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Informal electronic waste recycling: A sector review with special focus on China

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ABSTRACT

Informal recycling is a new and expanding low cost recycling practice in managing Waste Electrical and Electronic Equipment (WEEE or e-waste). It occurs in many developing countries, including China, where current gaps in environmental management, high demand for second-hand electronic appliances and the norm of selling e-waste to individual collectors encourage the growth of a strong informal recycling sector. This paper gathers information on informal e-waste management, takes a look at its particular manifestations in China and identifies some of the main difficulties of the current Chinese approach. Informal e-waste recycling is not only associated with serious environmental and health impacts, but also the supply deficiency of formal recyclers and the safety problems of remanufactured electronic products. Experiences already show that simply prohibiting or competing with the informal collectors and informal recyclers is not an effective solution. New formal e-waste recycling systems should take existing informal sectors into account, and more policies need to be made to improve recycling rates, working conditions and the efficiency of involved informal players. A key issue for China's e-waste management is how to set up incentives for informal recyclers so as to reduce improper recycling activities and to divert more e-waste flow into the formal recycling sector.

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1. Introduction

The management of Waste Electrical and Electronic Equipment (WEEE or e-waste) in China creates its own particular set of environmental challenges, particularly considering China produces, exports and consumes the largest portion of global electrical and electronic equipment (EEE) (Yang, 2008). E-waste, being one of the largest sources of heavy metals and organic pollutants in municipal waste and the fastest growing waste stream, has become a serious problem in China and other Asian developing nations (Bertram et al., 2002). These countries not only generate tremendous amounts of domestic e-waste due to their fast consumption rates of electrical and electronic (EE) products, but also receive enormous quantities of used information technology (IT) devices from overseas (Brigden et al., 2008). In China, e-waste is largely recycled by the informal sector, where numerous waste recycle workers are hired at extremely low wages applying crude and pollutive recycling methods for separation of reusable components and quick recovery of contained metals. These backyard practices often take place under the most primitive circumstances, exposing workers to extensive health dangers (Williams, 2005).

Over the past decade China has made great efforts to advocate better e-waste collection and recycling in both public and private sector. There is noticeable increase in domestic and foreign investments into recycling field, accompanied by encouraged transfer of international recycling technologies and western waste management principles. Recycling industrial parks have been established in several cities with purpose of promoting efficient and environmentally-friendly recovery of original and imported metal scraps (Shinkuma and Huong, 2009). Some brand companies in EE industry, e.g. Nokia and Lenovo also took the lead in offering free take-back services of old products to Chinese consumers. At national level, four pilot projects were launched to gain institutional and technical experiences in regulation preparation and collection network design. Apart from infrastructure build-up and industrial practices, Chinese government has also introduced a set of e-waste management regulations, in response to its speedy e-waste generation and to regulations and actions on EEEs and WEEE in other countries, e.g. Japan, USA, Canada, Australia, particularly the WEEE Directive[1] and the RoHS Directive[2] of the European Union which have substantial impacts on the exports of Chinese EE

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[1] Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment.

[2] Directive 2002/95/EC of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

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products (Ongondo and Williams, 2009). Meanwhile, different local administrative measures on control of e-waste have also been put into effect in several regions including Beijing, Shanghai, Jiangsu province, Zhejiang province and Guangdong province.

Yet despite such legislative and market progress, collection of household EEEs in China remains dominated by the informal individual collectors – a type of specialized waste buyers who purchasing multifarious waste materials from households then selling collections to best price bidders afterwards. And informal recycling operation, being carried out through simple yet highly profitable workshop production manners and being driven by industrial demand for secondary materials and expanding rural markets for second-hand EEE, also grew up and flourish in areas such as Guiyu of Guangdong province and Taizhou of Zhejiang province, where large-scale primitive handlings of e-waste have been causing severe environmental and health consequences. Not surprisingly because the informal collectors and recyclers absorb the majority of e-waste from waste owners, extensive supply deficiency problems in the developing formal recycling sector occur (Tong et al., 2004; Hicks et al., 2005; Kojima et al., 2009).

This paper examines the diverse factors that contribute to the current state of informal recycling sector in China. Beginning with a review of literature on informal waste recycling, the paper goes onto describe the status quo of e-waste management in China from economic and regulatory perspectives. It then proceeds to explore the differences, similarities and overlapping of the formal and informal recycling sectors; analyzing why the informal recycling thrives and highlighting some major challenges China faces in e-waste recycling system development. Finally, the paper proposes an innovative and integrated e-waste management approach and points out a few key issues for future research of informal e-waste recycling.

2. Literature on informal waste recycling

The concept of an 'informal sector' originates from studies embedded within the context of a so called 'Third World', and has, since the late 1950s, become increasingly recognized as important (Hart, 1970). Although the constructed opposites of formality and informality have been a constant within development discourse for more than half a century, there is still no clear definition of the concept of 'informal' which consistently applies across the whole range of theoretical, empirical and policy analyses. The term 'informal' has often been characterized as being beyond the reach of different levels and mechanisms of official governance, lacking in regulation, structure and institutionalization, and as non-registered and illegal (Briassoulis, 1999; Guha-Khasnobis et al., 2006). Informal activities are persistent, universal and increasing, occurring in countries and regions with very different levels of economic development (Castells and Portes, 1989). Real or perceived deficiencies and structural flaws of the formal socio-economic, political and institutional system encourage the development of informal activities (Briassoulis, 1999).

Schneider and Enste (2003) group informal economic activities into self-sufficient economy (legal) and shadow economy (illegal) activities. According to their definition, the *informal sector* is part of the self-sufficient economy and executes legal activities. They subdivide the shadow economy or illegal sector into an *irregular sector* which produces illegally, but has legal output (goods or services), and a *criminal sector* which has illegal outputs (drugs or forgeries). Gerxhani (2004) summarizes the features of the informal economy into political, economic and social criterion. According to her, the most prominently used sub-criteria in literature are the economic ones. These are: (1) status of labor, (2) avoidance of income tax, (3) size of informal business and (4) evasion from registration and regulation. One also frequently applied political criterion is (5) avoidance of government regulation.

Early studies on the informal sector (1960–1970) considered it as a separate economic domain. Since then, however, mainstream theory has come to recognise the interdependency between formal and informal sectors. This dependence can be either complementary (e.g. via sub-contracting activities) or competitive (e.g. unregistered business activities where labor is cheaper and prices are lower). Schneider's (1998) work demonstrates that the informal economy in Germany and Austria makes a significant contribution to the economy of these countries as a whole. It also reports that at least two-thirds of the income earned in the 'shadow economy' (informal) is immediately spent in the official economy, resulting in considerable positive stimulating effects. Similar conclusion was drawn by Adam and Ginsburgh (1985) based on their Belgium case study.

In the recycling sector, the literature shows that informal waste recycling is carried out by poor and marginalized social groups who resort to scavenging and waste picking for income and survival (Wilson et al., 2006). It is reported that up to 2% of the population in Asian and Latin American cities depend on waste picking to earn their living (Medina, 2000). The task of waste collecting is undertaken by young and old of both sexes, made up of a combination of the urban poor and rural migrants (Mitchell, 2008). Informal waste recovery and recycling has been studied in many developing countries, such as Ghana (Brigden et al., 2008), Vietnam (Mitchell, 2008), Tanzania (Kaseva and Gupta, 1996), India (Agarwal et al., 2005; Streicher-Porte et al., 2005; Hayami et al., 2006) and Turkey (Tinmaz and Demir, 2006). Poor wages, low prices and an absence of environmental and overhead costs create viable profit margins from the collecting and selling of secondary raw materials (Porter, 2002).

Own investigations found that the formality or informality of waste recycle professions vary considerably from country to country, and these recycling professions also have very peculiar local appellations. Table 1 lists the local names of four waste profession types as well as their formal/informal status in nine selected developing countries. It can be seen that in many countries, certain professions possess both formal and informal attributes and therefore categorized as intermediate.

While literature sources do not provide much information about how informal recyclers are interacting or competing with their formal counterparts, within the informal sector scholars have been paying close attention to the services that informal waste professions in developing countries deliver to society. For example, Perera and Amin (1996) state that the environmental hazards and conflicts associated with the informal sector are not inherent to the activities but generated by the constraints within which they operate. Medina (2000) believes scavenging cooperatives are an effective means of improving the income, working and living conditions of scavengers in Asia and Latin America. Li (2002) highlights the critical role that junk-buyers play in linking waste owners and redemption depots in urban China. Hayami et al. (2006) point out the contributions made by waste pickers and collectors in Delhi in terms of environmental conservation and saving government expenditure for waste disposal. Wilson et al. (2009) remark that the recycling rates achieved by the informal sector in four developing countries (Philippines, India, Pakistan and China) are quite high, often in the range of 20–50%.

The importance and potential of the economic and social benefits that can be gained by involving the informal sector into formal waste management are also recognized (Perera and Amin, 1996; Medina, 2000; Mitchell, 2008; Wilson et al., 2009). Ignoring the informal sector can result in unsustainable interventions (Nzeadibe, 2009), and an abrupt abolishment of the current informal system would be counterproductive due to the mature

Table 1
Local names of particular waste professions and their informal/formal status in nine developing countries.

Profession[a]	India	China	Brazil	Colombia /Peru/Chile	Morocco, Senegal	South Africa
Waste pickers from dumps	Scavengers	Shi huang zhe/ Jian po lan/Jian la ji	Catador/Gandaieiro	Recicladores-/Recuperadores- / Segregadores Informales de Materiales Reciclables (RIMR)	Récupérateurs	Informal re-claimers/waste pickers
Street waste pickers	Rag pickers	Shi huang zhe/ Jian po lan/Jian la ji	Catadores da rua, Catadores de materiais recicláveis (itinerant)	Recicladores/recuperadores/ segregadores formales	–	Street collectors/informal collectors/waste pickers
Itinerant or stationary waste buyers	Kabadiwallas	Fei pin hui shou zhe/Shou fei pin/Shou po lan	Sucateiro/ferro-velho (both stationary)	Cooperativas/intermediarios/ centros de acopio / chatarreros (all stationary)	Chiffoniers	Small recyclers (itinerant)/ scrap dealers / buy back centers (both stationary)
Municipal waste collection crew	–	Huan wei gong ren	Gari	Empresas de servicio público/ empresas de aseo público	–	Municipal collectors/refuse removers
	Informal	Intermediate	Formal			

[a] Four main categories of informal waste recycling defined by Wilson (2001).

network that is already well-established. Therefore integrating the informal sector into waste management planning while working to improve efficiency and the living and working conditions of those involved is a preferred option (Wilson et al., 2006).

Informal recycling is currently the prevalent e-waste recycling practice in China, especially in some coastal regions (Liu et al., 2006b; Terazono et al., 2006; Yang et al., 2008). In the early 1990s, the beginning of used EEE importation had stimulated early scale development of the informal e-waste recycling sector. During the following years, a booming increase of domestic EEE consumption alongside the country's rapid industrialization and urbanization quickly enlarged local demand of second-hand components and refurbished appliances, the most common outputs of informal recyclers. And China is not the only country going through the embryonic and flourishing stages of informal recycling. Many other parts of the world, including Bangalore, Chennai, Delhi and New Delhi in India, Lagos in Nigeria and Karachi in Pakistan, also record informal e-waste recycling activities (Williams et al., 2008). The reasons underlying the present low-end management of e-waste and the existence of informal recycling sectors in the developing countries include: (1) unwillingness of consumers to return and pay for disposal of their old EEEs, (2) uncoordinated high level of importation of e-waste as second-hand devices, (3) lack of awareness among consumers, collectors and recyclers of the potential hazards of e-waste, (4) lack of funds and investment to finance improvements in e-waste recycling, (5) absence of recycling infrastructure or appropriate management of e-waste, (6) absence of effective take-back programs for end-of-life (EoL) EEE, (7) lack of interest/incentive in e-waste management by multinational IT companies and (8) absence and/or lax implementation of e-waste specific legislation (Finlay, 2005; Hicks et al., 2005; Osibanjo and Nnorom, 2007).

Researches on informal e-waste recycling, initiated from observation on the related negative environmental results, have now extended to more explorative and insightful sector analysis on other crucial aspects such as material flows (Streicher-Porte et al., 2005), social impacts (Manhart, 2007; Williams et al., 2008), formalization and incentive system (Terazono et al., 2006; Streicher-Porte and Yang, 2007; Yang et al., 2008) and so on. Nevertheless, more information and discussion should be accumulated in this sector especially concerning the structure and organization of informal recycling industry, the production procedures and product outflows, the market relations between stakeholders and the codependency between formal and informal sectors throughout recycling chains. Meanwhile, integrating the informal sector into policy design is also theoretically desirable, but in policy practice this sector is seldom embraced in recycling system planning despite the awareness of its strong presence by both market players and government officials. As the following sections will reveal, in the way searching most suitable e-waste recycling systems, developing countries must explore, experience and conserve the right roles that informal recyclers can play in their e-waste management schemes.

3. Overview of e-waste management in China

3.1. Major sources of e-waste in China

The e-waste recycled in China comes mainly from three sources: consumption, importation and production. According to a recent study, China generated 1.7 million tons of e-waste in 2006, equal to 1.3 kg of e-waste per capita. By 2015, the figure is expected to increase to approximately 400 million units, or 5.4 million tons (Yang, 2008). The constant raise of domestic EEE consumption leads to a corresponding, time-delayed increase in e-waste, meanwhile we should also notice that today there is still a significant rural–urban difference in the possession levels of major EEEs (He et al., 2006; Liu et al., 2006a). Wang et al. (2009) have estimated the e-waste generation of five EE products in China. According to their study, between 2008 and 2012, there is a predicted sharp rise of obsolete personal computers (PCs), televisions (TVs) and air-conditioners, with the amount of obsolete PCs, TVs and air-conditioners reaching 93.36 million units, 74.31 million units and 63.9 million units, respectively in 2012. While refrigerators and washing machines are estimated to have more moderate obsolescence rates, the quantities of discarded refrigerators and washing machines also almost doubled and trebled within the defined eleven years from 2001 to 2012.

At the same time, illegal imports of used EE products or WEEE from overseas has been added to the volume of e-waste being treated in China. China now appears to be the largest dumping site of e-waste in the world, receiving continuously e-waste shipments from US, Europe and neighboring Asian countries including South Korea and Japan (Puckett et al., 2002; Terazono et al., 2004; Hosoda, 2007). Transboundary movement of e-waste is primarily profit-driven. Recyclers and waste brokers are taking advantages of the lower recycling costs and higher revenues accruing from machine reuse in China; meanwhile also trying to evade the entitled disposal responsibilities in home countries. The legislation gaps in e-waste management between countries and relatively weak custom control in China also provide opportunities for illegal entry of e-waste into the country.

The third source contributing to the huge e-waste amount is the electronics industry, being a major economic driver of China (Manhart, 2007) and one of the fastest growing sectors since the 1980s (Yang, 2008). Exports from the EEE sector earned China

Table 2
Number of household appliances owned per 100 rural and urban households in China at the end of 2002[a] Source: Wen et al. (2006).

Region	Color TVs	Refrigerators	Washers	Air-conditions	Mobile phones
Urban inhabitants	126	87	93	51	63
Rural inhabitants	60	15	32	2	14
Rural inhabitants in 12 western provinces[b]	48	6	21	0	6

[a] Numbers of appliances have been rounded to whole numbers in this table.
[b] Western provinces (12) refer to 12 relatively undeveloped provinces (autonomous regions and municipalities) in western China.

US$227.46 billion in 2003, accounting for 51.9% of the country's total export value (Hicks et al., 2005). Today, China is the world's largest producer, consumer and exporter of EEEs. Consequently, scraps generated during EE manufacturing processes are an unignorable part of the domestic e-waste streams, though the total volume of production e-waste is much smaller and easier to control compared to those coming from domestic EEE consumptions and illegal imports.

According to relevant regulations, the majority of e-waste imports into China are illegitimate and import permissions of wastes are only given to certain secondary materials, e.g. cables, wires, mixed metals and motors, as these can be used as raw materials and be recycled by authorized recyclers (Yang et al., 2008). However, such an import permission system for selective recyclable materials provides room for illegal e-waste inflow into China. In practice, a large proportion of EoL home appliances in Japan is exported to China as 'mixed metal' (Shinkuma and Huong, 2009). Furthermore, the importing of used electronics represents an additional legal loophole which, as long as the implementation of existing regulations and custom controls remains weak, enables unscrupulous traders to import e-waste labeled as second-hand products. Illegal e-waste imports provide abundant and stable supplies to the informal recycling workshops, often at favourable prices. It is observed that most of the e-waste recycled in Guiyu is of North American origin, with Japanese, South Korean and European waste witnessed to a lesser degree (Roman and Puckett, 2002). Therefore, improving the monitoring quality of the Chinese border agencies and providing technical expertise to identify specifically banned wastes is greatly needed.

The material and financial flow of e-waste in China is distinctive from other countries. Selling obsolete EE appliances to individual collectors is the preferred option chosen by Chinese households for the disposal of EE products (Streicher-Porte and Geering, 2010) and nearly 60% of the generated e-waste in China is passed into informal recycling processes (Liu et al., 2006a). Floating private collectors and a mass of second-hand shops and waste reclamation depots form the main channels of e-waste collection. Most collected e-wastes are sold to less developed regions after simple maintenance or repair. What can no longer be reused is dismantled manually, and then treated in unqualified household workshops or small factories to recover valuable components and materials (He et al., 2006).

Several economic and social factors lead to the current pattern of recycling. First, there is still a big disparity between rural and urban China in terms of income, living standard and household occupation of EEEs (see Table 2). The EE appliances which are obsolete but not yet waste can still find a user in rural areas (He et al., 2008). The growing rural demand for EEE, together with the shortened urban lifespan of these products stimulate the collection and movement of second-hand electronic appliances from urban to rural areas. Second, Chinese recyclers prioritize device or component reuse because economically speaking the remaining functional value of these products is usually higher than the inherent recoverable material value. Third, research also shows that waste collection and disposal services in developing countries make up a higher proportion of the average income than in developed countries (Cointreau, 2006). These factors indicate that the reuse and recycling of e-waste in China is essentially different from that of industrialized countries and, thus, requires a different recycling system.

3.2. Environmental regulations related to e-waste

The sheer magnitude of e-waste generation in China and its linked environmental and health consequences call for clear

Table 3
Overview of China's national WEEE management-related legislations and regulations.

Law or regulation	Major content	Effective date
Environmental Protection Law of the People's Republic of China	Introduction of two important principles for pollution control-'pollution prevention' and 'polluter-pays'	Effective December, 26, 1989
Clean Production Promotion Law	Introduction of 'producer responsibility'; encourages eco-design and the life-cycle approach for resource use and waste management	Effective March, 1, 2003
Law on the Prevention of Environmental Pollution from Solid Waste	Responsibilities of producers, retailers, importers and consumers; 3Rs (reduction, recycling and reuse)	Enacted in October, 30, 1995; amended in December, 29, 2004; effective April, 1, 2005
Measures for the Administration of Prevention and Treatment of Pollution by Electronic Information Products (China RoHS)	Restrictions on the use of six toxic and hazardous substances; 'green' product design; mandatory labeling and provision of information on components, hazardous substances and recycling	Enacted February, 28, 2006; effective March, 1, 2007
Technical Policies for Controlling Pollution of WEEE	Promotes eco-design; defines requirements on the collection, transport, storage, reuse and treatment of e-waste	Effective April, 27, 2006
Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE	Ministry of Environmental Protection (MEP) is designated as the competent department to supervise and administer the prevention and control of pollution caused by WEEE; environmental impact assessment (EIA) shall be undertaken for e-waste dismantling, utilization and disposal projects; definition of responsibility of manufacturers, importers and retailers of EE products	Enacted September, 27, 2007; effective February, 1, 2008
Regulation on the Administration of the Recovery and Disposal of WEEE (China WEEE)	e-waste management qualification; special e-waste treatment fund; encourages partnerships in recycling of WEEE; certification for second-hand EE appliances; requirements on the environmental performance monitoring institution and data management system in recycling enterprises	Enacted February, 25, 2009; effective January, 1, 2011

policies, regulations, systems and institutions if effective management and control is to be established (Ye et al., 2009). In light of the potential impact on its EE industry and the current state of domestic recycling, the Chinese government can be seen to have taken a gradual and cautious approach toward the regulating of e-waste. Table 3 lists out the present e-waste related laws and regulations in China and the key contents. Overviews and comparative discussions about China's e-waste regulations can be found in the work of Hicks et al. (2005), Yang (2008) and Streicher-Porte et al. (2010). Present regulations set control on EEE production and WEEE management mainly from four aspects: (1) restriction of the usage of six toxic and hazardous substances in electronic information products ('Measures for the Administration of Prevention and Treatment of Pollution by Electronic Information Products'); (2) pollution prevention and control on dismantling, utilizing and disposal of e-waste ('Technical Policies for Controlling Pollution of WEEE'); (3) certification requirements for e-waste recycling operation ('Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE'); (4) responsibility of producers and importers for their products and for the e-waste collection and treatment fund ('Regulation on the Administration of the Recovery and Disposal of WEEE'). These regulations have successfully provided timely industrial guidance and basic legal constrain on e-waste management, and have responded the international trend of cleaner EEE production (with less toxic use) and better WEEE disposal (with more environmental concern). On the other side, it can also be observed that in these regulations some key elements and principles are still defined in very general terms which undoubtedly restrict their legal power, and the lack of subsequent implementation rules and measures makes enforcement difficult. Aside from national legislation development, a number of local administrative measures were introduced in major regions such as Beijing, Shanghai, Nanjing and Guangdong province to regulate the behavior of enterprises, dealers and customers, and to build the local system of e-waste take-back, reuse and recycling (Jin, 2006).

However, so far the informal sector has not yet been included in the legislative framework, and the effectiveness of available regulations on informal recyclers seems to be rather weak. As we will discuss in detail in Section 4, ignorance of the informal sector has been resulting a series of difficulties in formal recycling plants, and sustainable design of recycling models in China should take the informal sector into account, as informal recycling operations are strong, pervasive and influencing the pattern of e-waste recycling in this country.

3.3. Scale of informal e-waste recycling

Out of the several informal e-waste processing domains in China, Guiyu and Taizhou are the most prominent ones. Guiyu is one of the largest e-waste recycling centers in China. With a population of 150,000 including 100,000 migrants, it has more than 300 companies and 3000 individual workshops making up more than 20 of the total 28 villages engaged in e-waste recycling work (Xing et al., 2009). Guiyu treats over 20 million tons of e-waste annually and the recycling output reached RMB 800 million in 2004. Most of the waste recycle labors are rural migrants from outlying agrarian regions such as Hunan and Anhui who take the menial jobs of dismantling and processing e-waste for an average wage equivalent to US$1.50 per day. Many of the workers are women and children (Puckett et al., 2002). Taizhou, a city famous for secondary material production, has been involved in e-waste recycling for nearly 25 years (Shen et al., 2009). Since the early 1990s, Taizhou began to process imported wastes including scrap metals, obsolete electric capacitors, household appliances, electric generators and cable wires, with an annual volume of dismantled e-waste exceeding 2.2 million metric tons (Chan et al., 2007).

Extensive manual dismantling and crude recycling methods are allocated in the informal sector in comparison to the highly automated processes in well-developed formal sectors for recycling. Examples of such crude techniques worth mentioning are:

(1) Physical dismantling by using tools such as hammers, chisels, screw drivers and bare hands to separate different materials (Puckett et al., 2002; Wen et al., 2006).
(2) Removing components from printed circuit boards by heating over coal-fired grills (Puckett et al., 2002).
(3) Stripping of metals in open-pit acid baths to recover gold and other metals (Wong et al., 2007).
(4) Chipping and melting plastics without proper ventilation (Wong et al., 2007).
(5) Burning cables to recover copper, and burning unwanted materials in open air (Wong et al., 2007).
(6) Disposing unsalvageable materials in fields and riverbanks (Huo et al., 2007).
(7) Refilling of toner cartridges (Puckett et al., 2002).

During these processes, reusable parts are directly reapplied and non-reusable ones 'recycled' further. Revenue is created both from component reuse and material recycling. These treatment methods are very 'cost-efficient', due to the use of non-skilled manual labor and disregard of any hazards to environment or health. These informal practices contribute to the release of toxic metals (such as lead) as well as persistent organic pollutants (such as flame retardants [polybrominated diphenyl ethers-PBDEs] and dioxins/furans [polychlorinated dibenzo-p-dioxins and dibenzofurans-PCDD/Fs]) into the environment (Wong et al., 2007), leading to severe and irreversible harm to the local environment and workers. A cluster of studies has disclosed the environmental and biological consequences of informal recycling activities in Guiyu and Taizhou, on aspects including soil and sediment (Leung et al., 2006; Luo et al., 2009; Zhang and Min, 2009), air (Deng et al., 2007), water contaminations (Wu et al., 2008) and health problems (Bi et al., 2007; Li et al., 2008; Zhao et al., 2009).

4. Two e-waste recycling sectors in China: why informal wins?

4.1. Coexistence of formal and informal recyclers

While the informal sector is growing steadily, the potential economic and environmental benefits of e-waste recycling have also attracted plenty of players from the formal sector. Under the trend of material reutilization and encouraged by recent positive legislation development, China has successfully consolidated many new investments in the e-waste recycling industry. Registered formal recyclers (including foreign invested ones) whose treatment facilities, environmental standards and recycling efficiencies still varying in certain degree, are now actively present in EE manufacturer dense regions such as Beijing, Tianjin, Shanghai, Jiangsu Province and Guangdong Province (see Fig. 1). A list of officially certified e-waste treatment plants[3] in the major cities of China is shown in Table 4 in Appendix.

In parallel with construction of private recycling plants, four national pilot projects (Hangzhou Dadi, Beijing Huaxing, Qingdao Haier and Tianjin Datong, see also Fig. 1) were launched

[3] These recycling enterprises are listed on the temporary catalog of certified recyclers. The catalog is published and updated regularly on the website of environmental bureau in respective city, according to the requirement set by the 'Administrative Measures for the Prevention and Control of Environmental Pollution by WEEE', effective in 2008.

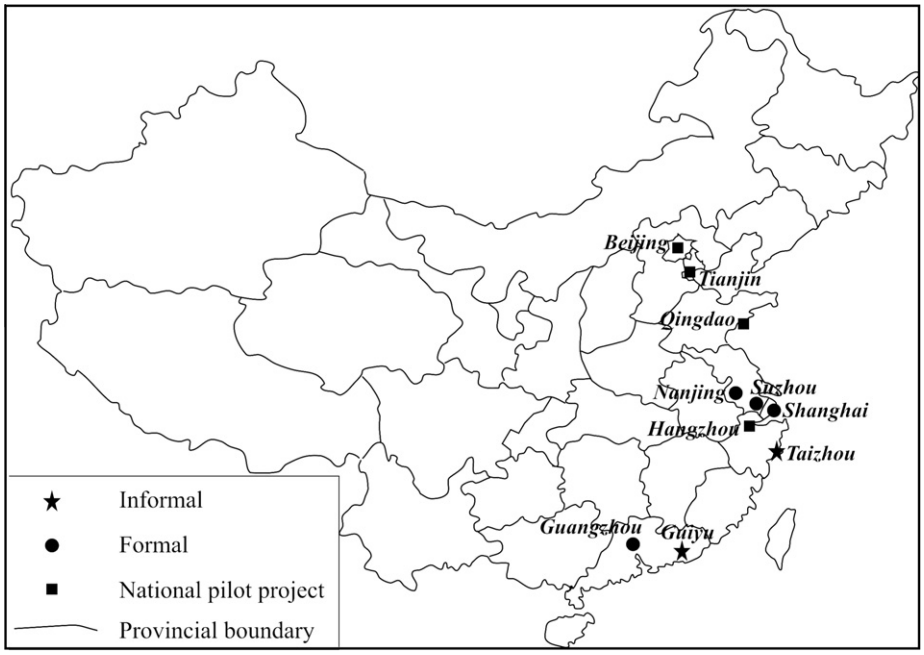

Fig. 1. Distribution of the major formal and informal e-waste recycling sites and national pilot project sites in China.

sequentially since 2004 in order to gain practical experiences in collection network design, e-waste management standards and regulations and recycling technologies (Yang et al., 2008). Besides, a few leading electronics companies are developing their own recycling initiatives in China. In 2005, Nokia and Motorola jointly initiated the 'Green Box' program with China Mobile (a major telecom operator in China) to collect consumer's obsolete cell phones and accessories in 40 cities across China. Another six cell phone producers including LG, Lenovo and NEC also joined the program in April of 2006, making the 'Green Box' one of the most influential e-waste take-back organizations in China now. In the same year, Dell and Lenovo both introduced free take-back services for their computers sold in China.

However, these government pilot projects and producers' take-back programs have not, as yet, seen any success, being unable to compete with the informal sector, most notably in collecting e-waste and in covering the costs of environmentally sound processing (Hicks et al., 2005; He et al., 2008; Yang et al., 2008). Taking Hangzhou Dadi as an example, despite of having 36 collection points and a treatment plant of 7000 tons annual capacity, between January 2005 and March 2006, it had just received 133 tons of e-waste and 1325 units of discarded home appliances, and had only dismantled 92 tons and recovered 59 tons of steel, copper and plastics (Kojima et al., 2009). Similarly, local media reported that up until April 2006 the 'Green Box' program only collected around 30,000 pieces of used cell phones and accessories nationwide (Zuo, 2006). Such low collection ratios not only questioned the projects' financial viability, but, in a step further, also challenged the sustainability of the whole formal recycling industry if sufficient supply of e-waste can not be guaranteed through formal collection channels run by public or private owners.

Informal collection is one of the essential causes of supply problems in the formal sector. Informal collectors are able to take obsolete EEEs from households at lower prices and treat them in the informal workshops at lower costs (Yang et al., 2008). For formal recyclers, first of all, they have no own household collection networks therefore can not offer the similar door-to-door collection services as informal collectors do, nor can formal recyclers take over other common waste materials generated by households such as papers, plastics and cans because these materials may not fall into their recycling categories. Second, formal recyclers can hardly afford competitive prices for old EEEs since they have to bear the significant treatment costs by themselves. Consequently, qualified recyclers are in danger of making losses, as the total burden including the costs for collection and treatment often exceeds the income gained from selling the reusable second-hand products and material recovery (He et al., 2006). The low profitability of formal recyclers limits their financial abilities to compete with informal collectors in purchasing e-waste from households, aggravating the supply deficiency problem in large e-waste plants yet further.

Whereas it is reasonably easy to understand and follow the treatment procedures and material flows of the formal sector, the informal sector consists of a chain of e-waste recycling processes which is far more difficult to grasp. Fig. 2 illustrates the generic chain of e-waste recycling processes and material flows as observed in China. Obsolete EE products are sold to the informal sector where components (such as power supply, compressors, etc.) and devices (such as processors, capacitors, etc.) are dismantled for reuse, as recovery of function. After manual separation, material-specific recovery processes are applied, as recovery of material. Generally these processes show low recovery efficiency and do not abate environmental emissions. Some processes, mainly formal, also apply recovery of energy from materials with high calorific value (downstream flows are shown in solid lines and recovery flows are shown in dotted lines in Fig. 2).

While the above descriptions have configured a few external and inherent attributes of informal recyclers which differentiate them from formal recyclers from a range of technological, environmental and institutional criteria, in the actual recycling chain there may not always be clear splits between the formal and informal sectors. In fact, the two sectors overlap at certain stages and sometimes highly relate to each other. This occurs especially in businesses engaging in the repair of second-hand products for the reuse or remanufacturing of second-hand or no name products by using components from obsolete EE products. These reuse and remanufacturing markets are generally not regulated, which is a major hurdle for the creation of a comprehensive and exclusive material and energy recycling market.

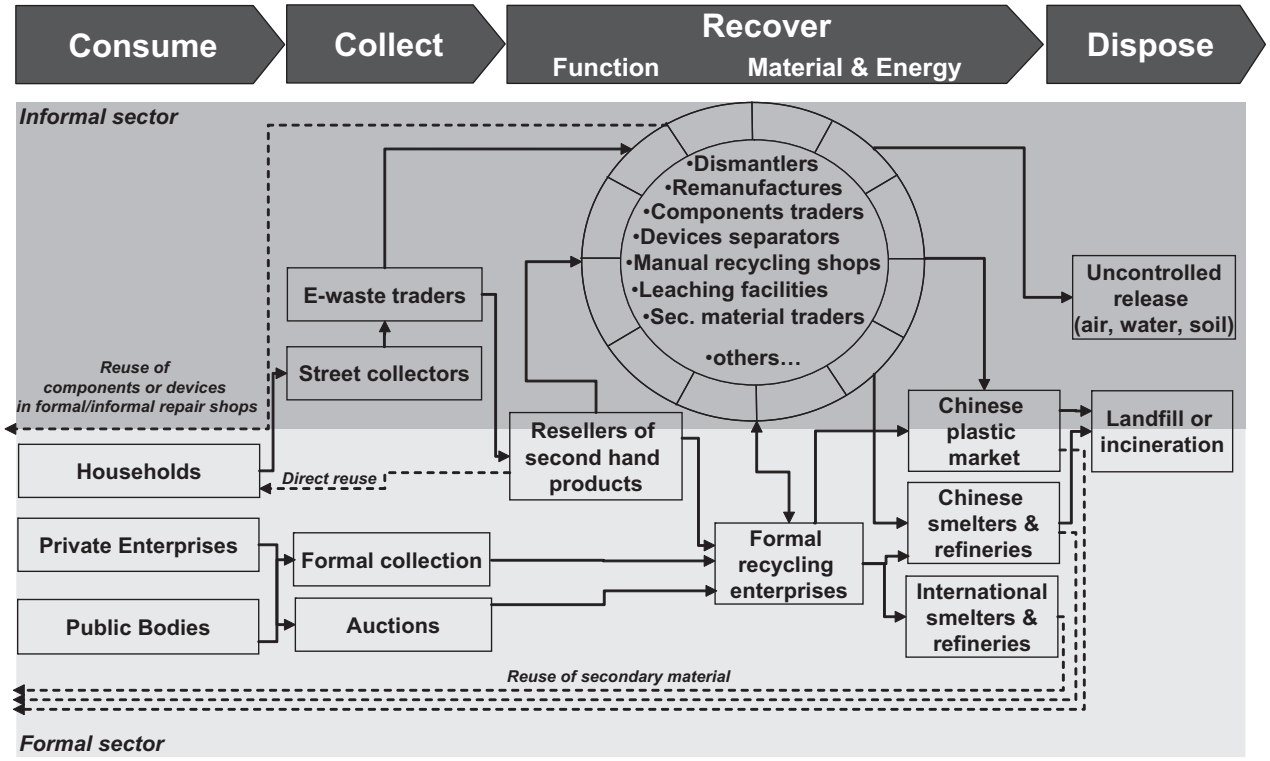

Fig. 2. Flow chart of informal and formal e-waste processes in China.

Another issue which needs to be addressed is that of the potential contribution of manual processing (widely used in the informal sector) toward achieving better overall recycling performances. Recycling of e-waste can go through numerous physical separation and smelting steps/unit operations as discussed by Van Schaik and Reuter (2010). Sophisticated EoL products, if shredded, create complexly linked materials after shredding, producing recyclates of varying quality. Even the best separation techniques nowadays cannot separate some of the components of electronic products. Hand sorting by humans is probably still the most efficient 'process/unit operation' for the separation of such components. If well trained and managed, the human sorter will produce recyclates which can easily be redirected for reuse or material recovery. Such pre-sorted recyclates can be optimized for metallurgical recycling processes. Pure and detoxified recyclates are less likely to interfere with metallurgic operations than uncontrolled linked materials created during mechanical separation. Therefore, possible adoption of manual separation and a good, improved application of the comprehensive sorting and dismantling procedures which informal sector uses in formal recycling operations certainly deserve academic attention and follow-up research.

4.2. Vitality of informal recycling

An analysis of the recovery chain reveals the major reasons behind the thriving state of China's informal recycling sector: (1) sufficient supplies brought by illegal imports and domestic individual collections; (2) low treatment costs maintained by applying simple and pollutive methods; (3) highly specified dismantling processes which maximize the recovery of functional value by efficient separation of reusable components and parts; (4) steady downstream demands which absorb the majority of different products from informal workshops. The lack of quality control of second-hand devices also permits free market entry of unqualified or untested products from illegitimate remanufacturing process.

On the other side, the vitality of informal recycling sector is also strengthened by its complicated self-organization and demand-driven treatment flow. The trading network of the informal recycling sector is more comprehensive and efficient than it is first taken to be. For instance, products from informal recycling sites in Guiyu, e.g. integrated circuits, cathode-ray tubes and capacitors dismantled from printed circuit boards, are regularly sold to big electronics centers in neighboring cities such as Shenzhen. Iron, copper and aluminum fractions separated from computers are supplied to metal refineries, often via waste brokers as intermediates, and shredded plastics are locally recycled to low or medium grade and offered to toy manufacturers in the nearby Shantou city – often at price 1/3 cheaper than original plastics (Chen, 2005). The substantial market needs for electronic parts and secondary materials are the primary economic dynamics of informal recycling, and the well-organized output flows and widespread trading networks facilitate quick sales of generated products. It also explains why informal recycling is able to gain the upper hand over formal recycling under the current market condition.

In addition to the most typical recycling methods as mentioned in Section 3.3, simply-designed and low-cost machines are also used during some stages of informal recycling processes, often achieving good separation rates similar to those within formal operations. Some examples of these are: density separation tables for shredded cables, shredders for copper plated boards and sorting machinery for plastics and copper mixtures. The use of machinery processing for more complicated materials which human sorting can not handle enables desirable production of certain recyclable materials. Nevertheless, labor is still the major driver of the informal recycling chain and maintains its very low operation costs.

4.3. Regulation and government intervention

As we can judge from its adopted recycling methods and instruments, informal recycling is flexible and easy to execute. Because

of this inherent flexibility and adoptability, radical government interventions, aiming at forbidding informal recycling by enforced removal of operation, often find it difficult to achieve their planned objectives. In Guiyu, under pressure from media and superior environmental bureaus, notable efforts have been by town government to close down those dismantling workshops and illegal recovery sites. However, it did not take a long time for local authorities to recognize that banning informal recycling is very challenging if not impossible, as informal recycling there is carried out through household production approach which has barely any requirements on labor skills and facilities, thus the whole recycling operation is highly relocatable. While economic stimulus driving the running of informal production stays persistent, mandatory removal merely result in either the change of operation site from one place to another, or a shift of operation time from day to night. Guiyu's difficulties in managing informal recycling are representative, leading to debates on right policies towards the informal sector. There are basically three approaches: use of regulation, or market, or both. Guiyu's experiences already challenged how enforceable and effective regulations can be in controlling or formalizing informal recycling, especially when the scale, mobility and motivation of these activities are concerned. In addition to the enforcement difficulty, authorities also need to consider the resulting social impacts when legally prohibiting a local industry which feeds many thousands of workers. Providing incentives, via approaches like offering fixed prices for certain e-waste types, may help to divert some e-waste flows from informal to formal, but unless the incentive system offers prices equal or higher than the profits accrued by self-processing the informal collectors and recyclers will not deliver e-wastes to official collection spots. Then the question remains how to afford such a price system in a longer run when the formal treatment of collected e-wastes may not be able to generate enough profits. Accommodation policy, often executed via industrial park setup, is now a popular approach. This approach focuses on concentrating scattered individual recycling activities and improving treatment processes through central management in production and pollution control. For instance, recycling industrial parks with impressive treatment capacities have been established in Tianjin, Taicang, Ningbo, Taizhou and Zhangzhou. In these parks most of the recycle works is still done by manual dismantling (Shinkuma and Huong, 2009), trying to make the best use of labor-intensive processes meanwhile providing more job opportunities for workers. In Guiyu there is also a clear policy alteration: away from the previous suppressing approach, government is now promoting technical upgrade in the informal workshops through manners like replacing coal-fired grills with electrical heaters when taking out components from circuit boards (Chen, 2005). The appearance of recycling parks and the attitude shift in Guiyu from simple prohibition to cooperative improvement both indicate that prohibiting informal recycling is probably not the best way ahead, and new policies or interventions on informal recyclers would benefit from a better understanding of the complete informal e-waste economy, particularly as far as the linkages between recycling stages and product outlets are concerned. Recycling processes can always be improved by tool-upgrading, but correct adjustments of market dynamics behind each recycling option throughout the informal recycling chain would achieve more sustainable results.

4.4. Major issues of China's e-waste recycling system

Collection and financing are two primary elements of any recycling system. Currently, there is no formal e-waste collection system in China, and the question remains of how to establish an efficient take-back system suited to China's needs in order to guarantee the supply of EoL products for qualified recycling plants. To a large extent, sound network design and effective incentives for consumers determine the success of China's e-waste collection system. Experiences gained in other countries show that e-waste take-back systems can be built upon existing logistic connections owned by producers, can be jointly developed by several recyclers and exclusively managed by specialists, e.g. logistic companies, and can also be approached by a combination of the above alternatives. However, without external funding and knowledge support, it is too demanding for Chinese producers or recyclers to construct e-waste collection network merely by themselves, particularly if the development costs, geographic and product coverage, and experiences of reverse logistics are taken into account. On the other hand, informal collectors have already formed a mature web for household collection of obsolete EEEs. This largely spontaneous network is widespread, well-structured and linked by different layers of collectors, intermediates and buyers, and is likely to be more organized and vigorous than we thought. Whether and how to utilize this informal collection system for the supply of formal recycling plants remains a point of interest, but again how to set up an incentive system has yet to be ascertained.

An appropriate funding scheme also needs to be founded, especially under present market condition where collection and treatment costs of formal recyclers are averagely much higher than that of their informal counterparts. The new regulation – 'Regulation on the Administration of the Recovery and Disposal of WEEE', effective on January, 1st, 2011, has set up a special fund for subsidizing formal e-waste collection and treatment. Under this regulation, producers and importers are made responsible for their products. Though the regulation applies Extended Producer Responsibility (EPR) as a principle and outlines a financing mechanism, how this funding programme will work remains to be seen, especially considering the fact that some crucial points of the regulation such as product coverage, financing mechanisms and ministerial responsibilities are yet to be specified and tested (Streicher-Porte et al., 2010). Added to this, the readiness of China's EE manufacturing industry to apply EPR should be carefully evaluated. Difficulties are embedded in many aspects of transplanting EPR to the developing countries, such as collection of funds from producers or importers, diverse incentives for policy practice and regional disparity (Tong et al., 2004; Kojima et al., 2009). For China, whether and to which degree domestic producers can bear the financial responsibility for the disposal of their EoL products is still uncertain, and adoption of additional policies, such as preferential tax treatment or an economic subsidy, might be necessary in order to ensure that formal recycling firms can afford to offer similar prices as offered by informal recyclers, especially during the early stage of formal recycling sector development when the economy of scale is limited.

5. Discussions and conclusions

Informal recycling is critical for research and analysis of e-waste management solutions in China, not only because it is directly associated with a set of negative and problematic consequences including environmental and biological damages, supply shortage of the formal recycling sector and quality problems of remanufactured EE products, but also because the multiple roles it has been playing in the domestic recycling chain, e.g. major collector of household appliances, stable supplier of second-hand EE products and primary processor of imported e-wastes. The emergence and growth of informal recycling is the result of intricate interactions between economic incentives, regulation gaps, industrial interdependence and the social reality of developing countries. Informal recycling may remain an influential recycling force for years to come in the collection and treatment of e-waste in China, and

the missing public awareness of e-waste toxicity and consumers' common habits of selling rather than paying for old EEEs are just some of the factors supporting persistent existence of informal recycling.

Yet the numerous stakeholders and extensive market networks within the informal recycling sector, coupled with the huge quantities of e-waste it collects and treats, all seems to indicate that this largely invisible sector should have own structures and planned productions so to run and grow at such a scale. Here treatment processes and resource allocation shift timely and innovatively in order to cater to the changing market demands throughout the recycling loops, thus achieving considerable profits. From this point of view, the whole informal recycling chain must be thoroughly investigated to understand: (1) which steps are environmental-harmless and should remain; (2) at which steps the material mass flow should be changed for better downstream environmental and recycling performance. Examination of economic reliance between stakeholders is critical for ascertaining and altering the determinant dynamics behind different informal recycling options. Besides, it should be noted that certain stages of informal recycling actually help to extend product life cycles through devices and/or parts reuse. From recycling flowchart point of view, as engineers observed, liberation or disconnection of the connected materials contained in e-waste during dismantling or shredding determines the quality of

Table 4
Main certified e-waste recycling plants in China.

Region	Number	Company Name	Business Scope
Beijing	2	Beijing Jinyu Mangrove Environmental Protection Technology Co., Ltd.	Collect and treat obsolete electronic components (including component, LCD, production scrap)
		TES-AMM (Beijing) Co., Ltd.	Collect and treat obsolete printed circuit boards and electronic components
Tianjin	6	Tianjin Hengchang Environmental Protection Technology Co., Ltd.	Dismantle waste household appliances and office electronic equipments
		Tianjin Green Angle Recycling Co., Ltd.	Dismantle waste household appliances and office electronic equipments
		Tianjin Ziya Environmental Protection Industrial Park	Dismantle waste household appliances and office electronic equipments
		Tianjin Loyalty Glass Material Co., Ltd.	Collect and treat waste tube and tube glass in waste catalog HW 31, HW47
		Taiding (Tianjin) Environmental Protection Science-Tech Co., Ltd.	Collect and treat hazardous wastes in waste catalog HW13, 22, 23, 25, 26, 29, 31, 46; Collect and treat electronic wastes containing Au, Ag, Pd, Rh, Zr, Pt, Ta, In
		Tianjin Hejia Veolia Environmental Services Co., Ltd.	Treat hazardous wastes except of catalog HW15, 20, 25, 27, 28, 30
Shanghai	7	Shanghai San Jing Xin Yun Precious and Rare Metals Recycling Co., Ltd.	Dismantle, recycle and treat: (1) electronic accessories and components (including copper/iron IC, connector, circuit board, transistor, not including CRT, LCD, PCB or PBDE contained wire and plastic frame); (2) metal scraps containing silver, nickel, cobalt, precious and rare metals from electronic production process, spent catalyst and sorbent; (3) obsolete cell phones
		Shanghai Central WEEE Recycling Co., Ltd.	Dismantle: obsolete electrical and electronic equipments (including PC, cell phone, TV, printer, copier, fax machine, telephone, server, router and DVD player);Dismantle, recycle and treat: hard disk and IC
		Shanghai Xin Jinqiao Industrial Waste Management Co., Ltd.	Dismantle: obsolete electrical and electronic equipments (including PC, cell phone, TV, printer, scanner, copier, fax machine, radio, telephone, server, router, DVD player, washing machine, heater, camera, etc.); dismantle, recycle and treat: (1) hard disk and IC; (2) used toner
		TES-AMM (Shanghai) Co., Ltd.	Dismantle: obsolete electrical and electronic equipments (including PC, cell phone, TV, printer, scanner, copier, fax machine, radio, telephone, server, router, DVD player, washing machine, heater, camera...); dismantle, recycle and treat: (1) IC, capacitor, resistor, diode, switch, transistor, connector and relay; (2) stannum slag, copper and aluminum foil, aluminum dust, metal frame, metal scrap, wires and tubes containing precious and rare metals
		Shanghai Solid Waste Disposal Center	Dismantle: obsolete electrical and electronic equipments (including PC, cell phone, TV, printer, scanner, copier, fax machine, radio, telephone, server, router, microwave oven, DVD player, washing machine, heater, camera, POS, motor, etc.)
		Shanghai Senlan Industrial Waste Management Co., Ltd.	Dismantle and treat (shred, sort, recycle): obsolete electrical and electronic equipments (including PC, cell phone, TV, printer, scanner, copier, fax machine, radio, dust collector, telephone, interphone, server, router, microwave oven, DVD player, washing machine, heater, camera, IC card, etc)
		TMC Metal (Shanghai) Co., Ltd.	Dismantle: obsolete electrical and electronic equipments (including PC and communication devices); dismantle and treat (shred, sort, recycle): (1) IC, capacitor, resistor, diode, switch, transistor, connector, relay; (2) stannum slag and powder, copper and aluminum foil, aluminum dust, metal frame, metal scrap, wires and tubes containing precious metals
Suzhou	4	TMC Metal (Suzhou) Co., Ltd.	Dismantle: obsolete electrical and electronic equipments (including PC, LCD and communication devices); dismantle and treat: (1) waste printed circuit boards and cut-offs (excluding PCBs capacitor and other hazardous components containing mercury); (2) obsolete electronic components and accessories(IC, capacitor, resistor, diode, transistor and connector; (3) stannum slag, stannum and zinc powder, copper and aluminum foil, metal frame, metal scrap, wires and tubes containing silver
		Fuji Xerox Manufacturing (Suzhou) Co., Ltd.	Dismantle: copy machine Dismantle and treat: CRU
		Suzhou Dowa Resource Recycling Co., Ltd.	Dismantle: obsolete electrical and electronic equipments, including (1) household equipments (air-conditioner, washing machine, TV, refrigerator, microwave, dust collector and hair dryer); (2) IT products and communication devices (PC, cell phone, telephone and server); (3) apparatus; (4) entertainment products (DVD player, video recorder, etc.); (5) office electronic equipments (printer, scanner, copier, fax machine, camera and heater)
		TES-AMM (Suzhou) Electronic Waste Recycling Co., Ltd.	Dismantle: (1) household equipments (TV, audio equipment); (2) IT products and communication devices (PC, CRT, LCD, cell phone, telephone and interphone); (3) office electronic equipments (printer, scanner, copier, fax machine and toner) (4) internet devices (modem, router) Dismantle and treat: (1) obsolete electrical and electronic components and accessories (IC, capacitor, resistor, diode, switch, transistor, connector and relay); (2) lithium battery
Huizhou	1	Huizhou Ding Chen Development Co., Ltd. (O'Meet Group)	Dismantle TV, refrigerator, air-conditioner, washing machine, PC, used LCD and laptop
Harbin	1	Harbin Qun Qing Environmental Protection Technology Co., Ltd.	Dismantle obsolete electrical and electronic equipments

recycling streams (Van Schaik and Reuter, 2008, 2010). Different methods and depths of manual dismantling and mechanical shredding result in different downstream refining alternatives and, consequently, influence the complete recycling efficiency. Therefore, whether informal recycling fosters or hinders the finding of a sustainable solution for e-waste management depends to a great extent on whether appropriate recycling techniques and models can reduce the negative environmental impacts accrued from primitive handling methods, while utilizing the strength of labor-intensive processing for the better preparation of particles entering metallurgical and thermal treatment. In addition to this, reuse of obsolete electronics should be considered in the recycling flow design and competent quality control institutions should be installed for second-hand products. In conclusion, the improvement of informal recycling sector lies on dedicated efforts from economic, technical and social aspects, including but not limited to: first, change of current economic networks by offering new financial or non-financial incentives to informal collectors and recyclers; second, suitable engineering designs which provide an optimum means of physical separation for different e-waste categories, thus optimizes reuse and recycling rates; and third, development of complementary infrastructures such as industrial parks and training courses, which ensure the job security, occupational safety and skill improvement of informal workers.

The actual situation of e-waste management in China calls for innovative and tailor-made solutions, and more empirical research should be undertaken if informal recycling industries are to be placed on the political agenda of developing countries. From the authors' perspective, out of the various issues relating to informal recycling, some are of particular importance and deserve close attention, such as how to divert more e-waste flows from informal to formal sectors; how to achieve positive utilization of informal collection networks for collecting EoL EEEs from households; how to develop efficient incentive system for informal collectors and recyclers; how to make technical improvements of informal recycling processes so to obtain better environmental performance without sacrificing the economic and social benefits it now offers to local industry and community; and how to build cooperative and complementary relationships between formal and informal sectors.

Developing a better understanding of informal recycling and, in a second step, implementing more supportive policy for the informal sector could result in hundreds of thousands of job opportunities for low-skilled workers being preserved or created. The future model of e-waste recycling in China should be shaped by people already active in this field, whether being formal or informal – this work is a first step and a pointer on this path.

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Appendix A

See Table 4.

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