Insight Report

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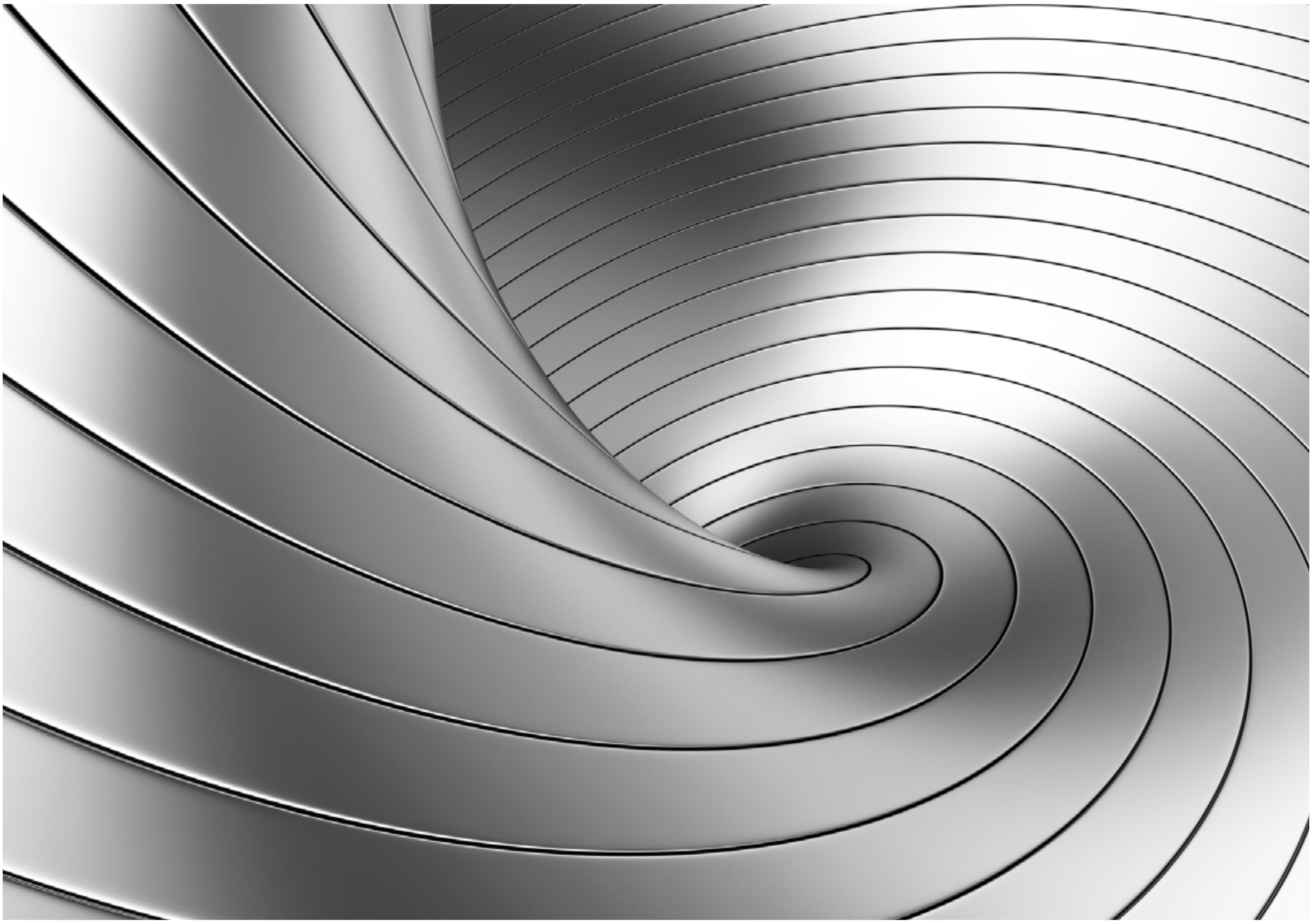
Recovery of Key Metals in the Electronics Industry in the People's Republic of China
An Opportunity in Circularity

September 2018



Prepared by: Tsinghua University School of Environment
Prepared for: The Platform for Accelerating the Circular Economy

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World Economic Forum
91-93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland
Tel.: +41 (0)22 869 1212
Fax: +41 (0)22 786 2744
Email: contact@weforum.org
www.weforum.org

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Foreword

Electronic devices are a crowning point of human ingenuity. They encapsulate the ability to manipulate elements to create a range of products – from personal computers to smartphones – that are having a vast, positive impact on people's lives and, more broadly, on society. The number of electronic devices is growing exponentially; in 2015, connected devices were expected to increase from about 10 billion to 25-50 billion globally by 2020.[1] Most of the growth is coming from emerging regions and will bring connectivity, increased quality of life and convenience to billions of people.

This huge increase in electronic devices will have an impact. These devices source a large quantity of metals and materials from across the periodic table, the supply of which can be volatile and subject to scarcity. Moreover, the devices become waste when their useful life comes to an end. Electronic waste, while not the largest waste stream, is the fastest growing waste globally.[2]

This waste has significant economic value. It contains many high-value and, in some cases, scarce materials, such as gold, platinum, cobalt, rare earths, and high quantities of aluminium and tin. The United Nations estimates that each year, $52 billion worth of electronic waste is thrown away, with only 13% recycled. This represents an incredible economic opportunity,[3] not to mention the further benefits of a secure supply of critical materials. In many cases, however, they can contain toxic substances that are dangerous for those working in the industry and for the general population.

Recycled metals are also two to ten times more energy efficient than metals smelted from virgin ore. In 2015, the extraction of raw materials accounted for 7% of the world's energy consumption, meaning that moving towards the use of more secondary raw materials in production could help considerably in reaching the targets set out in the Paris Agreement on climate change.[4]

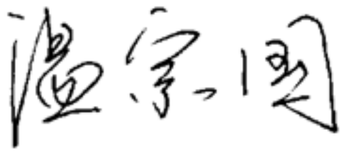
Increasingly governments and companies are moving to a new model of doing business – the *circular economy*. In it, nothing becomes waste and all products, components and materials are continuously cycled through the economy, maximizing their value at all times. A positive circular vision for the electronics industry would include products designed for longevity, repair and disassembly to facilitate recycling, and from which base materials can be constantly reused in new products rather than discarded in landfill or extracted under hazardous conditions. Companies could take back their products into their manufacturing stream in a "closed-loop approach", and any waste from manufacturing would be reintegrated into products. The benefits of such a system for jobs, economic growth and supply of critical materials are potentially vast.

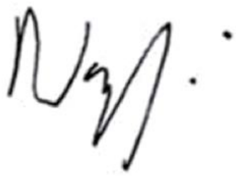
A number of leading electronics companies are committing to the circular economy and taking steps to change business models and product design, as well as setting targets to integrate recycled materials. Governments are also taking a lead; for example, the Government of China has set targets to source 20% of raw materials for new electronic products from recycled content by 2025 and to recycle 50% of electronic waste.

What is clear, however, is that capturing this economic and environmental opportunity will require unprecedented levels of innovation and collaboration. The distributed nature of electronic device production and use; the policy frameworks governing the flow and use of secondary materials; the economics of material recovery as well as the artisanal nature of waste collection and processing in many emerging markets, are all challenges that need to be collectively addressed by a broad range of stakeholders. Multinationals, supply chain actors, regulators, recyclers, universities and consumers all have a role and a responsibility in this effort.

As the global manufacturing hub for electronic products, producing some 39% of the world's electronics and 70% of its mobile phones,[5] China is the key link in the global electronics manufacturing value chain. The key to unlocking a circular future for electronics therefore lies in China. Thus, progress on challenges, however seemingly small, will have global ramifications.

This Insight Report is a collaborative effort between Tsinghua University and the World Economic Forum. It is a baseline study examining the current state of electronics recycling in China with a focus on aluminium, tin, cobalt and rare earths. The study starts to identify some of the critical levers that can lead to a fully circular system, such as e-waste collection, the role of the informal sector and the movement of secondary materials from and to areas of production, and sometimes across special economic zones. It also models the economic opportunity at stake from the materials covered and examines the related policy environment. We hope this report will act as a basis for meaningful collaboration between all the stakeholders needed to move towards a circular electronics system.





Zongguo Wen
Director, Tsinghua University Centre for Industry and Circular Economy
People's Republic of China

Dominic Waughray
Head, Centre for Global Public Goods
World Economic Forum

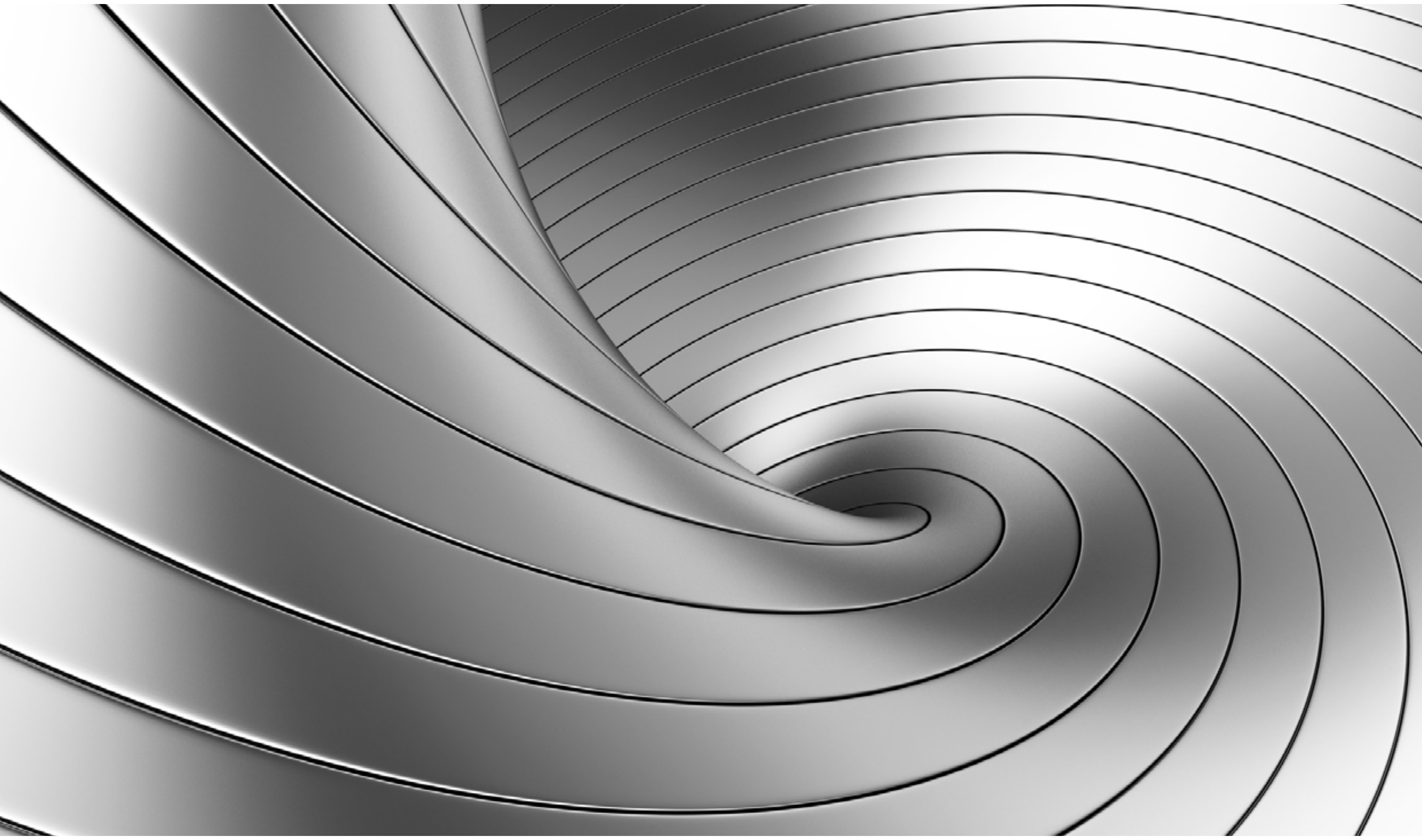
Executive summary

This joint study by Tsinghua University (China) and the World Economic Forum addressed three major research areas to assess the potential for recovery of key metals in the electronics industry. First, four key metal groups prevalent in electronic products – aluminium (Al), tin (Sn), cobalt (Co) and rare earth elements (RE) – were analysed for their circular potential. (The term "circular" defines systems where nothing becomes waste and all products, components and materials are continuously cycled through the economy, maximizing their value at all times.) Material flow analyses were conducted for the four groups, with a projection of their market value for recycling. Second, China's electronics industry was analysed, including a breakdown of recycling capacity by company and region. Third, the policy environment for electronics recycling was discussed, focusing on macro targets and waste flows through bonded zones.

Some of the major points from this study include the following:

- China has become the global centre for both the production and consumption of electronics, a key driver in the growing demand for materials and the increasing production of waste of electrical and electronic equipment (WEEE).
- In 2014, only $160 million of material value (of a potential $1.3 billion worth of materials) was recovered by the formal recycling industry. This potential is expected to rise to $4.4 billion by 2030.
- The Chinese government has ambitious targets for recycling, including sourcing 20% of raw materials for new electronic products from recycled content as well as recycling 50% of all WEEE by 2025. The plan is novel as it targets production-side issues, such as eco-design, and increases the use of recycled materials. In addition, it emphasizes the use of new technology (the internet of things) and e-commerce supply chains. Leading electronics companies also have significant internal targets for incorporating raw materials into their products.
- To support achieving these goals, this study serves as a baseline and overview of the current state of recycling for the four key metal groups. Recycling rates vary among them, ranging from 10.7% for aluminium to 6.1% for tin, 0.6% for cobalt and less than 1% for rare earths.
- Mixing various scraps of aluminium often produces a grade too low for the manufacture of high-end electronic goods, such as mobile phones, creating a significant barrier to circular sourcing of materials.
- Metal in WEEE can be difficult to recover. For example, recovery rates for cobalt are only 30%, the rest being lost in processing, and less than 1% for rare earths. The technology for recovering these metals is still in its infancy.
- The informal (unregulated) sector dominates China's waste from electrical or electronic equipment (e-waste). On average across the four metals, 78% of waste was collected by the informal sector. Many of these metals are still treated but often in a rudimentary manner, without measures to protect neither the health and safety of workers nor the environment. The quality of the recycled material is also significantly lower.
- The industrialization of recycling to engage the informal sector is therefore a key goal to move towards a more circular system of electronics production. Recycling capacity will need to grow by 100% to reach the Chinese government's 2025 target of recycling 50% of WEEE.
- Due to low metal prices and high recovery costs, waste metals are often stockpiled rather than recycled in anticipation of future regulatory and economic incentives. The government is addressing this with new policy measures.
- Government incentives have led to a large uptake in registered (formal) recycling enterprises, whose number increased from 36 in 2012 to 109 in 2017 with an annual recycling capacity of 4.2 million tonnes of WEEE.

- The WEEE subsidy system uses extended producer responsibility to fund proper waste management and recycling of WEEE. As of 2016, however, the WEEE treatment fund had a four-year running deficit of about RMB 6 billion (Chinese renminbi), showing a lack of long-term financial sustainability.
- The State Council, the National Development and Reform Commission and five key government ministries are involved in managing and enforcing China's WEEE collection and treatment. Those ministries are: the Ministry of Industry and Information Technology, the State Administration of Taxation, the General Administration of Customs of the People's Republic of China, the Ministry of Finance and the Ministry of Ecology and Environment.
- Two recent major policy pieces aim to foster a circular system for electronic products: the Extended Producer Responsibility System Implementation Plan (2017) and the Circular Development Leading Actions (2017).
- While some restrictions and inconsistencies in enforcement exist, policies on importing waste from bonded zones broadly allow for the import of non-hazardous wastes, especially those that can be reused. However, some enterprises find it difficult to transport scrap material into the mainland for closed-loop recycling – a barrier to increasing circularity, as many large manufacturers produce products in bonded zones. Inconsistent enforcement of policy concerning waste flows into China continues to be an issue for local government.



Uncovering the circular potential for China's e-waste

1

Over the past two decades, China's growing economy has increasingly taken a leading role in electronics, with rapid development across the entire value chain. It has a developed infrastructure in mining and the production of raw materials, and now supplies 46% of global aluminium[6] and 85% of rare earths.[7] Even so, China still relies on imports of certain scarce metals, such as cobalt and zinc. Raw materials are used to produce electronic goods, in which China has become a global hub. Its global market share of manufactured electronic goods (by volume) has reached 39%,[8] and in some sectors it dominates, such as the manufacturing of air conditioners (80% global share) and mobile phones (70%).[9] About one-third of its electronic goods are exported, with a significant portion to the United States and Europe.[10,11] Altogether, Chinese exports of electronic machinery totalled $544 billion in 2015.[12] Concurrently, demand for these products has also grown rapidly in China. In 2012, China surpassed the United States to become the largest market for personal computers.[13]

China's pattern of increasing consumption, however, has also led to increased generation of waste. Of that, waste of electrical and electronic equipment (WEEE), or e-waste, is some of the most difficult to deal with, and can have serious environmental effects. In this respect, China's State Council, the chief administrative authority, has set clear targets to recycle 40% of e-waste by 2020 and 50% by 2025. Additionally, a target was set to increase the use of recycled materials in producing electronics to 20% by 2025.[14]

Recycling e-waste has two major benefits. For one, e-waste represents a major opportunity for resource recovery, being rich in valuable metals, including gold and platinum, and in concentrations up to 50 times that of mineral ores.[15] China's WEEE had a recycling potential estimated at $16 billion in 2010, which is anticipated to reach $73 billion by 2030 due to the increasing demand for electronics.[16] Second, e-waste pollutant discharges have high concentrations of toxic substances (chromium VI, cadmium, brominated flame retardants).[17] If left unchecked, they can adversely affect human and environmental health, especially when environmental and safety measures are not used in their treatment, which is often the case in the informal (unregulated) recycling industry.

For these reasons, the Chinese government has passed legislation to develop e-waste recycling at the national level, including providing subsidies, investing in infrastructure and developing regulations for the recovery and recycling of high-priority electronic goods. The *Waste Electronic and Electric Equipment Processing Catalogue (1st batch)* of 2011, published by China's National Development and Reform Commission (NDRC), identifies five categories of WEEE as priority areas for development: televisions (TVs), refrigerators, washing machines, air conditioners (A/Cs) and personal computers (PCs). This was later expanded with a second batch in 2015 to include an additional nine categories (Figure 1).

Figure 1: Priority electronic waste product categories identified by China's National Development and Reform Commission

National e-waste product categories	
<u>1st batch (2011)</u>	<u>2nd batch (2015)</u>
Refrigerator	Kitchen exhaust fan
Washing machine	Electric water heater
Air conditioner	Gas water heater
Television	Fax machine
Personal computer	Mobile phone
	Telephone
	Printer
	Copier
	Computer monitor

Source: National Development and Reform Commission (2010). *Waste Electrical and Electronic Equipment Treatment Product Categories (first batch)* (Announcement 24 of 2010); National Development and Reform Commission (2015). *Waste Electrical and Electronic Equipment Treatment Product Categories* (Announcement 5 of 2015)

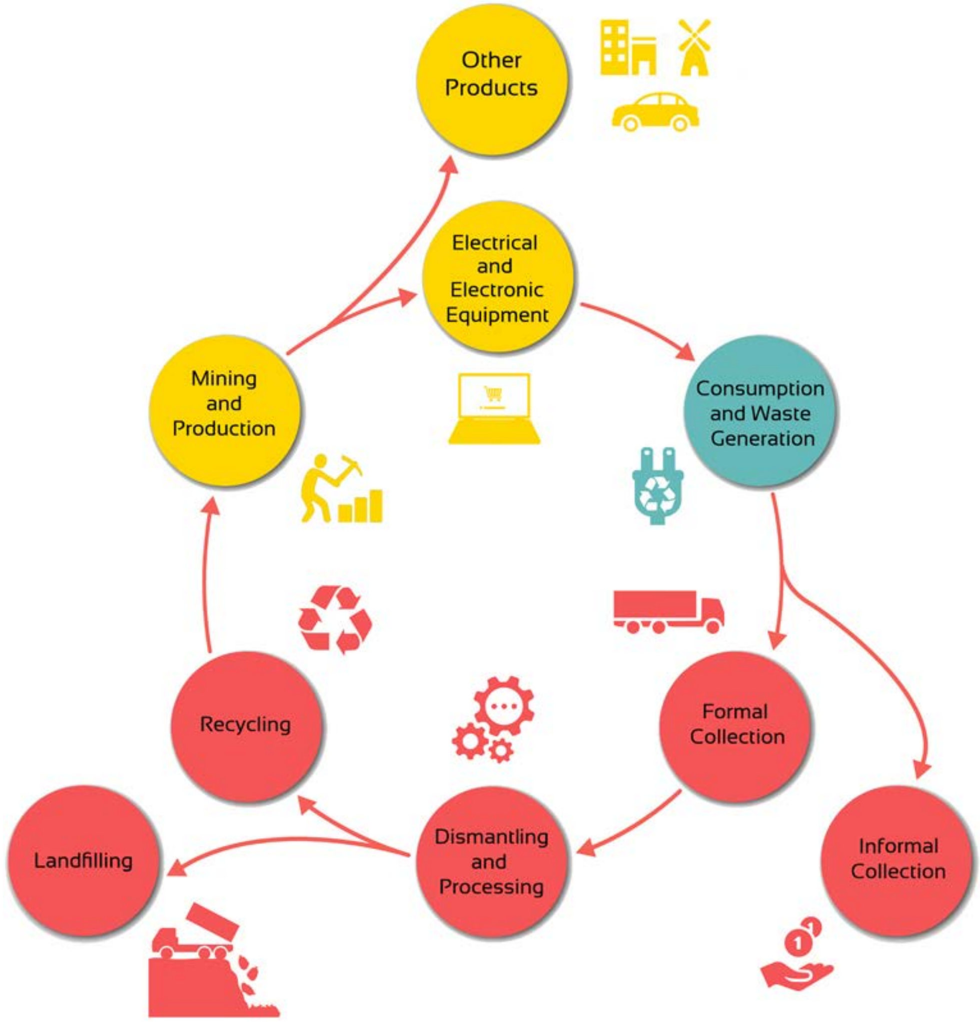
In the current WEEE sector, the recycling of the base metals aluminium (Al), tin (Sn) and cobalt (Co), as well as the group of rare earth (RE) elements, is lagging far behind recycling targets. They offer huge economic potential, however, and related development could soon see increased political support. In some cases, as regards aluminium, the electronics industry is not the largest consumer of raw materials; however, the lessons from electronics serve as a practical review of the systems and approaches which could be replicated across all sectors.

This study, undertaken by Tsinghua University (China) and the World Economic Forum, maps the current state of metals recycling in China, including material flows and related policies; draws key lessons; and summarizes some of the government's actions to increase recycling in the country.

Mapping the electronics life cycle

China has developed robust infrastructure across the entire electronics industry value chain. Upstream mining of ores and subsequent metal refining provides the primary products for manufacturing electronic goods and other products. Goods are exported and consumed domestically, and remain in society for a number of years before disposal as WEEE. Upon reaching the end of their productive life cycle, waste electronics are then collected for further treatment. As in many developing countries, informal collection and recycling by scavengers and small-scale enterprises are prevalent in China. Once collected, goods can be fixed and reused, broken down for parts or separated for metal recycling. Unfortunately, informal e-waste recycling has been characterized as artisanal processing of waste with crude and outdated technologies, and it often results in a down-cycling of metal quality. Furthermore, operations are not regulated, and recyclers have fewer incentives and are not required to meet environmental standards; they often discharge waste pollutants directly to the surrounding environment, leading to contamination of soil and groundwater.[18,19]

Figure 2: Electronic goods life cycle



Source: Authors

Conversely, formal collection and recycling are established and growing. The Chinese government has been developing a system where industry standards can be better enforced. Once in the formal sector, WEEE is sent for dismantling, smelting and recovery for reuse as a primary product (Figure 2). Depending on the efficiency of recycling technologies, some of the materials are lost in the refining process and sent to landfill. In most cases, recycled materials are returned to smelters for refining or co-processing into raw materials. Unfortunately, as further analysis will show, only 38% of WEEE is processed through formal recycling.

Estimating waste generation with the lifespan model

Waste generation is the culmination of different products coming to the end of their life. With the average lifespan of Chinese electronic goods ranging from three years (for personal computers) to 15 years (for refrigerators),[16] the past decade of their consumption will shape WEEE generation in the future. According to consumer statistics, the consumption of refrigerators, washing machines, air conditioners, TVs and PCs has increased steadily since 2000,[20] with especially PCs experiencing high growth in demand (Figure 3) consistent with the desire to keep up with modern Chinese society. These five categories, also identified by the government in the first batch of waste categories, will dominate WEEE generation to 2030.

Using the lifespan model with data obtained from the China Household Electric Appliance Research Institute (CHEARI)[21] and Tsinghua University,[16] the country's 14 product categories of WEEE are projected to grow from 4.9 million tonnes in 2010 to an estimated 29.5 million tonnes in 2030 (Figure 4). Disaggregating the results further shows that the first batch of five waste categories made up 72% of total WEEE generated by weight in 2015. This is projected to increase to 86% by 2030 as refrigerators, washing machines and TVs reach the end of their life cycle.

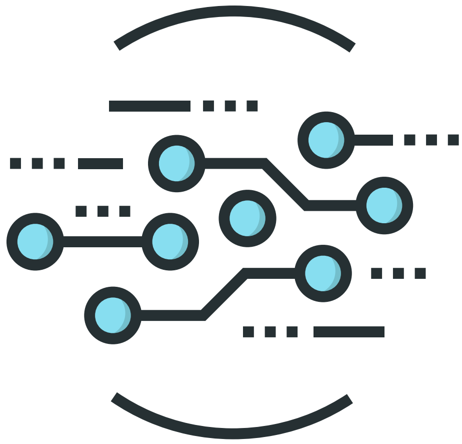
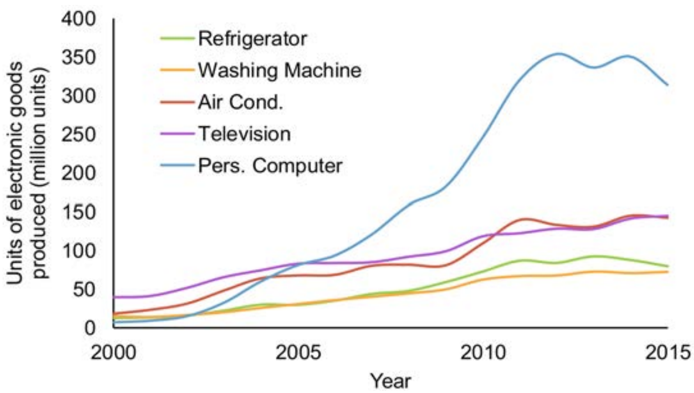
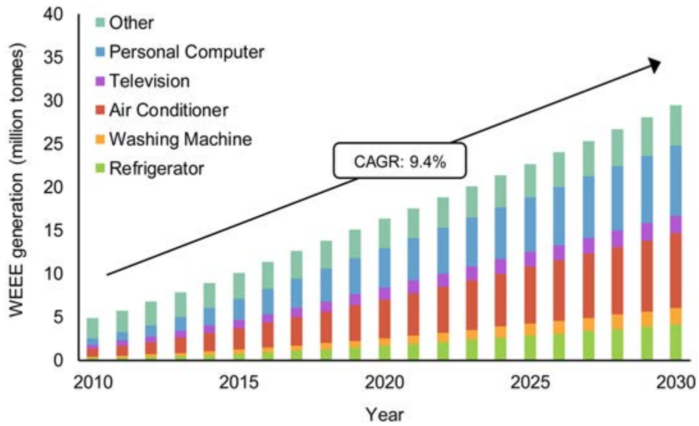


Figure 3: Historic growth in production of select electronic goods in China, 2000-2015



Source: National Bureau of Statistics of the People's Republic of China, "Statistics Database – Yearly Format" (online database), 2017, http://www.stats.gov.cn/tjsj/

Figure 4: Projected growth in WEEE generation in China, 2010-2030



Note: CAGR = compound annual growth rate
Sources: Zeng Xianlai, Gong Ruying, Chen Weiqiang and Li Jinhui, "Uncovering the Recycling Potential of 'New' WEEE in China", *Environmental Science & Technology*, 50, 2016, pp. 1347-1358; China Household Electric Appliance Research Institute (CHEARI), "White Paper on WEEE Recycling in China" (in Chinese), 2015

Analysis of the current flows of aluminium, tin, cobalt and rare earths in China's electronics sector

2

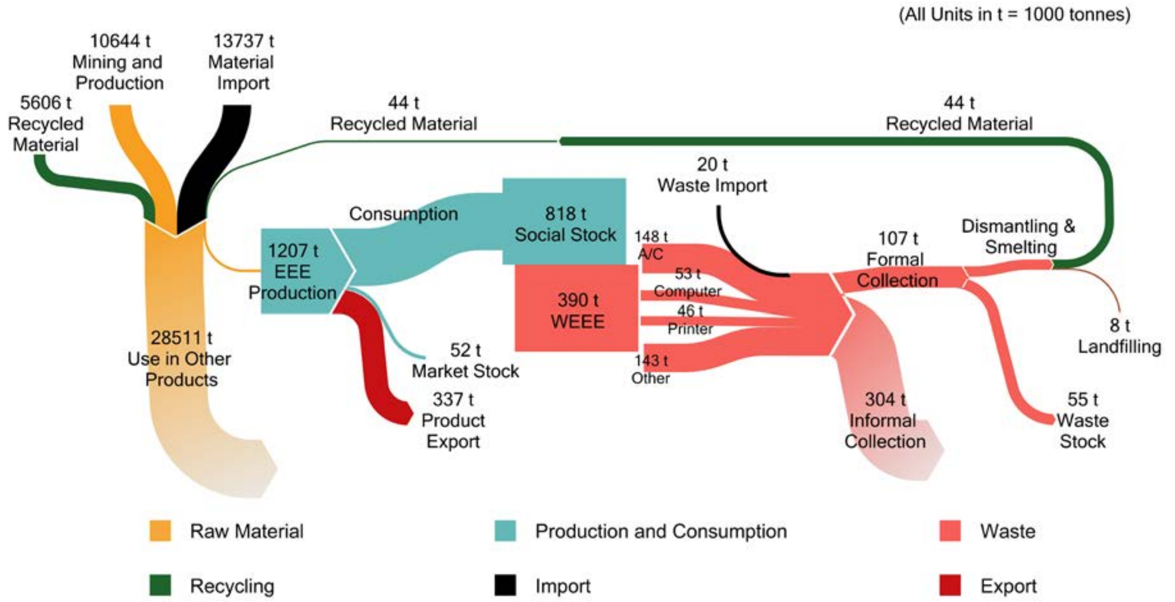
Aluminium (Al), tin (Sn), cobalt (Co) and rare earths (REs) are important to the electronics industry. This chapter focuses on assessing these four
metal groups by mapping how they flow through the Chinese electronics sector and estimating their recycling potential.

- All flows were calculated for 2014, the most recent year with a complete set of data for the entire value chain.
- Market stocks represent embedded metals in products stored in market that are not sold in the year they were produced. Stockpiles are generated from gaps in supply and demand. Generally, the four base metals account for a small portion of flows into or out of electronics production.
- Social stocks represent goods that are consumed and stay in households until they reach the end of their productive life. As goods reach their end of life, they enter the WEEE stream. For most of the base metals, the quantity consumed in 2014 vastly outnumbered the waste generated (or that was consumed in previous years).
- Waste stocks represent the portion of waste collected but not yet recycled in the year it was collected. A recycler would stockpile waste for several reasons, the most common being economics. After the recovery of select valuable substances, the recycling of base metals may not be economically viable; rather than disposing them, recyclers may save the remaining portion until metal prices increase or subsidies become available, thus making future recycling profitable.
- Most of the WEEE generated is collected through the informal sector. Unfortunately, data are scarce downstream from collection, meaning accurate figures are not available for how much is refurbished, recycled and disposed of. Thus, this portion is treated as a sink, i.e. an endpoint with no further in-depth analysis, in the model.

Aluminium (Al)

Aluminium is used for structural, electrical and thermotechnical functions in the electronics industry. In 2014, the quantity used in electronics made up only 4% of total demand for the metal but was still a considerable 1.2 million tonnes (Figure 5); as this study will show, it represents significant economic potential. Aluminium waste (post use) in electronics totalled 390,000 tonnes, 74.5% of which was found in four waste categories: air conditioners, PCs, commercial printers and personal printers. These are large, bulky items in which aluminium is used primarily for structural purposes, and in the case of air conditioners, for condensing coils.

Figure 5: Material flow analysis for aluminium through the electronics life cycle, 2014



Note: This graphic illustration of flows, or Sankey diagram, has been separated into three main sections: production (yellow), consumption (blue), and waste disposal and recycling (red). Flows within each are drawn to scale, but flows between the sections are not proportional. Material flows were constructed using data from 2014 (the most recent available).

Source: Authors

China's production and consumption of aluminium has grown consistently since the 1990s. By 2014, production of primary refined aluminium had reached 24.4 million tonnes, accounting for 45.8% of global supply.[22] Of that total, 10.7 million tonnes were processed from ores mined in China, while most of the production was processed from imported ores.[23] Secondary refined aluminium totalled 5.6 million tonnes (19% of total combined production), sourced largely from end-of-life vehicle scraps.

As with all metals covered in this study, most (74%) of the aluminium in e-waste was collected and treated by the informal recycling sector. As it is unregulated, this sector does not collect data on amounts and the quality of recycled output. The details in this study are thus not accounted for. In the formal sector, about half of the collected aluminium (55,000 tonnes) was stockpiled as waste, and the other half was processed further for resource recovery. The average process efficiency for official dismantling and smelting was 85%.[6] While 19% of all refined aluminium was from secondary or recycled aluminium in 2014, only 0.14% (44,000 tonnes) was sourced from WEEE.

Metal grade for aluminium recycling

Recycling plays a significant role in China's supply of aluminium and has been the target for further development. Based on polices such as Made in China 2025 (2016) and Circular Development Leading Actions (2017), the aluminium recycling rate is projected to grow to 22.5% by 2020.[24]

Aluminium from WEEE, however, does not factor too heavily in China's overall recycling, as evidenced by the metal's relatively low recycling rate (10.7%). Rather, scraps are primarily sourced from the auto industry, construction, packaging (beverage cans) and then WEEE. Growth of secondary aluminium is highly correlated with auto production,[24] suggesting significant ties between the two.

According to Jiwei Wang, Secretary-General, Metal Recycling Branch, China Nonferrous Metals Industry Association,[25] the recycling industry is structured so that most aluminium scraps are mixed, recovered and recycled together to produce low-grade aluminium die-cast alloys, suitable for applications such as engine blocks. In cases where closed-loop recycling is necessary to retain the properties of high-grade wrought alloys, manufacturers may employ reverse logistics, cooperating with suppliers to return metal scraps for remanufacturing.

Tin (Sn)

China produced 228,000 tonnes of refined tin in 2014, or about 62% of global demand.[26] Tin from secondary refined production made up 15% of this total, or slightly lower than the global average of 17%. In China, 61% of all tin was used to produce solder,[27] an essential component of electronic products. PCs require large quantities of solder (Figure 6) and are the largest source of tin in WEEE (55% of total) (Figure 7), followed by air conditioners and refrigerators. Of the waste tin flowing into the formal recycling sector, 67% (5,600 tonnes) is stockpiled as a waste stock; it is saved in storage for future dismantling and recycling when conditions become more favourable, for example if the government were to introduce a new subsidy.

The remaining 33% (2,900 tonnes) of waste tin is sent for further processing, where recycling technologies are fairly mature and end-of-life recycling rates relatively high. For waste printed circuit boards, thermal treatments are most commonly used.[27,28] They range from simple furnace heating and open burning to more controlled infrared heating, solder-bath heating and liquid-medium heating that can yield a relatively high recovery efficiency for tin (90%). In this study, the global average end-of-life recycling rate for tin (75%) was conservatively applied,[29] with the remainder being lost in production. Accordingly, the model yielded 2,200 tonnes of recycled tin in 2014 (Figure 7), or 6.1% of the amount generated in WEEE. Conversely, some industry experts estimate the actual quantity of tin going back into the economy is closer to 35,000 tonnes, or roughly equivalent to the theoretical potential. This suggests that the informal recycling sector is incredibly dominant in the recycling of tin.

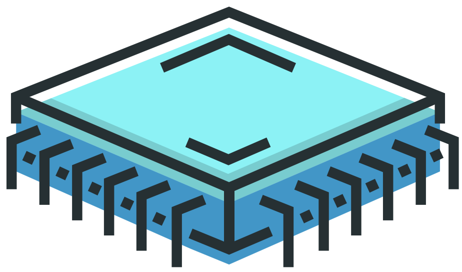
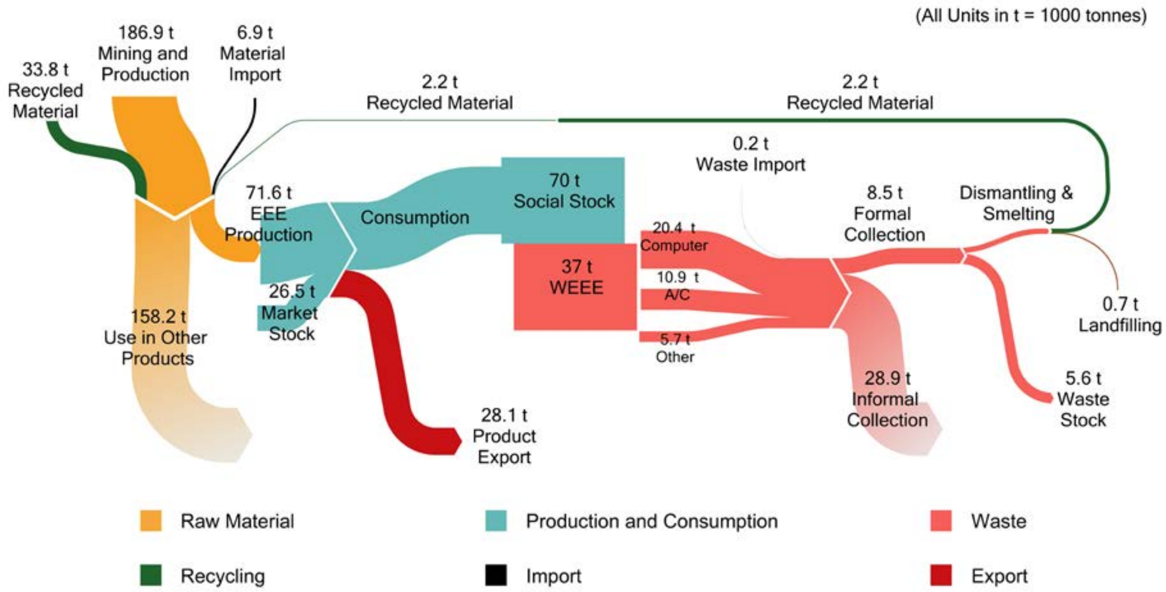


Figure 6: Concentration of tin in select electronic products

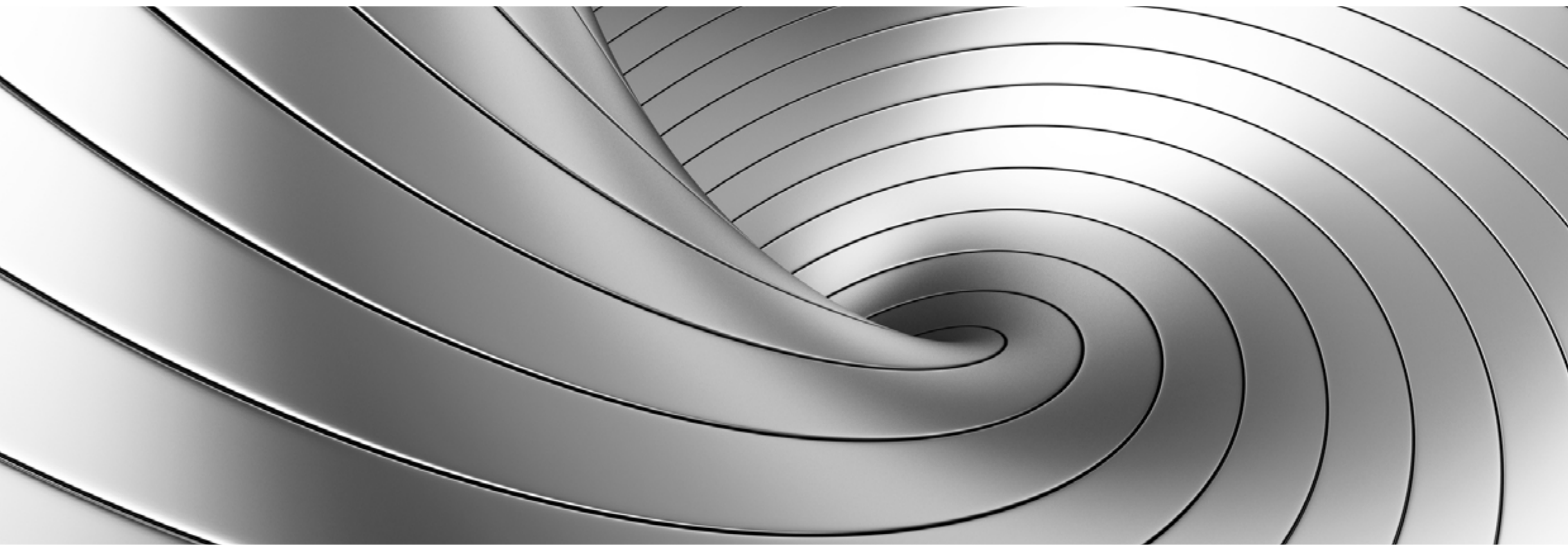
Electronic categories		Sn in PCB (mg/kg)	PCB in EEE (%)
Refrigerator		83,000	0.5
Washing machine		9,100	1.7
Personal computer		40,000	23.0
Air conditioner		19,000	2.7
TV	Cathode ray tube	18,000	7.9
	Plasma display	0	7.3
	Liquid crystal display	27,000	10.2

Note: PCB = printed circuit board
Sources: Cao Jian; Lu Bo; Chen Yangyang; Zhang Xuemei; Zhai Guangshu; Zhou Gengui; Jiang Boxing; Schnoor, Jared. “Extended producer responsibility system in China improves e-waste recycling: Government policies, enterprise, and public awareness”, *Renewable & Sustainable Energy Reviews*, 62, 2016, pp. 882-894; Habuer, Nakatani Jun, Moriguchi Yuichi. “Time-series product and substance flow analyses of end-of-life electrical and electronic equipment in China”, *Waste Management*, 34 (2), February 2014, pp. 489-497

Figure 7: Material flow of tin through the electronics life cycle, 2014



Note: This graphic illustration of flows, or Sankey diagram, has been separated into three main sections: production (yellow), consumption (blue), and waste disposal and recycling (red). Flows within each are drawn to scale, but flows between the sections are not proportional. Material flows were constructed using data from 2014 (the most recent available).
Source: Authors



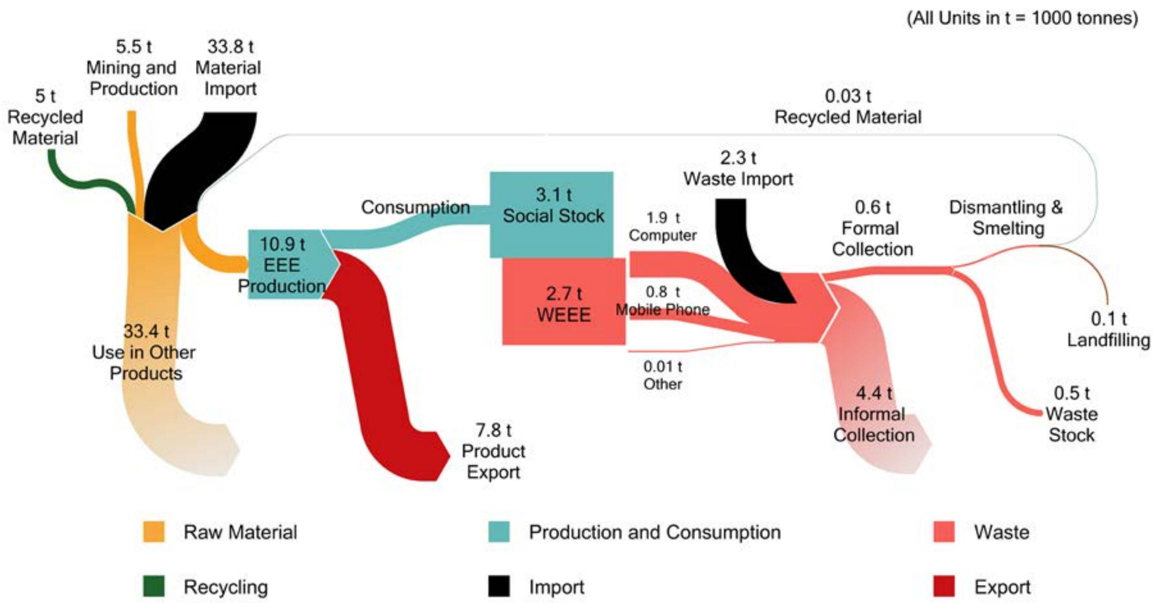
Cobalt (Co)

Globally, cobalt is largely considered a scarce resource, with high concentrations in a limited number of countries. Major reserves are located in Australia, Cuba and the Democratic Republic of Congo, with the latter having the largest deposits. As such, it supplies over half the world's cobalt.[30] Unfortunately, its mining industry has also been linked to severe socio-economic problems, including child labour, violent conflicts and environmental pollution,[31] and has cast a long shadow on downstream products, particularly consumer electronics.

With only 1.1% of the world's reserves,[32] China is a net importer of cobalt (Figure 8). It is an important component of lithium batteries, in particular the cathode. As of 2015, lithium cobalt oxide, the most commonly used type of cathode in commercial applications (by weight: 45,000 tonnes globally),[33] contains as much as 60% cobalt.[34] By contrast, lithium only constitutes 7% of those particular cathodes. Lithium-nickel-manganese-cobalt-oxide cathodes were next in volume (35,000 tonnes) and contain about 25% cobalt by weight. The development of batteries is constantly ongoing, with the possibility that lithium batteries will be replaced as the primary option for storing energy.[35] Nevertheless, cobalt-rich batteries will continue to be prevalent in WEEE generation in the short- to medium-term future.

As such, 25% of the China's cobalt goes into the production of electronics and electrical equipment, of which 79% is exported. In addition to lithium batteries, cobalt is also used for contacts in circuits and as a medium in magnetic recordings (e.g. hard drives).[36] As a waste, cobalt is primarily found in computers and mobile phones, with waste imports forming a significant source. Only 12% of cobalt was collected by the formal sector. While China's Ministry of Ecology and Environment (MEE; previously the Ministry of Environmental Protection) had explicitly promoted the collection and recycling of batteries in the *Technical Policy of Spent Battery Pollution Prevention (2006)*, a 2016 survey of collectors indicated little demand from recyclers.[37] Thus, most batteries were disposed of in landfill. In this study, only 30 tonnes of cobalt, from printed circuit boards and hard disks, were recycled from the formal sector.

Figure 8: Material flow of cobalt through the electronics life cycle, 2014



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Source: Authors

Lithium-Ion Batteries: A major source of cobalt

A Tsinghua University study[32] in 2015 showed that lithium batteries are and will continue to be the largest application for cobalt in the near future. China produced about 4.8 billion lithium-ion batteries in 2013, consuming over 50% of the refined cobalt within its borders. By 2030, total demand in China is projected to surpass 100,000 tonnes, with the proportion for lithium-ion batteries forecast to increase to 72%.

China's low reserves of cobalt mean that meeting future demand will rely heavily on a much-improved recycling industry.[32] The largest bottleneck is in collection, as lithium batteries are primarily collected by the informal sector. Returns for batteries, however, are significantly lower than other subsidized wastes. As a result, the collection rate is an estimated 10%, leaving formal recyclers with significant excess capacity.[37] In 2016, a survey of Shenzhen GEM High-tech Co., the largest formal recycler of lithium batteries, found that actual throughput of all batteries was 100,000 tonnes annually, of which 25,000-30,000 tonnes per year were lithium-ion batteries. Designed capacity was 300,000 tonnes per year. Major products recovered included 3,000 tonnes of cobalt.

The increased demand for electric vehicles, and particularly the lithium batteries used to power them, have incentivized further development for their recycling. For one, they will be a major source of cobalt and other resources in the medium term when batteries come to their end of life. However, recycling will be necessary in the short term to meet the increasing demand for cobalt, with projections for recycling rates of up to 90% by 2020. As such, more investments are being directed to the sector to achieve closed-loop recycling, and recent policies have focused on lithium battery recycling, particularly in the Extended Producer Responsibility System Implementation Plan (2017) that should address some of the issues with collection.

Rare earths (REs)

The group of rare earth elements (rare earths, or REs) includes 15 metals in the lanthanide series, as well as scandium and yttrium. They are co-mined and thus often classified as a group, despite having varied properties and uses. In electronics, they are valued for their use in strong permanent magnets, as well as in lamp phosphors in display screens. Their concentration in electronics and thus in WEEE, however, is generally very small, making them costly and difficult to recover. For this reason, recycling of REs is extremely rare in China; in fact, less than 1% were recycled globally in 2011,[38] and that proportion remains low in the present. In WEEE, REs are found primarily in TVs (as lamp phosphors) and computers in permanent magnets in hard disks (Figure 9), while quantities used in mobile phones are considered negligible. Whether through formal or informal collection, rare earths in WEEE ended up either in landfills or waste stockpiles.

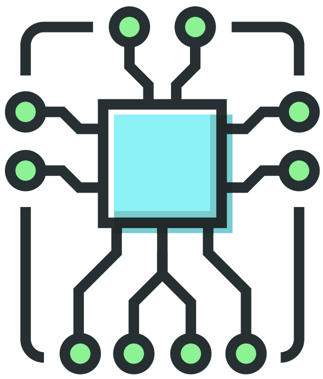
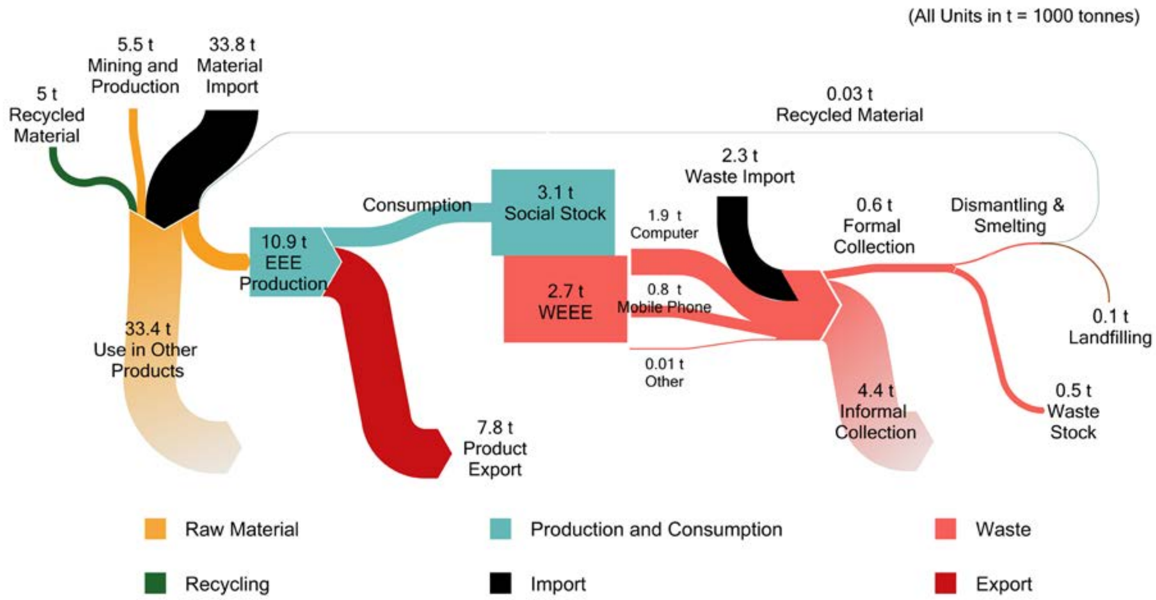


Figure 9: Material flow analysis for rare earths through the electronics life cycle, 2014



Note: This graphic illustration of flows, or Sankey diagram, has been separated into three main sections: production (yellow), consumption (blue), and waste disposal and recycling (red). Flows within each are drawn to scale, but flows between the sections are not proportional. Material flows were constructed using data from 2014 (the most recent available).
Source: Authors

Key findings from the material flow analysis

3

Three critical junctures along the waste value chain that determine recycling rates

Three major bottlenecks contributing to low formal recycling rates could be identified through the material flow analysis. The rates range from negligible for rare earths to just under 11% for aluminium.

1. **The informal sector dominates waste collection in China**

   Highly coveted on the Chinese market, WEEE is sold to those waste collectors offering the highest price.[17] On average across the four metals, 78% of waste metal in WEEE ended up in the informal recycling sector. While metals are still treated, informal recycling has several challenges. Outdated technologies extremely harmful to the environment are often used; they consist of open-air burning, acid leaching without safety measures, and indiscriminate dumping. Furthermore, resources are usually down-cycled into low-grade products, leading to inefficient reuse. While informal waste processing provides a basic livelihood for millions of workers, transitioning them towards safer and more efficient working conditions – through technology, training and support – can play an important role in enhancing the overall effectiveness and safety of the system while enhancing economic outcomes.

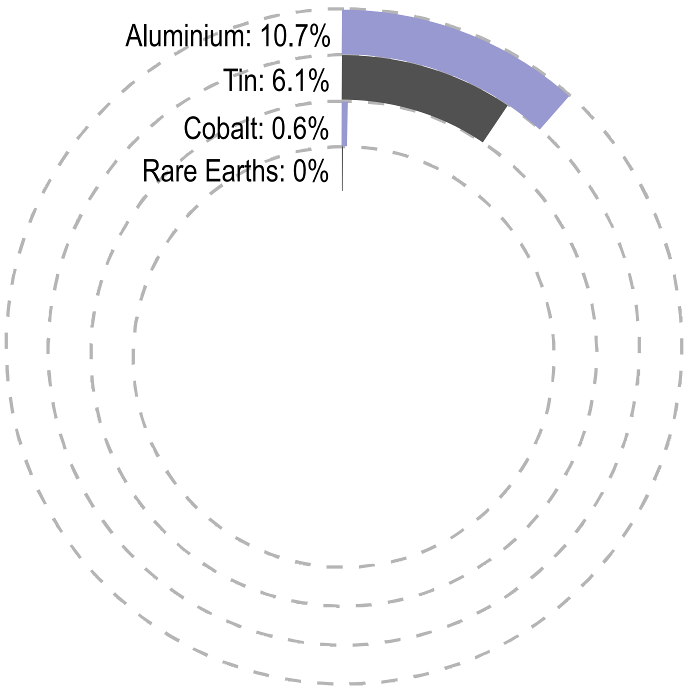
2. **Waste metals are stockpiled rather than recycled due to a lack of economic incentives**

   Low metal prices and high recycling costs create an unprofitable environment for recyclers and thus act as a major barrier to end-of-life recycling. Although the Chinese government has introduced subsidies to incentivize recycling, the system is fiscally unsustainable due to the high costs to the government and is undergoing improvements driven by new policy measures.

3. **Concentrations of metals in WEEE are very low, making them difficult to recover**

   While technologies for aluminium and tin recovery are quite mature with high end-of-life recovery rates (85% and 75%, respectively), recovery of rare earths is still in its technological infancy. Regardless, recycling rates of the four metal groups remain low at under 11% (Figure 10).

Figure 10: Recycling rates of key metals – a huge potential for improvement in the industry



Source: Authors

Circular potential of the four metal groups Al, Sn, Co and REs

By 2030, the selected metals in WEEE will reach 1.6 million tonnes. Using 2017 prices for each of the four metal groups,[39] their collective value is estimated to grow from close to $1.3 billion in 2014 to a total economic potential of $4.4 billion by 2030. Much of this concerns aluminium, which has one of the lowest prices of the four metal groups but makes up a much larger volume in the waste stream.

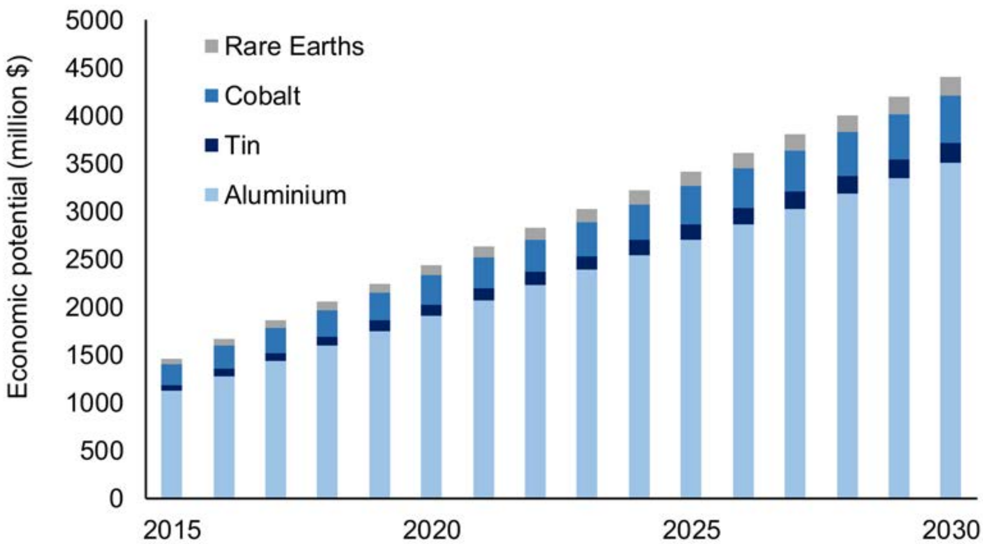
Assuming that 75% of the value can be recovered after losses from collection and recycling, the economic potential in 2030 becomes a more conservative $3.3 billion. This is still significantly higher than the $160 million recovered in 2014 and represents a huge opportunity to develop the WEEE recycling industry (Figure 11).

Environmental benefits of metal recycling

Besides its economic advantages, recycling also has significant environmental benefits. The need to move away from informal recycling, which can cause severe pollutant discharge to the environment, has already been discussed. Similarly, waste disposal in China is often uncontrolled. WEEE that ends up in garbage often has the same fate as open dumping and significantly contaminates soil and water via its heavy metals and flame retardants. Recycling can divert scraps from going to landfill, thus helping the broader environment.

Recycled metals further displace the demand for virgin production and mitigate a significant portion of the environmental effects involved in their mining, smelting and refining. Each kilogramme of REs mined in China, for example, can generate over 1 tonne of acidic waste water containing ammonia and thorium, and emits harmful substances to the air, such as hydrogen fluoride, sulphur dioxide and radioactive dust.[40] By contrast, the recycling of REs, it was found, lowers life cycle energy consumption by 88% and has a 98%-lower human toxicity potential.[41] Aluminium recycling is similar, as it only consumes 5-10% of the energy, emits 3% of the water pollution and generates 1-6% of the greenhouse gas emissions compared to bauxite mining and refining.[42,43]

Figure 11: Total economic potential of the four base metal groups to nearly triple by 2030



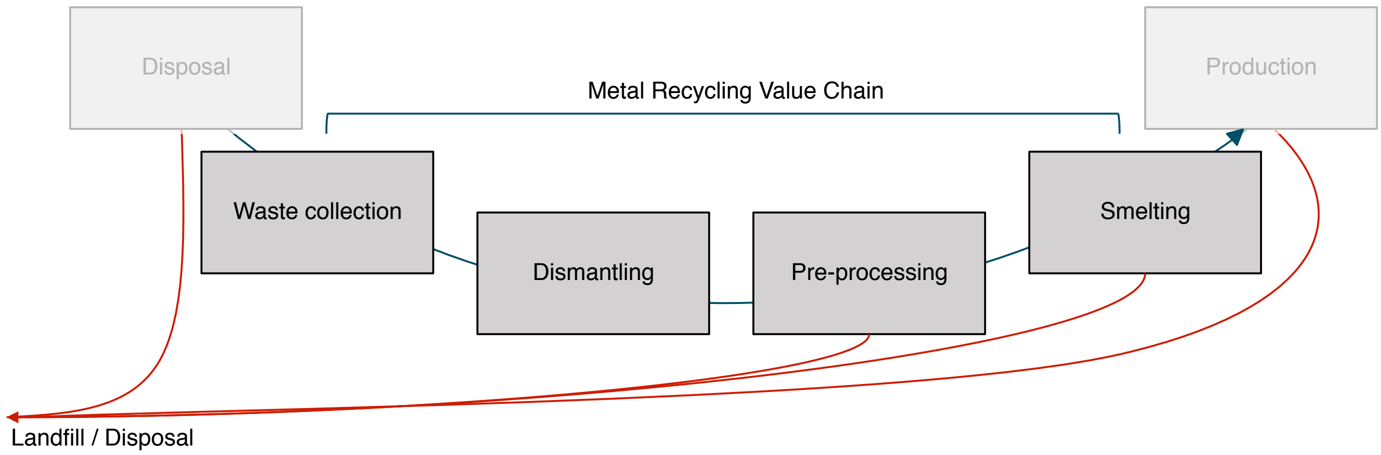
Source: Authors

The state of China's recycling industry

4

The metal recycling value chain (Figure 12) consists of four major steps: waste collection, dismantling, pre-processing and smelting.

Figure 12: Overview of WEEE recycling value chain



Source: Authors

Waste collection is the transfer of WEEE from consumers to the waste treatment value chain. E-wastes are generally collected as a mix with other waste types, and then separated into their different waste categories (paper, plastic, WEEE) for further treatment.

Dismantling involves further breaking down waste to isolate high-value parts to be sent for further resource recovery.

Pre-processing generally includes preliminary sorting of materials (automatic or manual), then shredding and separating them further into material categories for further processing. In this study, pre-processing and smelting are combined under the label "smelting".

Smelting is the process where metals are recovered from the waste and then refined into usable grades.

Informal sector collection and recycling

Chinese residents have two main incentives to sell WEEE to informal collectors. The first is convenience. Peddlers, who make up a large part of the informal sector, often go door to door to collect waste and/or provide a telephone number for residents to recycle waste on demand. The second and more prevalent[17] incentive is economics. The informal recycling value chain has lower costs from top to bottom than formal recycling (no registration, no regulation, no tax), meaning informal recyclers can offer a higher price for WEEE while staying within a margin for profit. Competing against the informal sector is thus very difficult without regulatory and/or financial support from the government.

Sorting and separating WEEE in the informal sector is not unlike the same processes in the formal sector. Collected goods that are still usable are resold on the second-hand market for refurbishing or direct sales to consumers. Goods with little to no value are sent to distributors, who act as middlemen for formal dismantling companies or informal smelters. While no official data have been collected on the proportion going to each, material flow analyses of waste suggest that the amount of material processed by informal recyclers is significantly higher.

The complex relationship between formal/informal collection, dismantling and smelting can be shown using mobile phones (Figure 13). Only 2% of mobile phones are collected formally, usually through product takeback programmes. Their destination after formal recycling, however, is not fixed; they may be sent to either formal- or informal-sector dismantling and smelting. For mobile phones, formal recycling is relatively low due to lack of subsidies. But the concept is the same for other types of WEEE, such as TVs and computers, whereby the line is blurred between the formal and informal sectors.

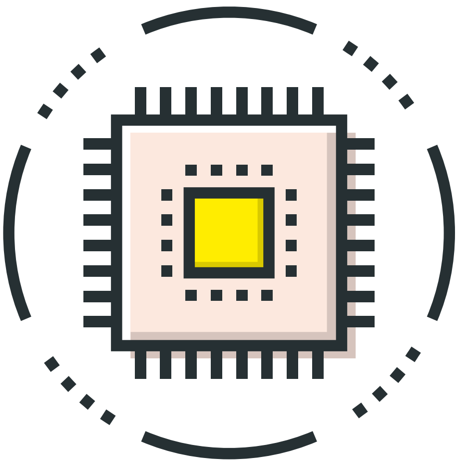
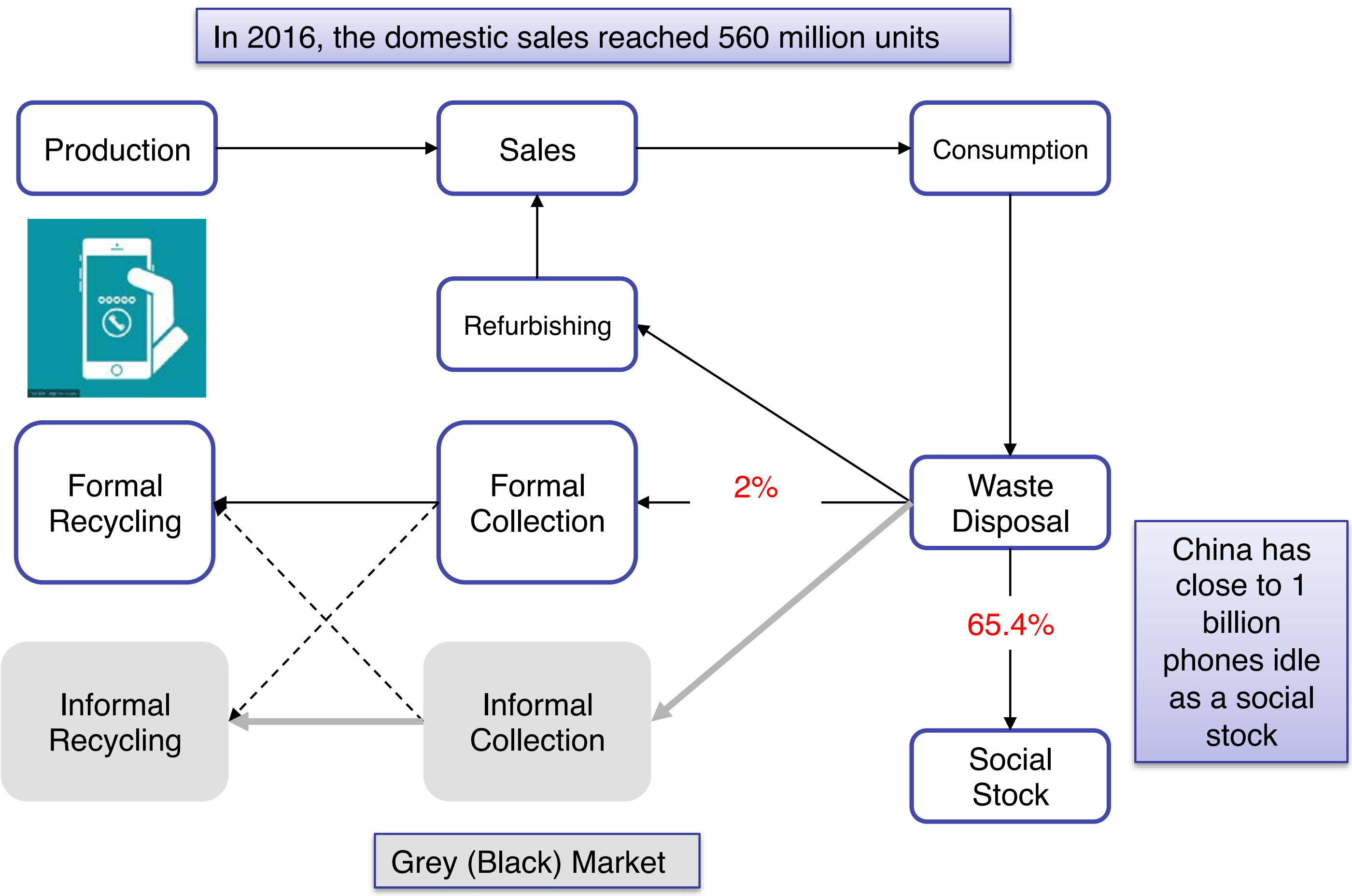


Figure 13: Product life cycle for mobile phones in China



Source: Authors

Informal WEEE dismantling and smelting are not regulated by the government and often consist of primitive methods to separate and recover valuable metals. These include open burning of wires and circuit boards to recover metals, acidic chemical stripping along waterways, and open indiscriminate dumping of toxic material.[18] Operations are often clustered in certain regions, with major centres in Zhejiang, Hebei, Hunan and Jiangxi. The province with by far the largest informal recycling sector is Guangdong. The city of Guiyu, with a population estimated at 250,000, is a prototypical example of WEEE recycling. In 2013, it was home to 300 companies and 3,000 individual workshops engaged in predominantly WEEE recycling.[18]

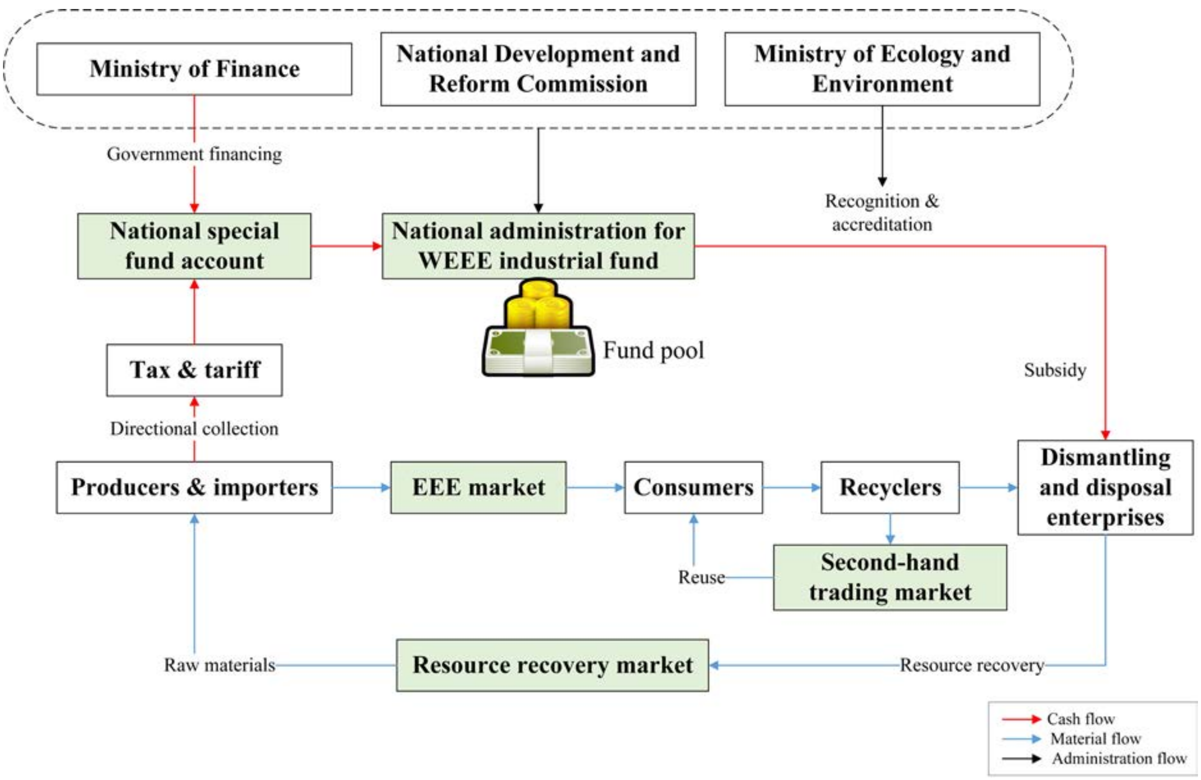
Nationwide, an estimated 18 million people (1-2% of the population) work in the informal waste collection sector. The number working specifically with waste electronics is harder to discern, as collectors often gather several types of waste and separate them into different waste streams: for example, plastics for plastic recyclers, and paper for paper recyclers. Eliminating an industry that supplies income and livelihoods to such a significant portion of the population would risk creating other social problems; thus, focus has shifted from abolishing informal recycling to integrating it with the formal sector. In the city of Suzhou, the government has formed a public-private cooperative to use informal waste collection channels and drive collected recyclable waste to formal processing facilities. In Guiyu, the local government has set up an industrial park to consolidate informal WEEE dismantling and smelting, giving those involved a dedicated space to operate and at the same time increasing regulatory enforcement of waste processing.

Extended producer responsibility as the basis of the formal recycling system for WEEE

The waste management system for waste electronics (Figure 14) is centred on the WEEE treatment fund, which is jointly administered by the NDRC, the Ministry of Finance (MOF) and the MEE. Taxes and tariffs on electronics producers' domestic sales and/or imports, serving as payments into the fund, are sent to the MOF and earmarked expressly for WEEE management and recycling. The MEE distributes funds through its local branches, which audit recycling enterprises to determine where subsidies should be appropriated. In the end, funds are distributed to formal recycling enterprises (responsible for dismantling) as a subsidy for proper treatment of WEEE. They pass on the subsidy to collectors by buying waste, or by developing their own collection systems.

Unfortunately, several drawbacks still exist within the current system. For one, subsidies are only applicable for the first batch of five product categories. While this encompasses most of the WEEE generated, it still leaves a significant portion of waste electronics and their embedded resources unaccounted for in the waste value chain. Furthermore, the fund had a running deficit to the central government of almost RMB 6 billion (Chinese renminbi), or roughly $923 million, in the 2012-2015 period,[44] suggesting a lack of long-term sustainability. For example, producers pay only RMB 13 to the fund for each TV, while the fund pays out RMB 85 to dismantling companies in subsidies.[45]

Figure 14: Subsidy management system for WEEE in China

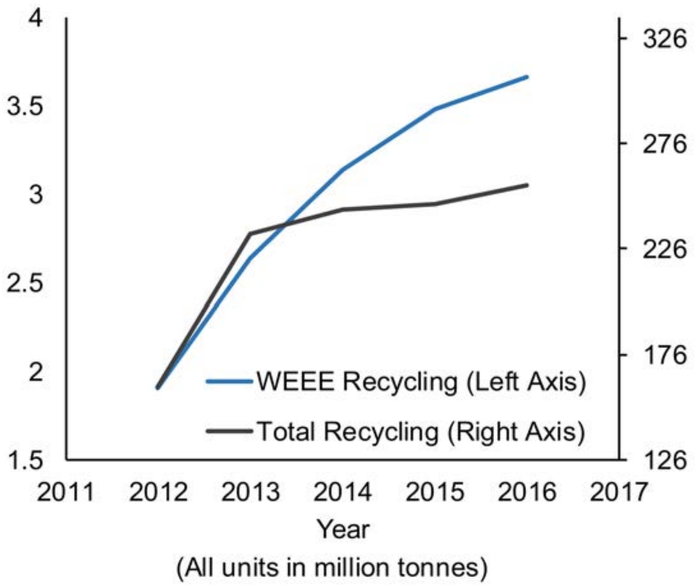


Source: Authors

Growth in formal recycling: From 36 to 109 registered enterprises

Growth over the past five years in WEEE recycling has been faster compared to 10 other waste categories, including cars, paper and plastics,[45,46,47] due in large part to a boost from the government's Old for New programme. Launched in 2011, the programme offers subsidies for WEEE recycling to channel more waste products through the formal sector (Figure 15). Since then, the number of formal WEEE recycling enterprises registered with China's MEE has grown from 36 in 2012 to 109 in 2017.[48,49]

Figure 15: Growth in recycling – WEEE vs 10 major waste categories



Note: Total Recycling includes WEEE Recycling.
Sources: Ministry of Commerce Circulation Development Division and China Material Recycling Association, 2013, 2015 and 2017

The capacity of WEEE dismantling for registered enterprises ranges between 5,000 and 135,000 tonnes annually. The interquartile range[50] is between 18,000 and 48,000 tonnes per year, suggesting that most facilities are on the smaller end. The Herfindahl-Hirschman Index[51] for the list of enterprises is 146 (based on recycling capacity) and indicates an extremely decentralized market. The list includes subsidiaries of larger groups, however, and thus over-represents the actual number of actors in the industry. According to Keli Yu, Secretary-General, E-Waste Division, China Resource Recycling Association, the WEEE recycling industry is in fact fairly concentrated. Major enterprises include GEM (operating 7 facilities), Sound Group (11 facilities) and China Recycling Development Corporation (8 facilities) (Figure 16). Altogether, he estimates six enterprises account for about 60% of WEEE dismantling in China.

Figure 16: Recycling capacity of top three WEEE recycling companies in China

Enterprise	Dismantling capacity (million units)	Estimated dismantling capacity (thousand tonnes)	Market share (%)
GEM Co.[52]	15.0	40.0	10.0
Sound Group[53]	22.6	44.0	14.0
China Recycling Development Corp.*	23.1	61.6	15.0

* Estimated based on companies registered with the MEE[48]
Source: Authors

China's annual dismantling capacity for WEEE of 4.2 million tonnes, a slight excess in capacity given the amount currently processed through formal recycling channels, is still considerably lower than the 11 million tonnes theoretically produced in 2016 (Figure 17). The remaining 6.8 million tonnes are sent to the informal sector; some of that is recycled, and some is disposed of. As with most industries, recycling is more developed in eastern China, correlating to a higher GDP per capita and thus a higher generation of WEEE compared to other regions. Indications are, however, that this geographic divide is starting to narrow, as both industrialization and urbanization are projected to gain a strong foothold in western regions by 2020.[54]

With WEEE generation set to grow to almost 30 million tonnes annually by 2030, recycling capacity will need to grow considerably to keep up. Even with linear growth, and with formal recycling maintaining its proportion of total WEEE treated, capacity will need to more than double to 10 million tonnes. For its part, the Chinese government is targeting even greater growth to displace more of the informal sector and more ambitiously meet its recycling and environmental protection targets. For example, achieving 50% WEEE recycling by 2025 translates into 9.4 million tonnes of treatment, requiring 100% growth of the industry.

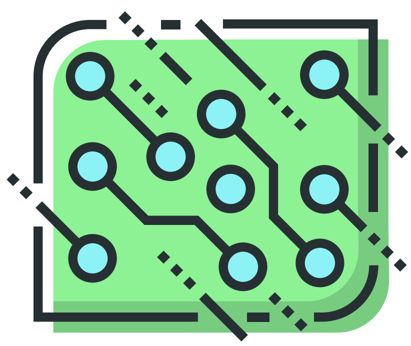
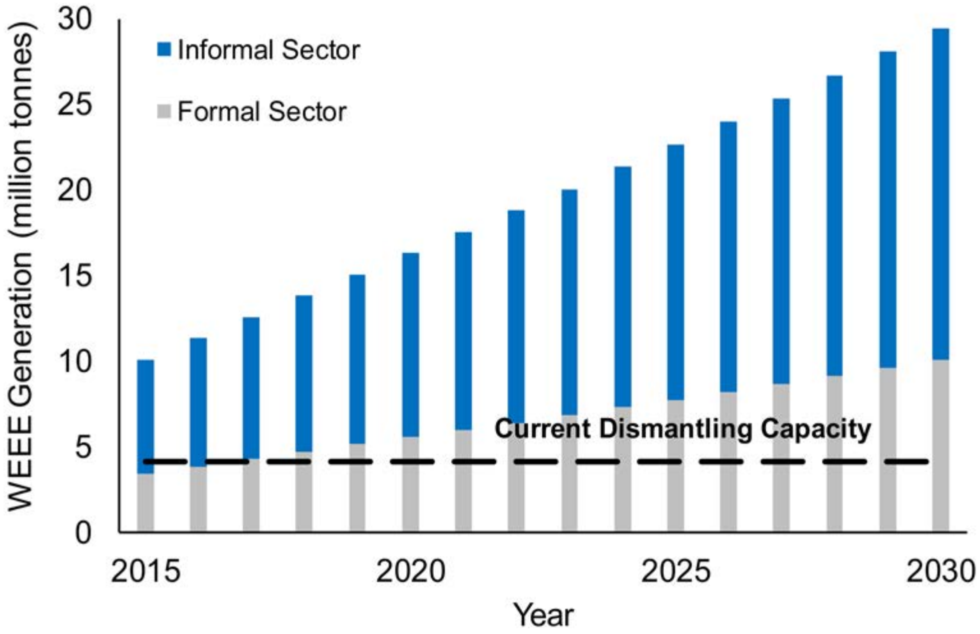
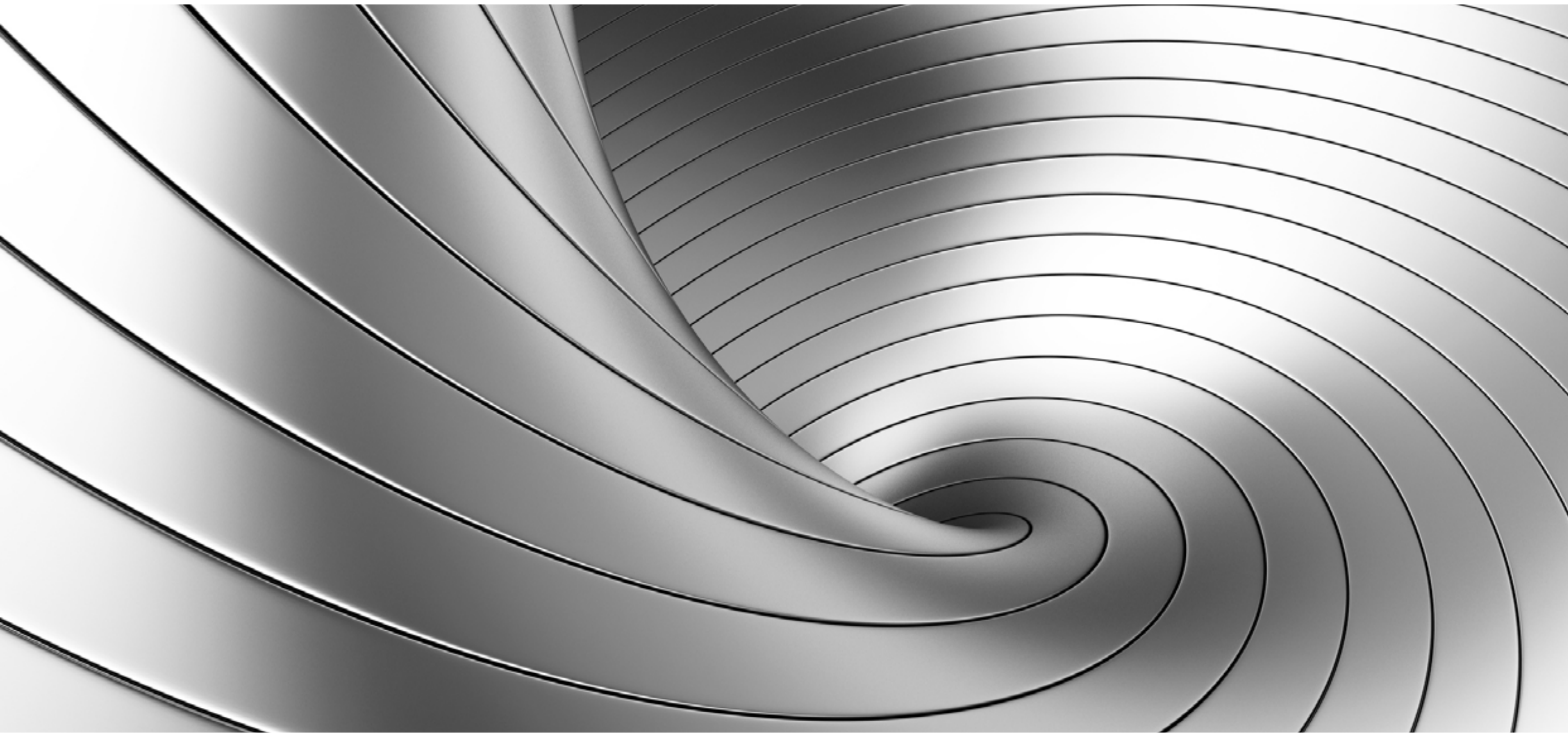


Figure 17: Projected WEEE generation in China against formal and informal sector collection and recycling



Note: The informal sector refers to the informal collection of WEEE. The fate of WEEE further downstream is unknown. The formal sector refers to dismantled WEEE.
Sources: Zeng Xianlai, Gong Ruying, Chen Weiqiang and Li Jinhui, "Uncovering the Recycling Potential of 'New' WEEE in China", *Environmental Science & Technology*, 50, 2016, pp. 1347-1358; China Ministry of Ecology and Environment (Ministry of Environmental Protection). *Waste electrical and electronic products processing enterprises across the country* (in Chinese), Waste Electronics and Electrical Equipment Treatment Information Network, 2017, http://weee.mepscc.cn/Index.do?method=flow



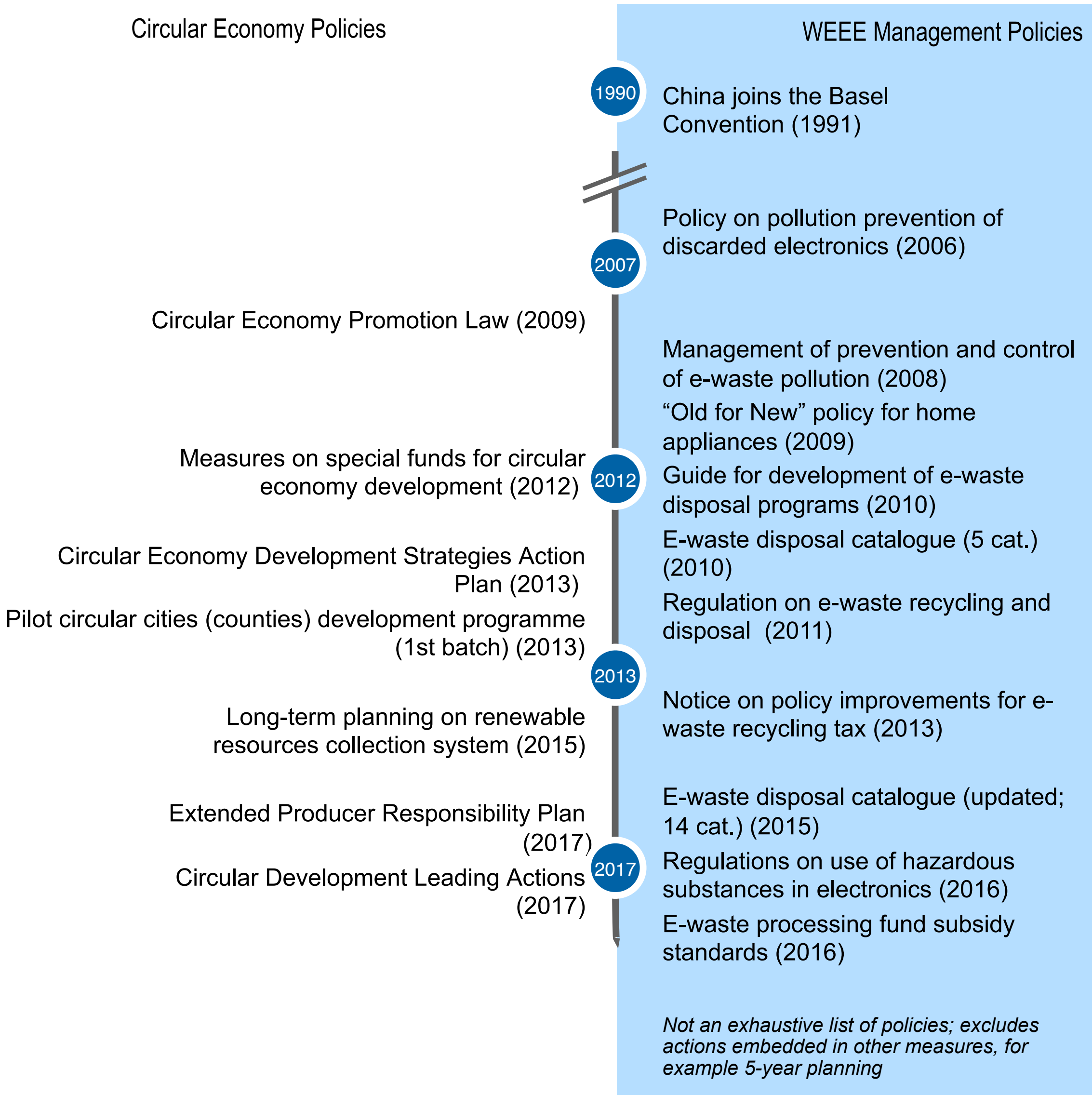
China's policy environment for e-waste

5

Recent top-down development of China's recycling sector

China's shift towards circularity began as a national policy objective.[55] The country has a short but intense history of circular economy policies designed to transform the country (Figure 18), officially starting with the State Council's Circular Economy Promotion Law (2009). The Promotion Law launched a series of direct measures to spur circular development in China, including the Circular Economy Development Strategies Action Plan (2013) that established the 100 Circular Pilot Cities Program and the Urban Mining Pilot Bases Program (both part of the 12th Five-Year Plan), and more recently the Extended Producer Responsibility System Implementation Plan (2017) [also referred to in this report in shortened form as the Extended Producer Responsibility Plan (2017)].

Figure 18: Development of circular economy and WEEE management policies



Source: Authors

E-waste management has a much longer history, starting with China joining the Basel Convention in 1990 to regulate the flows of hazardous waste (including WEEE) imported into the country. However, it was not until 2006 that the MEE (then known as the State Environmental Protection Agency) passed ad hoc national legislation on preventing WEEE pollution. Since then, the Chinese government has implemented several measures to promote recycling of WEEE, such as the Old for New programme for home appliances, which resulted in drastic increases in WEEE recycling in the pilot year (2011) when it was well funded. The focus of the past several years was on developing extended producer responsibility to ensure the programme's financial sustainability for the future and on expanding the programme across additional key waste categories.

Two new policies in particular are set to drive further development of WEEE recycling. The Extended Producer Responsibility Plan (2017) lays out a roadmap to 2020 for connecting the product value chain from production to waste treatment and disposal. Circular Development Leading Actions (2017) is a broader policy piece that promotes development of the recycling industry as a whole. Several parts of the plan have targeted WEEE recycling, improvements to the extended producer responsibility (EPR) system, policy support for remanufacturing, and support for regional recycling systems. No specifics were given for either policy, except that they will start with several demonstration projects prior to full-scale dissemination. Together, these plans point to a supportive policy environment for WEEE recycling and a government willing to adopt new trends in circularity.

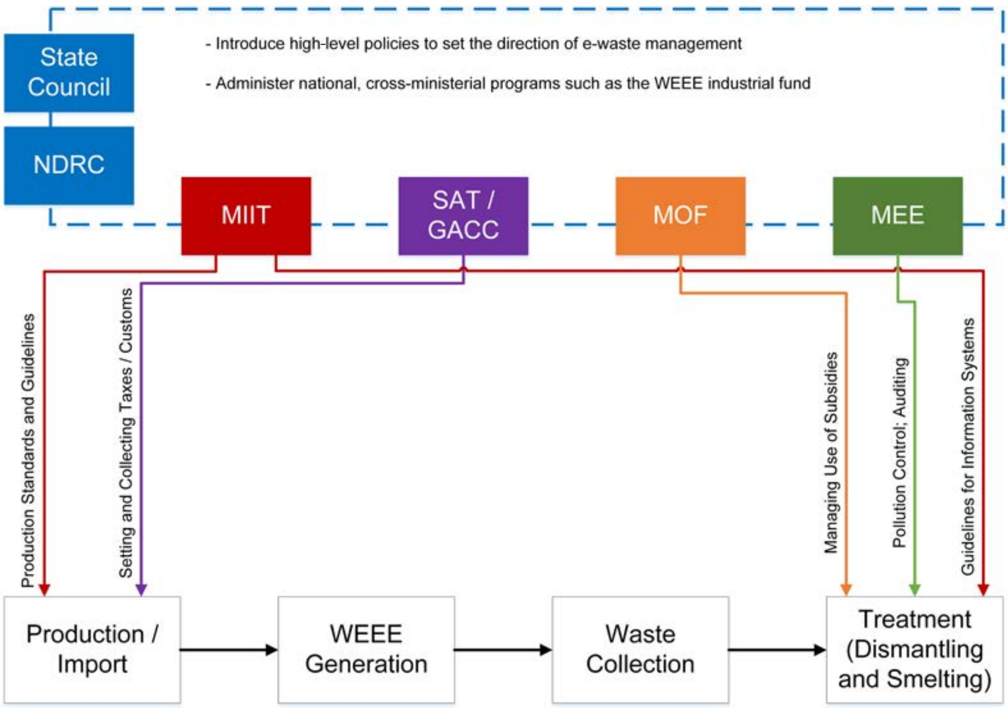
WEEE management regulatory framework

Several ministries are involved in policy-making and management of formal WEEE recycling in China. At the highest levels, the State Council and National Development Reform Commission set the overall tone and direction for WEEE management. Key ministries are also involved in managing and overseeing WEEE flows from consumers to recyclers (Figure 19).

As electronic products are used, discarded and recycled, they pass through several actors: from producers and importers to consumers, then to waste collectors and eventually to recycling enterprises, where they are disassembled and recycled. Five ministries have a role in managing this value chain:

- The Ministry of Industry and Information Technology (MIIT) ensures adherence to local regulations and standards by monitoring producers and importers. It is also responsible for implementing data collection systems used to audit recyclers.
- The State Administration of Taxation (SAT) and the General Administration of Customs of the People's Republic of China (GACC) levy EPR fees on producers and importers. These are payed as taxes or customs charges and calculated according to domestic sales and/or import volumes.
- The MOF receives these fees and allocates them towards waste management.
- The MEE receives the data collected by the MIIT and uses it to calculate and distribute subsidies. It is also responsible for auditing the dismantling and recycling enterprises to ensure they comply with environmental standards.

Figure 19: Organization of regulatory bodies managing WEEE in China



Note: NDRC = National Development and Reform Commission; MIIT = Ministry of Industry and Information Technology; SAT = State Administration of Taxation; GACC = General Administration of Customs of the People's Republic of China; MOF = Ministry of Finance; MEE = Ministry of Ecology and Environment
Source: Authors

New developments in the circular economy: Extended producer responsibility plan

The historical development of EPR regarding WEEE in China can be broken down into two phases.[48] During the first or preparatory stage (2009-2012), China established a pilot subsidy system under the Old for New policy for collecting and treating WEEE in the first-batch Product Catalogue (2011). Subsidies were given for both the collection and treatment of waste and drove a large portion of the market to formal avenues. In 2011, 56 million units of WEEE were collected by formal dismantling enterprises, accounting for an estimated 85% of the theoretical potential in that year vs just 33% for 2010. Unfortunately, once the subsidies were scaled back, the recycling rate dropped back down to 36% in 2012, highlighting the programme's lack of long-term financial sustainability.

Two major developments started to emerge at the beginning of 2012. For one, China released a series of policies to regulate and support formal dismantling and recycling enterprises. These recyclers received permits to legally work and receive subsidies from the central government. Currently, 109 enterprises are formally registered for WEEE dismantling. In the other development, the government began collecting fees from producers (in the form of taxes) to subsidize downstream waste collection and treatment activities. However, several issues persisted with the programme, and subsidies paid out still vastly exceeded the amount collected from producers. The system in this form has existed up to today, with minimal changes.

In the second phase (post 2012), the second-batch Product Catalogue was released in 2015 with nine additional WEEE categories, indicating the government's intent to include these product categories within the formal recycling system. In 2017, China's State Council released the Extended Producer Responsibility System Implementation Plan, which lays out a roadmap to 2020. The plan focuses primarily on four sectors: electronics, automobiles, lead-acid batteries and packaging products. The goal for 2020 is to reach a 40% recycling rate for these products. The plan aims to increase that rate to 50% by 2025 and achieve a rate of 20% of recycled materials used in production. Transformative to the industry, the plan targets production-side issues, such as eco-design and improving the use of recycled materials. While measures to assess progress of these indicators have not been laid out, Keli Yu of the China Resource Recycling Association indicates that they might be based on evaluating smelters and recyclers, and labelling their products as certified recycled materials.

The electronics industry was highlighted, and several key areas were singled out for development. These included improving the current EPR subsidy system, using information technology ("internet+") to facilitate integration with existing supply and collection chains, and emphasizing eco-design.

New developments in the circular economy: Guiding action plan

Released in July 2017 under the 13th Five-Year Plan, the Circular Development Leading Actions (Leading Actions) is a broader policy piece that lays out the development of the recycling industry as a whole. Several parts of it are linked to WEEE recycling, such as implementing EPR, establishing a robust recycling system, providing policy supports for remanufacturing, developing regional recycling systems and promoting the use of recycled materials. A more detailed description of those parts of the plan related to WEEE recycling follows:

Clause 11 – Recycling system construction. The Leading Actions will promote the construction of reverse logistics systems using the supply chain of traditional sales companies, engage with e-commerce and logistics companies, test recycling machines and incorporate internet+/internet of things recycling network with renewable resources. Together, the goal is to open up different avenues for waste collection, and ultimately to increase recycling rates. The Leading Actions will further strengthen household waste separation, recycling systems and recycling of renewable resources, promoting the convergence of the two networks. At a systemic level, the Leading Actions reference urban mining demonstration bases and their importance in improving the quality of recycled products and efficiency of recycling processes. Informal WEEE collection and recycling will be agglomerated into larger enterprises to regulate best practices and environmental standards. Further, guidance will be given to recycling enterprises, likely in the form of shared research and best practice standards for the industry. New waste types are listed, including solar voltaic modules, batteries and energy-efficient light bulbs. A pilot project will be developed targeting the collection and processing of these wastes.

Clause 12 – Remanufacturing industry. The Leading Actions will support standardization and large-scale development of the remanufacturing industry. As it relates to electronics, this refers primarily to large mechanical and electrical products (e.g. office equipment). A list of restrictions on remanufacturing will be established, and a review will be conducted on the rules restricting the circulation of remanufactured products. The Leading Actions will look to encourage the sale and use of remanufactured products and to continue support of a number of successful industrial bases that remanufacture waste.

Clause 13 – Development of mega-scale recycling systems. A large focus is on urban agglomerates, such as the Beijing-Tianjin-Hebei area, the Yangtze River Delta, the Pearl River Delta and the Chengdu-Chongqing economic zone. The Leading Actions will promote the construction of a recycling system suitable for these mega areas where a higher concentration of waste, including e-waste, is generated. Overall plans include the recycling and treatment of industrial solid waste, renewable resources and household garbage. While WEEE was not referenced directly, it will undoubtedly be included in overall plans.

Clause 14 – Extended producer responsibility. The Leading Actions reinforce the framework for the Extended Producer Responsibility System Implementation Plan (2017), emphasizing the development of regional pilot projects to test EPR and promote eco-design. Going into further depth on the system and mechanisms for implementation, the Leading Actions include establishing the following: third-party management systems for recycling, a credit evaluation system to assess the performance of producers treating WEEE and of producers treating waste in other select industries, an improved system for collecting fees and issuing subsidies, and annual reporting for EPR development in China.

Clause 15 – Sourcing recycled materials. The Chinese government will take the lead in using recycled materials by updating its procurement system to give priority to recycled and remanufactured products, particularly for electronic goods. Other measures include disseminating standards and catalogues of recycled products or materials to make it easier for enterprises to source recycled materials.

Transboundary flows of waste: Increasingly regulated

China became a party to the Basel Convention in 1991, cooperating with the international community to regulate imports and exports of restricted waste. This was followed up with stronger domestic regulations in the *Solid Waste Import Management Measures* (2011) and *Imported Solid Wastes Catalogue*, which was first published in 2008, then modified in 2015, 2017 and 2018. Together, these measures prohibit imports of most waste into China.

The 2015 catalogue separates wastes into three categories: waste strictly prohibited from importation, waste restricted as imports, and waste exempt from regulation. According to the policy, waste electronics and machinery are generally strictly prohibited from being imported into China, including electronic parts and disassembled wastes. Specific items include household appliances, computers and audio-visual products. Wastes that have undergone considerable processing can be reclassified as raw material, and thus imported.

Other items with a greater potential for high-value recycling, including electrical hardware appliances, such as waste motors and wires, were initially classified as restricted items for import. While their import was permitted, they were regulated by the MEE and required pre-shipment and arrival inspection by an inspection agency. Surveys of enterprises in China have found, however, that interpretation of policies can be inconsistent between regions, and that moving restricted wastes across borders can be difficult despite being technically allowed. In 2018, the MEE published the *Announcement on Adjustment to the Catalogue for the Administration of Import Solid Waste* (Announcement No. 6 of 2018), moving even high-value waste electronics to the strictly prohibited list. In particular, this included waste wires, motors and machinery for the primary purpose of recovering the base metals copper, aluminium and steel. These changes will come into effect at the end of 2018.

Second-hand electronic products are not covered by the waste legislation; rather, they are regulated by the Ministry of Commerce, primarily under the Electronic Import Measures (2008) policy. Three categories were created in 2015 to group how imports of second-hand electronic equipment are treated: those strictly prohibited, those restricted, and those automatically permitted. Very old equipment, for example that which includes chlorofluorocarbon refrigerants, is prohibited. Larger industrial and commercial equipment is restricted and requires permitting before imports are allowed. Most electronics used daily, such as refrigerators and air conditioners, are automatically permitted and are subject to the results of quarantine and inspections.

Despite strict regulations, up to 462,000 tonnes of WEEE are estimated to be imported illegally every year.[16] A report published by the United Nations University StEP programme identified three pathways for transboundary WEEE shipments into China:[18]

- **Direct shipments to Chinese ports**: This method is becoming rarer due to stricter enforcement at the border and increased cooperation with the international community.
- **Mixed shipments with other scraps**: Recyclers have frequently reported opening shipments of WEEE mixed with other scrap material. The WEEE fraction can be 10% of the mix and is often shredded into fine particles and blended into the mix, making it difficult to separate and process further.
- **Transit through a third country or region**: Hong Kong and Viet Nam are known hubs for redirecting electronic wastes to mainland China. In Hong Kong, WEEE may be relabelled as local waste or as second-hand electronic goods and reshipped to mainland China. In the case of Viet Nam, WEEE may also be falsely labelled as a second-hand electronic product; or, due to geographic proximity, smugglers may simply move the waste across the border with China at night.

Perhaps for these reasons, and particularly for mixed shipments of WEEE with other scraps, the MEE has moved to more strongly enforce regulations on waste imports of scrap metals and electrical equipment, despite their potential value. Over 2017 and 2018, the ministry published updates to the *Imported Solid Wastes Catalogue* (Announcement No. 39 of 2017 and Announcement No. 6 of 2018), which expanded the number of wastes and scraps on the prohibited and restricted lists, including paper, plastic, and certain ferrous and non-ferrous metals. The changes, some of which already came into effect in early 2018, were accompanied by a notice to the World Trade Organization emphasizing the ban.[56] More changes will take effect in 2019.

Principles of the Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (the Basel Convention) was adopted in 1989 and entered into force in 1992. It has jurisdiction over waste in two categories: "Hazardous waste" is identified in Annexes I and VII, as well as determined by national legislation of the Contracting Parties; and "Other waste", identified in Annex II, includes waste collected from households and residues arising from incineration of household waste. At its core, the Basel Convention has implemented the Prior Informed Consent Procedure, which stipulates that exporting countries are required to submit prior notice for importing countries to accept before transboundary movements of hazardous waste are allowed. All transboundary movements must also be properly documented to be considered legal. This is to ensure that importing countries wilfully accept the wastes, and that environmentally sound management has been agreed upon.

The special case of bonded zones: Regulatory mechanisms

Bonded zones are trade zones in China with special regulations for import/exports, duties and supervision. For example, goods can enter bonded zones without paying duties, but if they are shipped to the mainland, they are subject to domestic regulations and duties that would normally apply to imports. Wastes produced in the bonded zone are a source of controversy. With regard to goods shipped into bonded zones for the purpose of refurbishing, the Chinese government's stance in principle is that China should not bear the unwanted waste burden produced abroad. Rather, waste produced from refurbishing processes should be shipped back to its country of origin. On the other hand, enterprises find this process expensive, that it can actually do more life-cycle harm to the environment than treating waste domestically, and that it misses out on potential economic benefits. A list of policies for manufacturing and refurbishing in bonded zones, as they relate to WEEE flows, is provided in Figure 20.

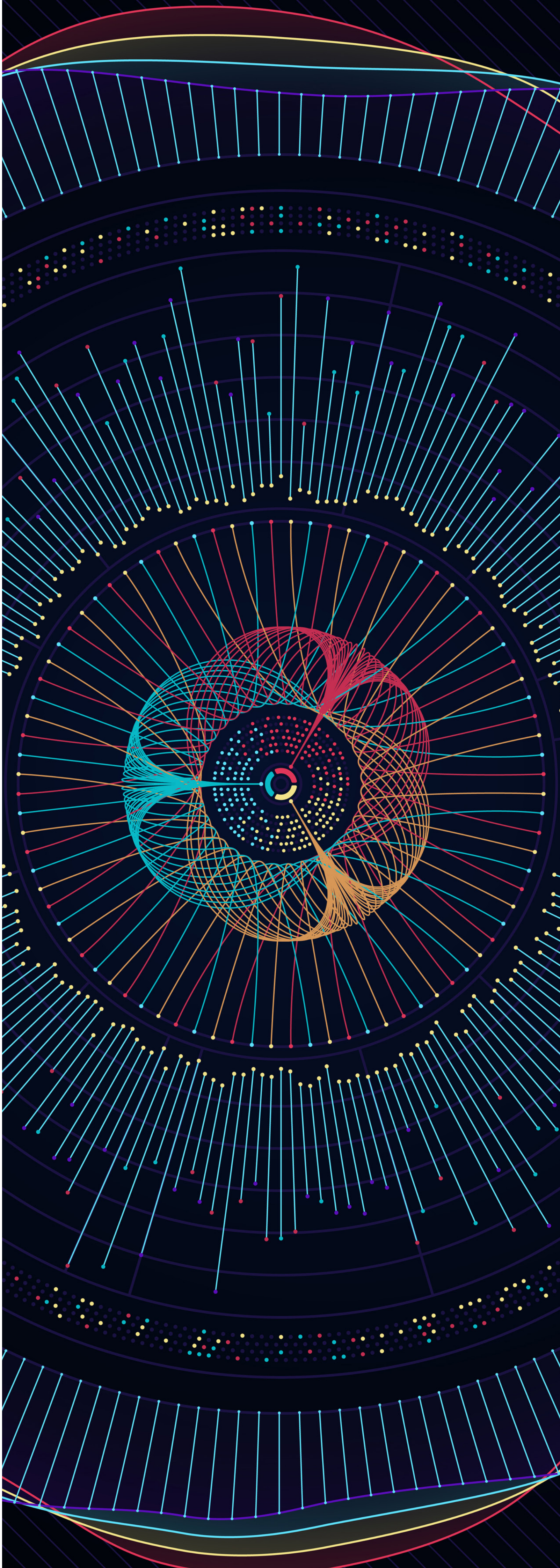


Figure 20: Relevant policies and notices on the regulation of bonded zones

Year	Policies and Notices
2015	Notice on Regulatory Issues Concerning Bonded Refurbishing and Maintenance Activities in Special Customs Supervision Zones
2014	Interim Measures for the Administration of Customs Bonded Port Area (Comprehensive Bonded Area) of the People's Republic of China (Order No. 191)
2010	Interim Measures for the Administration of China's Customs Bonded Port Area
2009	Notice of the General Administration of Quality Supervision, Inspection and Quarantine of the Ministry of Commerce of the General Administration of Customs on Issues Concerning the Disposal of Trimmings, Scrap and Residues in Export Processing Zones
2006	Customs Bonded Logistics Park Management Measures in the People’s Republic of China
2005	Measures on Administering the Taxation of Import and Export Goods in the People’s Republic of China
2005	General Administration of Customs Order No. 111 (Measures of the Customs of the People's Republic of China on the Administration of Extrusions, Residual Materials, Residues, By-Products and Damaged Bonded Goods in Processing Trade)
2005	Interim Measures for the Administration of Processing Trade in Export Processing Zones

Source: Authors

In principle, all waste and leftover scraps produced from refurbishing should also be re-exported back to the country from which products were imported. In cases where export is not possible, enterprises can apply for the waste to be transported to the Chinese mainland for handling and treatment. Regulations allow for non-hazardous scraps to be moved from bonded zones into the mainland with written approval from local authorities. In practice, however, there have been cases where movements of recyclable, non-hazardous waste across bonded zones have been unsuccessful. Additionally, taxes should be considered (and paid) as standard imports that enter the country; they are sometimes applied to scrap materials as if they were finished goods, changing the economics of recycling. Any hazardous waste must be reported to and approved by the local bureau for environmental protection, and proper documentation needs to be shown to customs as it is moved across borders.

As to refurbishing plants, imported equipment and parts are not subject to additional permits and licensing beyond customs declaration procedures. When declaring goods at customs, the importing party must also submit the maintenance contract and import tax guarantee to relevant authorities. This applies to all equipment, parts and raw materials used for maintenance (parts and raw materials imported for maintenance can only be used for this purpose and in this field). All equipment, parts and materials must be re-exported after the allotted time frame, which can constrain the reuse and recycling of components from repair and precludes domestic recycling.

Byproducts and metal scraps to be sold in the Chinese market as goods are exempt from certain steps normally required when importing. These include obtaining permits and additional quarantining and inspection. However, they are subject to the same taxes and fees applied to standard imports, which again may be based on the value of the finished goods. Materials considered as solid waste can be grouped into two categories: restricted wastes, which are exempt from waste import permits and quarantine and inspections because they are sourced from a bonded zone; and prohibited wastes, for which a permit must be obtained from local authorities in the customs and environmental protection departments.

Surveys of enterprises have found that scrap metals from bonded zones may be subject to a virtual bidding system, where Chinese recyclers can bid for the recyclable materials. Unfortunately, this system also restricts enterprises from engaging directly with recyclers and smelters, and thereby limits them from achieving more customized, potentially closed-loop metal recycling.

So, while some restrictions exist, policies on imported waste from bonded zones broadly allow for the import of non-hazardous waste, and especially for those wastes that can be reused. Ultimately, however, each local MEE and customs authority must decide on the fate of waste imports, which has led to some uncertainty over how they are dealt with. Several enterprises have reported difficulties in dealing with waste from bonded zones, as it is handled differently across the country; thus, a uniform procedure for treatment cannot be developed. In this regard, the World Economic Forum is seeking involvement from higher-level authority (e.g. State Council) to coordinate among different ministries in defining clear roles and responsibilities, and to align the practical procedures of importing restricted/prohibited waste from bonded zones.

Interim Measures for the Administration of Customs Bonded Port Area (Comprehensive Bonded Area) of the People's Republic of China (Order No. 191) (2014):[57]

Article 23**:** Where the enterprises in the zone producing scrap materials and scrap products during processing, packaging, production, storage, transportation, etc. may, after submitting a written application and obtaining the approval of customs, be transported outside the area. The customs will be taxed according to the actual status of the district. Goods that have import quotas or require permit are exempt from import quotas and permits. Goods belonging to the list of "banned imports of wastes" and other hazardous wastes must submit relevant documentation from the local municipal environmental protection bureau to be approved by the customs procedures for the district.

Taxes on defective products and byproducts produced by the enterprises in the zone during the process of production and processing shall be levied according to the actual state of the domestic sales. For items that have an import quota, or permit management, enterprises should issue relevant documentation on the quotas and permits to the Customs.

On Changes to the Interim Measures for the Administration of Customs Bonded Port Area of the People's Republic of China (2010):[58]

Article 32: The enterprises applying for the maintenance business in the bonded port area shall have the qualifications of a legal enterprise and register with the Customs in charge of the bonded port area. The products maintained by the enterprises in the region are limited to the export of mechanical and electrical products in China. After repairing the products, the replacement parts and the materials produced during the maintenance process should be re-exported.

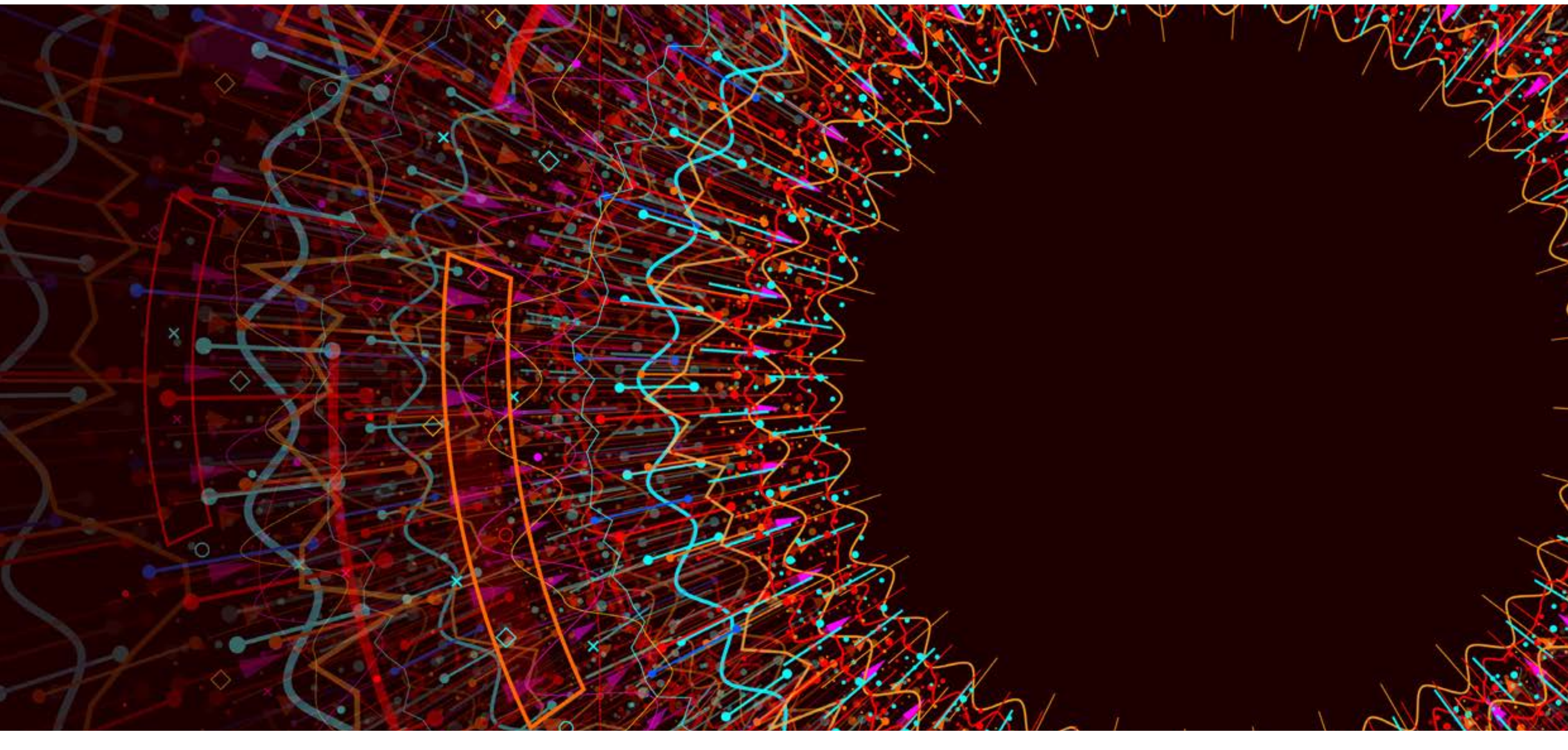
Customs Bonded Logistics Park Management Measures in the People's Republic of China (2005):[59]

Article 39: An enterprise applying for a maintenance business within a park shall have the qualification of a legal enterprise and be registered with the competent customs authorities of the park. Products and spare parts maintained by the park enterprises are limited to those from outside. After inspection, products, spare parts and the materials produced during the repair process shall be re-exported.

Article 8: Commercial retailing, unlicensed processing, refurbishment, dismantling and other businesses unrelated to the park shall not be carried out in the park.

Interim Measures for the Administration of Processing Trade in Export Processing Zones (2005):[60]

Article 15: After-sales maintenance of China's export of electromechanical products can be carried out in export processing zones. Before enterprises carry out maintenance work of electromechanical products in the export processing zone, and in addition to the provisions of Article 7 of these Measures for formal approval, enterprises will need to prove to the Management Committee that products under maintenance originate in China. Furthermore, the enterprise must be the manufacturer, or authorized by the manufacturer to carry out related maintenance business on the approved materials.



Conclusion

This study assessed the potential for circular development of the electronics industry in China, namely by quantifying the flows of four metals and metal groups prevalent in the industry, by breaking down the status of China's WEEE recycling, and by uncovering the policy environment for circular economy development, particularly within the electronics industry. An in-depth material flow analysis of aluminium, tin, cobalt and rare earths shows a relatively low formal recycling rate of key metals in the country, ranging from less than 1% (rare earths) to 10.9% (aluminium). This translates to a value of $199 million recovered in 2015 out of an estimated theoretical potential of $1.5 billion.

Recent trends show a positive outlook for the foundations of WEEE recycling (the infrastructure and policy support) in China, and therefore an increasing recovery of waste. At the same time, this study identified several key challenges and opportunities in scaling and for the long-term sustainability of the recycling system. The policy foundations in place include government programmes, namely the Old for New initiative, which has sought to build the economic case for WEEE recycling, attracting more businesses to develop recycling capacity. As a direct result of these programmes, WEEE recycling rates have grown faster than the average for other materials, and the number of WEEE dismantling enterprises has grown from 36 in 2012 to 109 in 2017, or an annual capacity of 4.2 million tonnes of WEEE.

In the future, other policies passed in 2017 aim to bolster extended producer responsibility and the circular economy for WEEE, such as by introducing ambitious targets for recycled content in new products, emphasizing eco-design and taking advantage of new technologies (e.g. the internet of things). This demonstrates an innovative "circular" approach, using solutions across the whole value chain while embracing technological and business model innovation.

To maintain this growth trend and fulfil targets, a number of barriers and opportunities must be addressed. Special attention is needed, for example, to ensure product quality in secondary raw materials and thus to integrate more recycled materials in new products. This may require bespoke partnerships between recyclers and manufacturers and a re-examination of smelting practices and waste regulation. Further research is also required on the role of other circular business models, such as repair and remanufacturing, in extending the life of electronics and therefore avoiding waste in the first place.

Another challenge in the value chain that needs attention is the accumulation of scrap metals as a waste stock at the point of dismantling and recycling. This suggests that even if a larger quantity of metal were to flow into formal recycling, it would continue to be a bottleneck. Several factors may contribute to low recovery during processing, including low concentration of metals in the waste, underdeveloped recycling technologies or a lack of infrastructure, and this requires further research to fully unpack them.

Moving upstream in the value chain, the informal sector dominates WEEE collection and is an inherently complex issue to address. Several pilot projects are under way across China to consolidate formal and informal recycling, and case studies from around the world, particularly from Egypt and Brazil, are providing lessons. Take-back programmes run by the private sector could also play a larger role in collection.

From a policy perspective, China's central government has shown increasing political will to push the circular economy in the country. In local government, one persisting concern is the uncertain interpretation of policy on waste flows into China. Many electronics manufacturers, for example, are based in bonded zones, where the movement of materials to specialized recyclers to reintegrate in their products continues to be an issue. Additional research could be useful to better understand how environmental protection bureaus and other local authorities address flows of waste across bonded zones.

Given these opportunities and challenges, the private sector and the government are strongly aligned to commit to a circular economy for the electronics industry. This study serves as a baseline contribution for a larger project aimed at catalysing public-private collaboration in WEEE recycling in China. It has already opened up the possibility for future research and economic modelling that go into more depth regarding recycling of the key metals.

The Platform for Accelerating the Circular Economy, a project accelerator and platform for public-private collaboration, will convene workshops with key stakeholders and experts from the electronics and recycling industry, industry associations, academia and government. The workshops will seek to create tailored recommendations to industry and government on how to jointly build a more circular electronics industry in China and globally. If seen as advantageous to the partners involved, this could evolve into a series of public-private pilot projects to test innovative strategies in reaching China's ambitious circular economy goals.

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744

contact@weforum.org
www.weforum.org