' reduction of chemical pollutions, and more importantly, prevention of waste through reuse and recycling — all relevant to the issue of e-waste.



2.5 BUSINESSES

The production and consumption of e-products today are based on economic incentives. Minimizing production cost and increasing revenues have been a priority in the global manufacturing and supply chains that do not necessarily consider the lifecycle impacts of products. Given the vast differences in environmental standards across the globe, environmental externalities caused by production and EoL management are not reflected in the price of modern e-products. This so-called 'linear' business model is partly responsible for the growing e-waste problem.

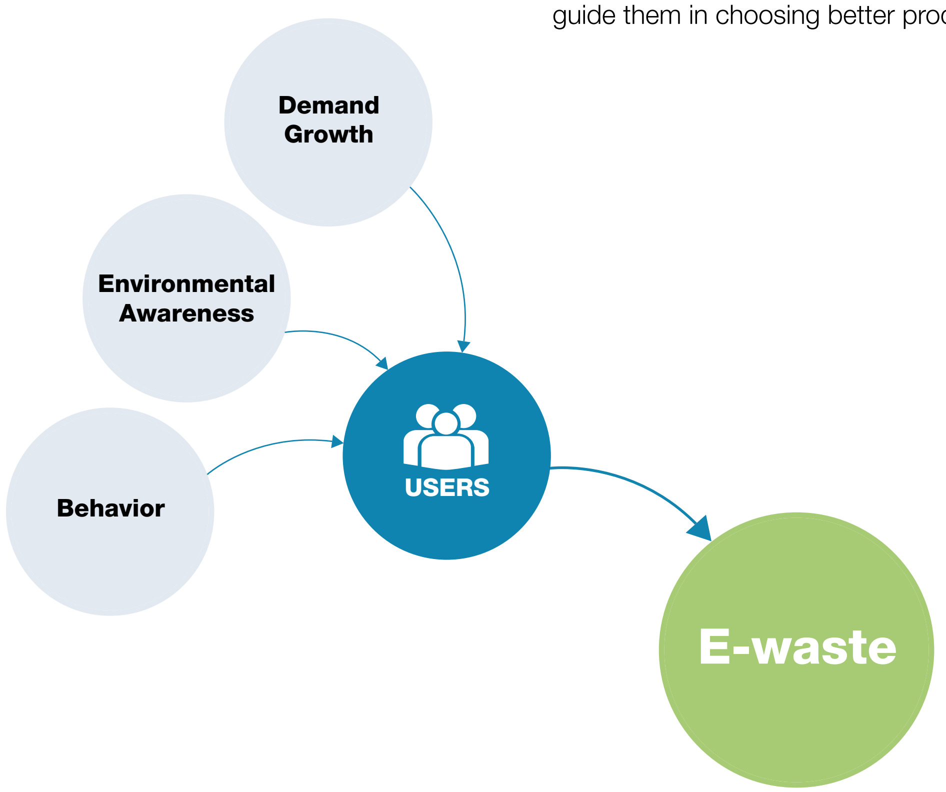
Even though there are legislations, businesses often only do the required minimum. Apart from a few exceptions, manufacturers are not looking beyond compliance. Ever more so, they are reported to have taken action against standards that, for example, facilitate repair and reuse of products that can help prevent e-waste[15]. At the same time, businesses operating at the product EoL face challenges. Recyclers, for example, are struggling because of the lowering concentrations of valuable metals in e-products and in miniaturized products that are more difficult to recycle. And the reuse sector is under constant pressure because warranty arrangements encourage consumers to purchase brand-new products over reuse (i.e., reused products shall meet the same standards as new products, depreciation systems favoring new products only, etc.).



2.6 USERS

Finally, end users play an important role in the consumption patterns of e-products and the management of e-waste. Although disposal and management of household waste have become social norms in many industrialized countries, the e-waste stream is not perceived in the same way. Among other factors, the lack of awareness of the e-waste issues is leading to EoL appliance stockpiling in households. EoL products are thus unavailable for collection and subsequent resource recovery.

As the price of new products decreases and labor costs increases, repair becomes less desirable for users, compared to the cheaper option of simply replacing broken e-products. On the bright side, environmental awareness is growing among certain consumer groups. Grassroots initiatives, such as repair cafés, are gaining popularity in many developed and developing countries. Although limited, there is a demand for 'greener' and more 'ethical' products, but unlike organic food products, for example, there are no labels for e-products to show their lifecycle environmental impacts. More action needs to be taken in regard to making information available for users that will guide them in choosing better products.



3. OUTLOOK

As technological advances continue, the use of e-products in people's daily lives will only grow. Although future developments are impossible to predict precisely, speculations can be made based on past experiences and current trends in this sector.

BOX 1
SPECULATIONS

DEMAND: As a combined result of population growth, higher purchasing power, and availability, the demand of e-products will increase. However, with more efficient technologies, the total number of devices used on average may not rise in the same proportion. Smartphones are an example of how one product can replace several others (e.g., GPS, camera, and music player).

USE: Along with stand-alone appliances, e-products and e-components will be an integrated part of furniture, vehicles, buildings, and other infrastructure.

DESIGN: Products will get smarter, more powerful, and more complex in terms of design and materials, making the recovery of materials from e-waste even more difficult. However, new technologies may also result in less resource-intensive products, lowering the overall lifecycle impact of e-products.

SECTORAL GROWTH: Specific product categories (displays, solar panels, batteries, lighting equipment) will be more frequently used. In another example, higher summer temperatures and pervasive heat waves, which can be expected to grow in the future, have resulted in increased sales of air conditioning and cooling equipment, even in northern European countries.

MATERIAL COMPOSITION: As technology develops, new and advanced materials will be used in e-products. This could include, for example, substitution of critical resources and the introduction of more recycling-friendly and biodegradable materials. Innovation and geopolitical issues will play a role in this, which would affect EoL material recovery effort.

Among these speculations and uncertainties, one simplified approach to forecasting e-waste quantities is based on the GDP. There is a modest correlation between the weight of e-waste generated per person and GDP per person (R^2 = 0.71), based on data from 168 countries in 2015[2]. This correlation was combined with the population and GDP-growth forecast under the Shared Socioeconomic Pathway 2 Baseline Scenario*[16] to estimate future e-waste generation. This estimate shows the global amount of e-waste will be 75 million tonnes by 2030 and grow to 111 million tonnes by 2050 (see Figure 4).

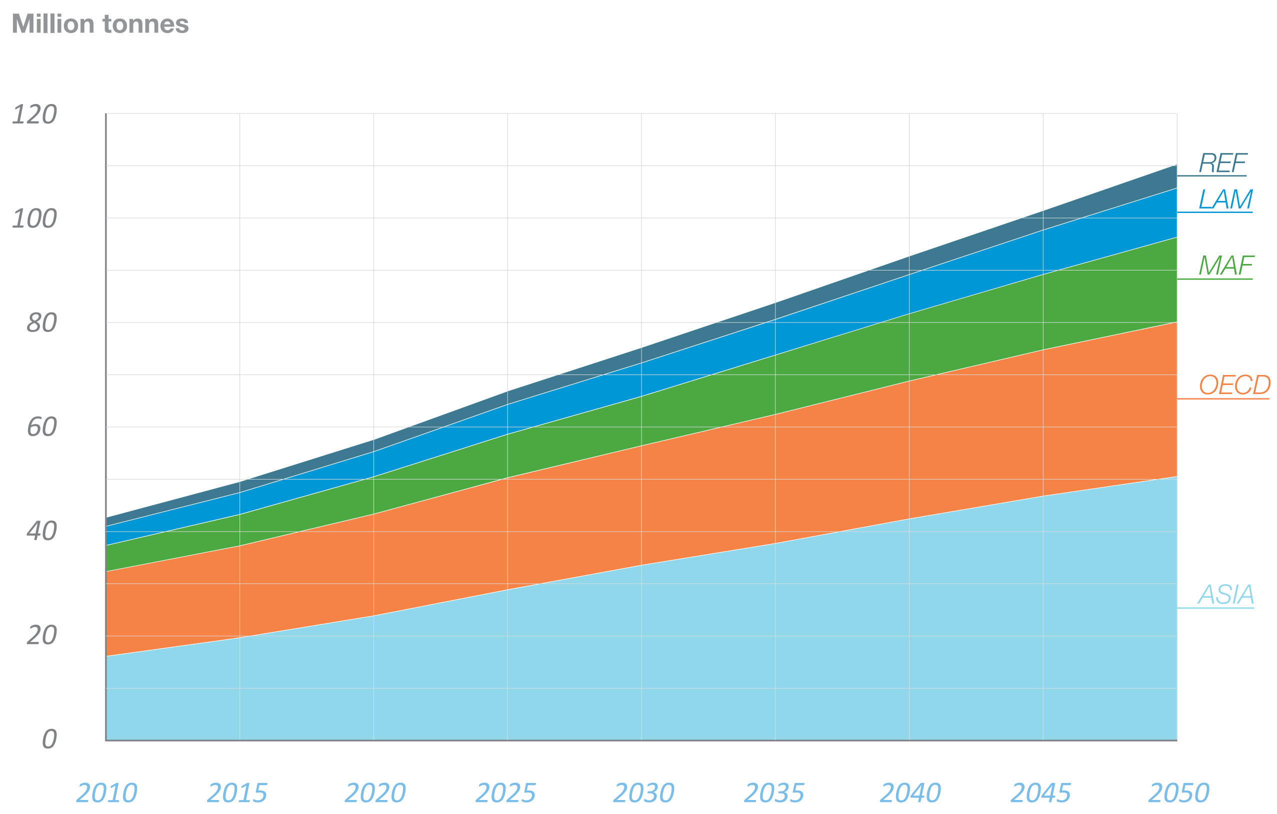
The Middle East and Africa (MAF) and Asia (ASIA) will see more than three-fold increase by 2050 compared to the e-waste generated in 2010. The OECD will be the second largest generator of e-waste with less than double quantity for the same period.

BOX 2
LIMITATIONS OF OUR ESTIMATES

We must acknowledge that these estimates for future e-waste quantities, based on population and GDP, come with some degree of uncertainty and are subject to socio-economic and technological changes (summarized in Box 1). A more comprehensive effort and robust methodological approach are needed to determine better estimates for future scenarios that address these uncertainties.

* The Shared Socioeconomic Pathways are part of a new scenario framework, established by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.

FIGURE 4 *Forecast of e-waste quantities per region based on population and GDP growth*



REF: countries from the Reforming Economies of Eastern Europe and the Former Soviet Union
LAM: countries of Latin America and the Caribbean
MAF: countries of the Middle East and Africa
OECD: OECD 90 and EU member states and candidates
ASIA: Asian countries with the exception of the Middle East, Japan and Former Soviet Union states

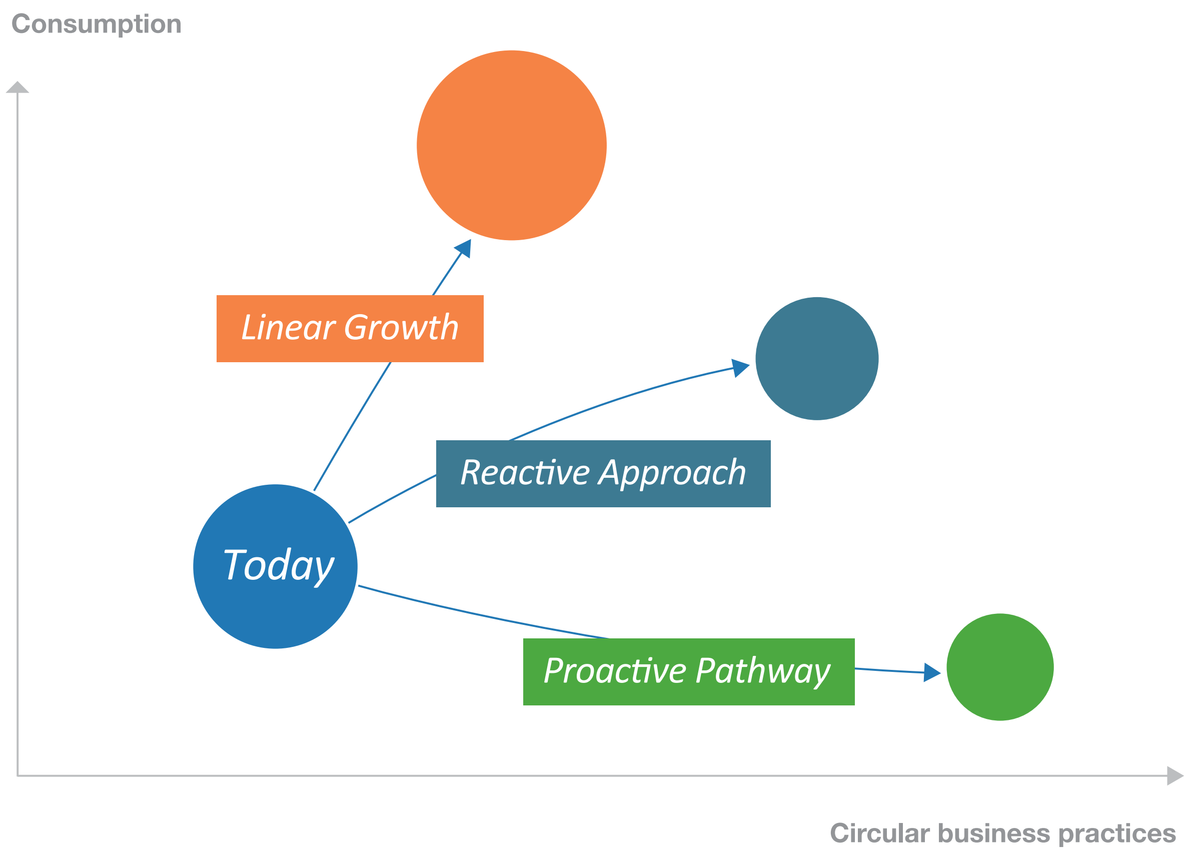
The growing quantities of e-waste alone, however, do not tell the entire story. The size and severity of the future e-waste problem will ultimately depend on our production and consumption models. Technological innovation and growing use of e-products are inevitable, and the way in which these products will evolve cannot be controlled. However, better practices can be adopted throughout the product lifecycle, including their design, manufacturing, use, and EoL management.

The framework for optimizing the "technical cycle", laid out by the concept of circular economy, is of high relevance in tackling the e-waste problem. This includes better product design in order to facilitate **a)** lifetime extension through repair and reuse of products and components and **b)** better recovery of valuable resources by making products easily recyclable. On the consumption side, the adoption of business models based on sharing and product-service systems could mean less consumer ownership of products. This could help reduce the amount of e-waste and streamline end-of-life management for producers. In the globalized market of products as well as secondary resources, businesses and governments will play crucial roles in facilitating such transitions towards more 'Responsible Consumption and Production', as envisioned by SDG 12. Considering business practices and policy instruments as the two key drivers in shaping the future, three scenarios can be imagined:

1. ***Linear Growth***,
2. ***Reactive Approach***,
3. ***Proactive Pathway.***

As the quantity of e-waste will inevitably increase, the severity of the problem under these scenarios will be defined by how businesses operate and what regulatory frameworks are available to drive transformative changes in production and consumption practices.

FIGURE 5 *A depiction of the future of e-waste problem within the axes of consumption patterns and business practices under three imagined scenarios*



The size of bubbles qualitatively illustrates the scale of the problem, which depends not only on the quantities of e-waste produced, but also (more importantly) on consumption and production patterns.

The following provides detailed accounts of three scenarios and how the elements linked to the e-waste problem will evolve under each scenario.

3.1 SCENARIO 1: *LINEAR GROWTH*

The business-as-usual scenario, where a standard growth-based economic agenda is the priority, continues, resulting in a Linear Growth scenario. The consumption of e-products and the amount of e-waste grow at the usual rates. Conventional business models remain dominant with only a few exceptions. E-waste management capacities are also lagging behind.

All these factors combined result in an increased consumption and a severe e-waste problem.

TECHNOLOGY

- The pace of e-product technological innovation continues but little is achieved in terms of breakthroughs for making e-products' lifecycle more sustainable
- Ongoing market segmentation results in less wealthy markets, allowing lower-tier manufacturing of low-quality products (with consequences for resource use and toxicity)
- Products are designed and built for demand in growing economies, which results in cheaper but low-quality products with shorter life
- Consumer e-products increasingly become disposable, 'single-use' quality, but e-waste recycling is limited due to a combination of material heterogeneity and cost of recycling

IMPACTS

- The growing use of critical resources and fossil-based polymers increases environmental footprint of e-products
- Toxicants are still used in manufacturing processes, which are occasionally released to local environments, and the toxic substances also pose challenges at the product EoL
- The development inequality between rich and poor countries makes it even more difficult to control e-waste exports to places without proper management systems

MANAGEMENT

- EoL systems are designed mainly to minimize costs but they fail to improve e-waste collection and subsequent recycling
- The potential for reuse of products and components are not utilized
- Material recycling is driven by economic interests, in both informal and formalized settings
- 'Cherry-picking' of valuables and disposal of unrecyclable items and hazardous substances continues despite formalization of e-waste recycling in developing countries
- Lack of collaboration among stakeholders hinders possible optimization of resource use

POLICIES

- No significant changes in e-waste policies, product design, or circular economic policy
- Although the existing regulations have set targets for collection and reporting for EoL products, they are not strictly implemented
- Product design does not improve because Eco-Design initiatives are not implemented effectively
- Robust implementation of export bans is lacking, resulting in illegal flows of e-waste
- Toxicants in new products decline as manufacturers conform to RoHS-like legislations, but aggregate toxicity never fully dissipates as global demand for EEE rises

BUSINESSES

- Market is flooded with several cheaper options for e-products that do not reflect the true/environmental cost of production
- The core idea of EPR system is limited to sales and collection data reporting; no physical 'take-back' takes place, hence no feedback loop for improving product design
- Reuse, lifetime extension, and alternative business models (e.g., leasing) are tried only by a few companies for select product types (that are profitable)
- Conventional consumption models that continue to dominate are sales-driven with no consideration for lifecycle impacts of e-products or recyclability

USERS

- Users are unaware of impacts linked to production, use, and EoL management of e-products
- Not many users know how they can help improve the situation, for example by purchasing better-designed products and facilitating e-waste collection and recycling
- Reuse and repair are not mainstream options, and many users are buying new items
- Even informed people fail to act due to technological, social, and economic barriers

3.2 SCENARIO 2: *REACTIVE APPROACH*

Strong regulations and monitoring frameworks are in place. Businesses are reluctantly taking the Reactive Approach to comply with the new set of legislations. As a result, some changes appear in the production and consumption patterns. This helps to tackle the localized issues linked to manufacturing and e-waste management, mainly in developed countries.

But the changes in the global practices of production and EoL management of e-products are slower.

TECHNOLOGY

- The technological development and use of e-products continue to grow with little change
- 'End-of-pipe' recycling technologies develop, driven mainly by the value of secondary resources
- Advanced sorting and material recycling techniques make it possible to recirculate resources, creating closed-loop supply chains
- As the demand and price of some critical resources increase, material substitution is a priority for producers

IMPACTS

- Strict policies improve the situation in leading economies but the issues linked to EoL management (informal handling, material losses, and pollution) in emerging markets persist
- Regulatory push for substantial reduction and elimination of toxicants, in manufacturing and in final products, helps to achieve per unit improvements. However, the aggregated risk of toxicity persists with the growing demands of e-product

MANAGEMENT

- Higher e-waste collection and reuse targets for all product groups are set and are being slowly implemented
- Material recovery targets for critical resources from e-waste are also introduced
- The EU has begun to issue fines to member states who fail to achieve these targets, which puts pressure on businesses operating in the region
- The implementation of EPR-based e-waste management is not yet effective in countries with newly introduced EPR legislations

POLICIES

- A patchwork of EPR regulations have arisen across the world. Policy response continues along the same line but in a more extreme direction for collection & resource recovery targets
- E-products are required to have longer warranty period, which has forced producers to design products for durability and easy repair
- Green Public Procurement is now mandatory for all public purchases in Europe and further incremental changes to the criteria are being incorporated
- WEEE, EcoDesign, RoHS, and associate policies are de facto regulatory frameworks globally

BUSINESSES

- Producers adapt, more or less grudgingly, to policy frameworks shifting. This helps to improve the consumption pattern and encourages businesses to adopt more circular models.
- Specific legal requirements (e.g. spare parts and software updates, ease of repair, replaceable batteries, and standardized components) are incorporated into e-products
- Businesses are obliged to be responsible for their EoL products in countries with no EPR legislations

USERS

- The cost of compliance to these measures forces companies pass those costs to users, and thus depresses sales in established markets and delays launches in emerging markets
- Users are still not ready to change their consumption habits mainly because of lacking awareness and little financial motivation
- Hoarding used products in people's homes and incorrect disposal remains frustratingly high and makes EoL targets more expensive to achieve

3.3 SCENARIO 3: *PROACTIVE PATH*

This utopian world envisions a drastic reduction in consumption in which businesses are choosing the Proactive Path towards sustainable production and consumption practices. Businesses develop more sustainable consumption practices along the e-products' supply chain, which are supported by governments and accepted by users. All stakeholders, including economic actors, are supporting the commitment from producers to take a lifecycle approach in manufacturing and EoL management of e-products.

TECHNOLOGY

- With a shift towards renewable energy and use of batteries, there is a growing demand of some resources (e.g. Lithium and Cobalt)
- Products are designed to last longer, to facilitate easy maintenance during use, and for the ease of dismantling and recycling at the EoL
- Technologies like 3D printing help product-lifetime extension by making it possible for users to create spare parts
- The EoL resource-recovery technologies better meet the need of e-waste

IMPACTS

- Although the amount of e-waste generated increases, the management capacity ensures environmentally-sound practices with little impacts
- Reuse of e-products and their components, along with recycling of e-waste, helps to control the demand of virgin resources
- Responsible mining practices are more common with less social and environmental issues
- Significant reductions in toxicants entering the environment from e-products manufacturing

MANAGEMENT

- EoL management is an integral part of product development and concepts such as 'design for recycling' are part of design checklist
- Producers and EoL managers (e.g., collectors, repair shops, recyclers) are working together to optimize EoL resource recovery from consumer products
- Following circular economy principles, priorities are put in place to facilitate the reuse of products and components before material recycling

POLICIES

- Policies are based on ambitious goals of achieving truly circular systems and businesses are leading the process of drafting and implementing progressive legislation
- Regulations function as a guidance rather than a compliance instrument
- Less resource-intensive products and consumption models are encouraged through rewards and recognition
- All countries are covered by legislation that addresses all lifecycle stages of e-products, including e-waste management

BUSINESSES

- Businesses are the leaders of a shift towards sustainable production and consumption practices with due diligence
- Products, services, and supply chains are designed to facilitate a closed loop of materials
- Businesses also enjoy the potential savings from resource reuse
- New technology and innovation make this possible, along with the growing acceptance of business models that discourage consumers to privately own several e-products
- Thanks to information campaigns led by grassroots initiatives, businesses, and governments, users are aware of the e-waste problem and the environmental footprints of e-products

USERS

- User behavior is considered when designing e-waste collection systems to create more functional infrastructure and achieve higher collection and recycling rates
- Alternative business models (e.g., leasing and product-service systems) are becoming 'mainstream', which is made possible by the proactive industries
- More people are opting to repair broken products — thanks to repair businesses and grassroots initiatives

BOX 3

A PRODUCT UNDER THREE SCENARIOS

Since the introduction of smartphones, the mobile phone industry has seen incredible growth and technological evolution. Today there are more mobile phones than people living on earth, and most of the metals in the periodic table can be found in a single smartphone. During the last decade, a wide range of phone features and prices have become available. Further increase in demand for mobile phones is inevitable, but a sustainable mobile phone has yet to be designed.

SCENARIO 1: *LINEAR GROWTH*

The business-as-usual approach will only result in phones with shorter lifespans that are neither suitable for lifetime extension (e.g. through repair and reuse) nor efficient material recovery. In the race of selling more, better, and cheaper mobile phones, environmental and social issues linked to sourcing of metals and product manufacturing are ignored by the producers, who are not even taking their minimum legislative responsibility seriously. Hence, producers are unable to take their phones back at the EoL, but consumers are also not demanding large-scale recovery, mainly due to lacking awareness.

SCENARIO 2: *REACTIVE APPROACH*

Stricter regulations force producers to take more responsibility in providing software upgrades and designing hardware to support easy repair for a few years after purchase. Components with higher and faster failure chances (e.g. batteries and screens) are available as spare parts; however, repair costs remain high. EoL collection is still a logistical challenge and material recycling is not financially viable, though technologically possible, for all elements used in a smartphone. A large number of EoL phones are stocked in users' drawers, as there are no promising incentives to increase collection rates.

SCENARIO 3: *PROACTIVE PATH*

Modular phones are becoming popular, giving consumers the best choice for the features they need. New operating systems are also available for previous models across different makes and models, giving old phones a new life. In addition, purchasing smartphone services, instead of simply the product itself, is popular. Users pay for the data and phone services, and are offered hardware upgrades at no extra fee. Producers retain ownership, which makes take-back and eventual EoL management smoother. Users are incentivized to return the old phones they no longer use, which ensures that most phones enter the proper EoL management system. EoL management operation, including recycling and reuse of phones, as well their components, are also eased due to better design considerations.

4. OPPORTUNITIES

Although there are uncertainties about how future technology will evolve, the use of e-products — and thus the generation of e-waste — will almost certainly grow, at least during the next few decades. It is especially true for rapidly growing economies that are yet to be flooded with the myriad of e-products that come with economic prosperity. It means more challenges, as well as opportunities, for all players in the global e-waste arena: producers, users, e-waste collectors, recyclers, and policy makers. Regardless of which direction the future evolves, ensuring a sustainable production and consumption system for e-products will require significant efforts from all stakeholders.

With insights into the future, producers probably have the best opportunity to design a future-proof electronics sector that is sustainable economically as well as environmentally. Besides manufacturing and recycling, innovative businesses can also tap into the huge product and component reuse potential. This can create local businesses and help countries, especially those with no reserves for primary resources or e-products manufacturing, to utilize the functional value of products for a longer period, avoiding the import of new items. Many products ranging from household appliances (washing machine and lighting equipment) to ICT equipment (mobile phones and computers) can be offered as a service or leased instead of selling products. Such business models can provide better opportunities for product lifetime extension and smoother take-back at the EoL.

Exercising due diligence, businesses can minimize the potential challenges of critical resources and stricter legal requirements. Some big brands are hitting the limits of business models that rely on sales of new products, whereas others who prioritize product longevity are gaining popularity. There is also demand for more sustainable products, which can be attributed to growing consumer awareness. Businesses will be better off by proactively addressing users' demand.

There is also an opportunity for policy makers (local as well as global) to facilitate the transition towards a more circular system. The EPR-based take-back system has been a noteworthy milestone in e-waste management. However, the current e-waste management systems have not been able to fully capture the functional and material value of EoL products. In part, this is also linked to a lack of incentives for actors in the value chain, which could promote the best possible (both environmentally and financially) EoL solutions. Similarly, lack of collaboration among stakeholders in the product lifecycle has been an issue when it comes to implementing 'design for EoL' solutions. And at the very fundamental level, lack of public awareness has also been an issue in e-waste management, which may be addressed by policy-level actions.

Today, many developing countries lack effective policies and proper infrastructure for the management of not only e-waste, but also for other streams including municipal solid waste. This situation offers a great opportunity for countries in Asia, Africa, and South America where more rapid technological growth is expected. Institutionalizing informal recycling activities can help create safer working environment for waste workers, less environmental impact, and a more sustainable recycling industry. The lessons learned during the last two decades from the European Union in developing and implementing e-waste regulations and setting up management systems can be of value in this process.

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