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Review

Challenges in legislation, recycling system and technical system of waste electrical and electronic equipment in China

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ABSTRACT

Waste electrical and electronic equipment (WEEE) has been one of the fastest growing waste streams worldwide. Effective and efficient management and treatment of WEEE has become a global problem. As one of the world's largest electronic products manufacturing and consumption countries, China plays a key role in the material life cycle of electrical and electronic equipment. Over the past 20 years, China has made a great effort to improve WEEE recycling. Centered on the legal, recycling and technical systems, this paper reviews the progresses of WEEE recycling in China. An integrated recycling system is proposed to realize WEEE high recycling rate for future WEEE recycling.

1. Introduction

Over the last decades, the consumption of electronic products has increased enormously and thus generated huge quantities of waste electrical and electronic equipment (WEEE) at the end of its life. According to the United State Environmental Protection Agency, approximately 5 million tons of WEEE are generated in the US with an annual increase of 3–5% and 7 million tons in European Union (Tanskanen, 2013). WEEE contains lots of valuable copper and precious metal elements (Ogunniyi et al., 2009), along with plenty of hazardous heavy metals, flame retardants and refrigerants (Eric Williams et al., 2008; Wienold et al., 2011), which make it an attractive secondary resource and an environmental contaminant simultaneously.

At present, only a small portion of WEEE is recycled though the formal recycling channels, while the overwhelming part is being disposed of in landfills or by incineration (Chi et al., 2011; Nnorom and Osibanjo, 2008). Effective and efficient management and treatment of WEEE has become a global problem (Gutierrez et al., 2010; Kiddee et al., 2013). In the last decade, many countries have issued relevant laws and legislation, and formed mature recycling systems, including Korea (Manomaivibool and Hong, 2014), Switzerland (Wäger et al., 2011) and Japan (Menikpura et al., 2014). In China, one of the world's largest electronic products manufacturing and consumption countries, the total sales of electronic products has reached 166.35 billion US dollars and the output has been up to 50% of the whole world in 2013 (MIIT, 2013). A report by the United Nations Environment Program (UNEP) indicated that more than 2.3 million tons of electronics waste (e-waste) were annually generated in China, second to the United States (Feng Wang et al., 2013). In addition, it was estimated that 1.5–3.3 million tons of WEEE was exported to China via various illegal routes each year and the percentage of WEEE from overseas had increased to 70% (Feng Wang et al., 2013). Management and recycling of WEEE is a big challenge in China.

From the systems integration viewpoint (Liu et al., 2015), management and recycling of WEEE in China significantly impact human and natural systems across all dimensions (organizational level, space, and time). Hence, over the past 20 years, many researchers have focused on the WEEE recycling problem and have made efforts to improve the situation (Wang et al., 2009; Zhou and Xu, 2012). The key parts of legislation, recycling and technical systems are closely related, but are often separately studied and discussed (Kong et al., 2012; Xue and Xu, 2014).

Therefore, to address the connections between the legal, recycling and technical systems of WEEE, and to promote the social and technology-driven system within the self-supporting functional frame, this article reviews the status of WEEE recycling in China. Compared with the WEEE recycling experience in developed countries, challenges for WEEE recycling and future directions in China have also been addressed.

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2. WEEE recycling systems in developed countries

The generation of WEEE continues to increase globally, resulting in great challenges of the WEEE management and recycling (Ongondo et al., 2011). In order to achieve high recycling efficiency, developed countries, such as EU, United States and Japan, have issued legislation and laws for the WEEE management (Li et al., 2013). The legislation and laws identified the responsibilities of different stakeholders, including consumers, manufacturers and distributors (Kiddee et al., 2013; Manomaivibool and Hong, 2014). WEEE collection and treatment are centralized, indirectly promoting the integrated technical systems development. The state-of-the-art technologies make it possible to recover a high percentage of metals and other materials (Hagelueken, 2006). The experience of WEEE management and recycling in developed countries has certain significance to China for responding the WEEE challenges.

2.1. Related legislation and laws of WEEE recycling system

Legislation and laws related to WEEE management provide the basis for WEEE recycling implementation. Frontrunner in institutionalization and implementation of WEEE with legislation and laws, some developed countries have already formed well-established recycling systems and achieved efficient recycling (Torretta et al., 2013; Gomes et al., 2011).

2.1.1. Legislation

In the latest decades, legislation has focused on achieving waste minimization and reduction, followed by product reuse and materials recovery to avoid disposal to landfill (Khetriwal et al., 2009; Stewart, 2012). The EU Directives for restricting the use of hazardous substances in electrical and electronic equipment (Directive 2002/95/EC, the RoHS Directive), and promoting the collection and recycling of WEEE (Directive 2002/96/EC, the WEEE Directive) have been in effect since February 2003. The Directives provided guidelines for the creation of collection schemes where consumers return their WEEE free of charge, aiming to increase the WEEE recycling and/or re-use. Moreover, in order to tackle the fast increasing waste stream, the EU has adopted new rules for WEEE. The new WEEE 2012/19/EU Directive entered into force on August 13, 2012 and became effective on February 14, 2014. The directive introduces a set of collection targets, including 45% of electronic equipment sold that will apply from 2016 and, as a second step from 2019, 65% of equipment sold, or 85% of e-waste generated (EC, 2012).

Apart from EU, similar legislation and laws for WEEE management have been in force in other developed countries, such as US and Japan. Plenty of states in the US have enacted their own related legislation and laws for WEEE management. For example, California has enacted landmark legislation (Electronic Waste Recycling Act of 2003) to establish a funding system for the collection and recycling of certain electronic wastes (CA, 2015). The recycling system in California is shown in Fig. 1. The 23 states in the US have some sort of WEEE take-back requirements (Özdemir et al., 2012). In Japan the WEEE recycling has achieved great success since the implementation of WEEE management legislation (The Law for Recycling of Specified Kinds of Home Appliances) in April 2001 (Aizawa et al., 2008). In 2011, recycling rate for air conditioners was 89%, and for refrigerators, washing machines and televisions it was 87% (Menikpura et al., 2014).

2.1.2. Legislation principles

In order to carry out the promulgated directives and solve the WEEE problems, many countries have adopted extended producer responsibility (EPR), including Germany (Walther et al., 2009), Finland (Walther et al., 2010), Portugal (Niza et al., 2014) and Japan (Yoshida and Yoshida, 2012). According to the Organization for Economic Cooperation and Development (OECD), the principal goals of EPR are: (i) source reduction, (ii) waste prevention, (iii) design of more environmentally compatible products, (iv) promoting sustainable development via the closure of material loops (Khetriwal et al., 2009). EPR requires producers of electrical and electronic equipment (EEE) to take back and recycle their products at the end of life. EPR is an environmental protection strategy to decrease total environmental impact by making the manufacturer of the product responsible for the entire life cycle of the product and especially for taking it back, recycling, and final disposal (Lindhqvist, 2000).

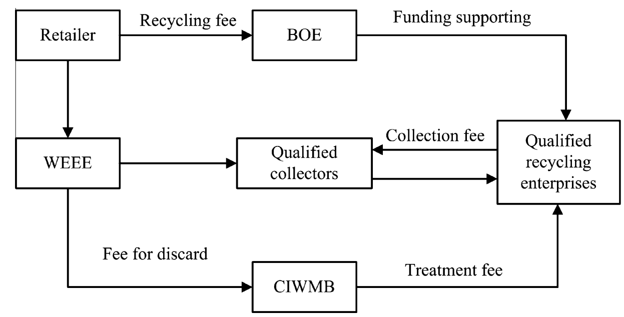

Fig. 1. The WEEE recycling system in California. BOE: California State Board of Equalization; CIWMB: The California Integrated Waste Management Board.

It should be noted that the actual implementation measures of EPR differ among other nations and regions. The differences are mainly manifested in the range and type of producer responsibility (collective or individual), and funding mechanism (who pays, how much and at which points?) (Atasu and Subramanian, 2012). The legislation and laws set relevant responsibilities for involved stakeholders playing specific roles in the recycling chain, ranging from collection to the final treatment of WEEE. It is beneficial to optimize the collection efficiency, maximize the recovery of valuable metals and minimize the environmental impact by enacting related legislation and laws.

The WEEE recycling systems in EU are basically the same in terms of setting up permanent collection networks and infrastructure to fulfill the requirements imposed by the WEEE Directive. In EU countries, producer responsibility organizations (PRO) have been set up to share the same collection system and the associated costs among many producers (Tanskanen, 2013). From the legislation and perfect recycling system perspective, it can be said that the WEEE management and recycling in Europe have achieved great success.

2.2. WEEE recycling technologies

Along with the development of legislation and recycling systems, many researchers have focused on WEEE recovery for resource conservation and environmental protection, developing recycling technologies, such as pyrolysis (Chen et al., 2014; Lin and Chiang, 2014), biometallurgy (Bas et al., 2013; Lee and Pandey, 2012), mechanical–physical technology (Cui and Forssberg, 2003; Li et al., 2014), hydrometallurgy (Birloaga et al., 2014) and pyrometallurgy (van Heukelem et al., 2004).

Extensive literatures indicate that to achieve comprehensively high recycling rates of different materials and reduce the environmental impact, selective disassembly, targeting hazardous and valuable components, is an indispensable process in the practice of WEEE recycling (He et al., 2006). General recycling processes of WEEE are shown in Fig. 2.

According to the International Precious Metals Institute, the most environmentally sound final disposal of WEEE is through metal recovery by a copper smelter, followed by electro-refining (Izatt et al., 2014). There are some industrial applications, such as Umicore's integrated metals smelter and refinery, Rönnskär smelters in Boliden, Dowa Metals & Mining Co., Ltd. in Japan, and other integrated recycling plants. A brief summary of integrated pyrometallurgical processes for WEEE recycling is given in Table 1.

The element radar chart indicates that element tendency for oxidation, volatilization, and alloying (Nakajima et al., 2010). According to the elements distribution, during the copper smelting, most precious metals are collected in the metal phase, while more active metals are turned into oxides in the slag phase. Those oxides, however, are reduced to metal or alloys in the lead blast furnace and are eventually recovered. Elements remaining in the metal phase cannot be separated, except for Cu and Pb smelting, where further steps allow for the alloying elements separation. The combination of copper/lead smelting and refining can make full utilization of metal properties and maximize the recovery rate of metals. For example, the Umicore and Dowa integrated recycling technologies can recover 17, and 18 kinds of elements, respectively. The advanced recycling technologies in developed countries make it successful in WEEE recovery.

3. Status of WEEE in China

In China deficiencies and malfunction of the legal system lead to inefficient collection systems (Chi et al., 2011), while low-technology processing using informal recycling sectors sharply decreases the recycling efficiency of WEEE (Huang et al., 2009). Over the past decade, the Chinese government had issued a variety of environmental laws, legislation and standards related to WEEE management, making a commitment to establish a formal recycling system (Yu et al., 2014; Zhou and Xu, 2012). Meanwhile, specialized companies have been started to participate in the WEEE recycling industry in China (Hicks et al., 2005).

3.1. Related legislation and laws in China

Over the last decade, Chinese government had issued a variety of laws, legislation, standards and norms related to WEEE management and recycling. The most important ones are shown in Table 2.

As seen in Table 2, evolution of the WEEE legal system is ongoing. The Technical Policy on Pollution Prevention and Control of WEEE indicates that the focus on WEEE management has transferred from "waste disposal" to "pollution control and resources recycling". The purposes of these laws and legislation are to reduce, reuse and recycle WEEE. They not only encourage environmentally friendly processing for recycling of WEEE, but also provide special subsidies to support the WEEE recycling system and create a set of standards.

In drafting WEEE recycling legislation, it is important for the Chinese government to follow the advanced experience of developed countries, as presented in Section 2.1. From products manufacturing to e-waste disposal, the laws and legislation cover most aspects of national WEEE management in China, including manufacturing, collection, transport and final disposal.

The Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products is regarded as China's RoHS Directive. This Ordinance not only restricts the use of hazardous substances, but also requires manufacturers to provide detailed information about their products. Administrative Measures for the Recovery of Renewable Resources encourage establishing modern recycling enterprises, which promotes the formal collection system development. Administrative Measure on Pollution Prevention of Waste Electrical and Electronic Equipments regulates the activities of disassembly, recycling and disposal of WEEE. Moreover, this administrative document has put forward the principle of EPR. Regulation on Management of the Recycling and Disposal of Waste Electrical and Electronic Equipments is similar to the EU WEEE Directive to some extent, aiming at increasing WEEE recycling and establishing formal recycling system. It also points out that the recycling fee must be paid by producers and a special financial subsidy for the WEEE recycling system is set by the government. The funding model for WEEE management in China is clearly outlined within the Administrative Measures for Levy and Use of Treatment Fund for Waste Electronic and Electric Products (AMLUTF). The Ministry of Finance levies money from producers and importers of e-products through local taxes. The levy standards are 13 RMB, 12 RMB, 7 RMB, 7 RMB and 10 RMB, for each television, refrigerator, washing machine, air conditioner and personal computer, respectively. Enterprises and recognized dismantling facilities can get 85 RMB, 80 RMB, 35 RMB, 35 RMB and 85 RMB for each unit of the above products. Currently the exchange rate between RMB and US Dollar is 6.22 RMB for $1 USD. Manufacturers are encouraged to establish specialized factories for WEEE disposal and consider formal recycling systems for the first time. The implementation of AMLUTF makes it possible to deal with WEEE by the cooperation of manufacturers, distributors and disposal enterprises.

Aside from national legislation development, some major regions, such as Beijing, Shanghai, Zhejiang and Guangdong provinces, also have promulgated a series of local administrative measures. For instance, Beijing has published "Twelfth Five-Year Plan" period of waste electrical electronic products processing development planning in Beijing" and "Beijing waste electrical electronic products processing fund subsidies audit approach" (ILO, 2013). The measures aim to regulate the behaviors of enterprises, dealers and consumers, and to build the local system of e-waste take-back, reuse and recycling.

However, problems still exist when it comes to the implementation and execution at the present stage. Recycling and technical systems are still facing great challenges. First, the laws have established the qualified requirements for the licensed recyclers, which enable more centralized monitoring to ensure that standards are met. However, the issue of informal recycling has been largely ignored. In contrast to the formal recyclers, informal recyclers are numerous, widely distributed and operate on a small scale. Improvement of the informal recycling practices and environmental control of polluted sites is therefore must be timely planned.

Second, no single administrative institution fully supervises and executes the issued laws. Specific monitoring administrative institutions and departments are important to realize the goal of legislation and laws due to the centralized administrative powers. However, these are currently absent in China.

Third, no clear recycling target has been established. For instance, the amount of WEEE to be collected and treated annually by the formal sector has not yet been referred to in legislation. This lack of clarity will make execution difficult for local planning of collection activities and treatment capacity based on the targets.

Last, too many laws have been issued in recent years, leaving the stakeholders in a muddle. On the one hand, there is no sufficient time for them to update their technology to fit the legislation. On the other hand, the ever-increasing amounts of WEEE in China bring huge pressure on the limited specialized enterprises.

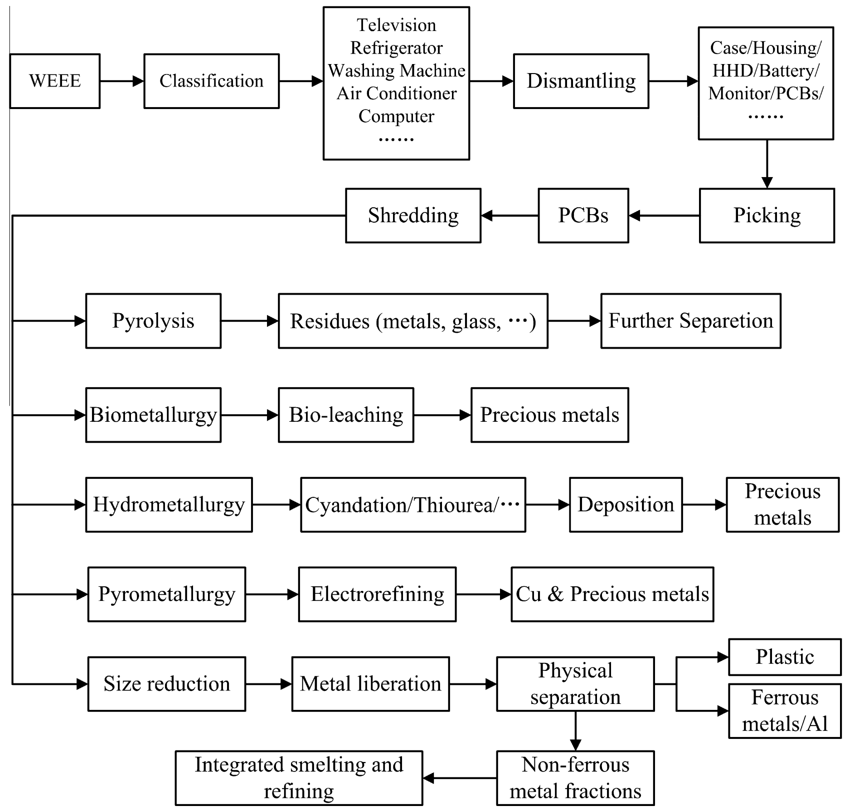

Fig. 2. General recycling processes of WEEE.

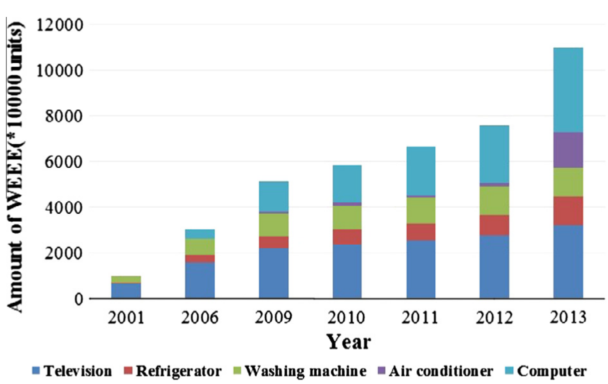

Fig. 3. Obsolete volume of five types of major electronic products from 2001 to 2013. (Date source: (CHEARI, 2013)).

3.2. Recycling system

With rapid urbanization, technical innovation and economic development, the total amount of typical WEEE generated in China had increased dramatically from 9.91 million units in 2001 to 109.80 million units in 2013 (CHEARI, 2013). Typical WEEE normally include televisions, refrigerators, washing machines, air conditioners and computers. Theoretical obsolete volume predictions (2001–2013) of these five electrical appliances are presented in Fig. 3 (CHEARI, 2013), where it is shown that the obsolete volume increased year by year with an average annual growth rate of 29.7%. On the other hand, although Chinese government has banned the import of WEEE after launching restricting legislation in 2002, large amounts of e-waste are still transported illegally from developed countries to coastal areas of China (Feng Wang et al., 2013). China has become the largest WEEE disposal center, and the recycling activities are complex. However, compared with the organized recycling of WEEE in developed countries, the recycling activities in China are mostly spontaneous (Li et al., 2013).

3.2.1. The informal recycling system

It is profitable to recycle WEEE for the informal sector. Chi et al. have reviewed the informal electronic waste recycling in China (Chi et al., 2011). According to their research, the situation of coexistence of the formal and informal recycling sectors led to a tough competition for WEEE, resulting in serious supply problems in the formal system.

Selling obsolete electronic products to individual collectors is the preferred option chosen by the households (Li et al., 2012). This behavior results in over 60% of the generated e-waste in China flowing into the informal recycling system (CHEARI, 2013). The main destination channels for WEEE are second-hand markets and private backyard workshops (Yang et al., 2008). Economic, social and technical factors contribute to the current pattern of recycling.

Essentially, the flourishing of WEEE informal recycling is driven by economic benefits. For most Chinese, the end-of-life electronic products are regarded as wealth, not waste, which is distinctly different from the developed countries. Yang et al. have depicted the situation in Beijing, and showed that the end-of-life electronic products were probably sold to street peddlers when a considerable price was given (Yang et al., 2008). Generally, the price offered by the individual collectors was higher than by the formal recycling enterprise.

China is still a developing country with more than 50% of the population living in rural areas (Qin and Zhang, 2014). According to a report by the Chinese Academy of Social Sciences (CASS), the average annual income of people in rural areas was about 1500 US dollars in 2014 (CASS, 2014). Due to a big gap in income and

Table 1
Some integrated pyrometallurgical processes for WEEE recycling. TSL: top submerged lanced; PGMs: platinum group metals.

Industrial processes	Metals recovered	Main process features	Refs.
Umicore's process; in Hoboken, Belgium	Au, Ag, Pd, Pt, Se, Ir, Ru, Rh, Cu, Ni, Pb, In, Bi, Sn, As, Sb	Isasmelt smelting, copper leaching and electrowinning and PMs refinery, lead smelting and refining	Hagelueken (2006)
Boliden Rönnskär smelters; in Sweden	Cu, Ag, Au, Pd, Ni, Se, Zn, Pb, Te	Smelting in Kaldo reactor, upgrading in copper and followed by refining, high PMs recovery	Lehner Theo (2009) and Sundqvist (2012)
Dowa; in Japan	Cu, Au, PMs, Ag, Ga 18 metal elements	WEEE TSL smelting in secondary copper process; combination of copper/lead/zinc smelting and refining	Naka (2006)
Outotec process; in Finnish	Zn, Cu, Au, Ag, In, Pb, Cd, Ge	Ausmelt TSL furnace, smelting of WEEE in copper/lead/zinc processes	Outotec (2013)
Noranda process; in Quebec, Canada	Cu, Au, Ag, Pt, Pd, Se, Te, Ni	Smelting of WEEE (14% of total feed) with Cu concentrate; upgrading in converter and anode furnaces; electrorefining for metal recovery	Khaliq et al. (2014)
LS-Nikko's recycling facility; in Korea	Au, Ag and PGMs metals	Recycling in TSL copper smelting and electrolytic refining	LS-Nikko (2013)
Aurubis; in Germany	Au, Ag, Cu, Pb, Zn, Sn and PGMs	Cu concentrate and WEEE in TSL reactor, black copper processing and electrorefining	Aurubis (2013)

Table 2
Major laws and legislation related to WEEE management in China (Yu et al., 2010; Zhou and Xu, 2012).

Laws/legislations/standards	Major contents	Issued by
Notification on importation of the seventh category waste (February 1, 2000)	Ban on the import of the seventh category of waste	Ministry of Environmental Production (MEP)
The technical policy on pollution prevention and control of WEEE (April 27, 2006)	Set principles of "3R" and "polluter pays principle"; stipulates eco-design; makes provisions for the environmentally sound collection, reuse, recycling and disposal of WEEE	MEP
The ordinance on management of prevention and control of pollution from electronic and information products (March 1, 2007)	Requirements for eco-design; restrictions on the use of hazardous substances; Requirements for producers to provide information about their products	Ministry of Industry and Information Technology (MIIT)
Administrative measures for the recovery of renewable resources (May 1, 2007)	Encourage processing of renewable resources recycling environmentally and technological innovation; Establish modern renewable resources recycling system and qualified certification for recycling enterprises	Ministry of Commerce (MOFCOM)
Administrative measure on pollution prevention of waste electrical and electronic equipments (February 1, 2008)	Intend to prevent the pollution caused during the disassembly, recycling and disposal of e-waste; licensing scheme for e-waste recycling companies	MEP
Regulation on management of the recycling and disposal of waste electrical and electronic equipments (January 1, 2011)	Mandatory disassembly and centralized recycling of WEEE; establish a special fund to assist e-waste recycling; certification for recycling Enterprises	National Development and Reform Commission (NDRC) MIIT
Administrative measures for levy and use of treatment fund for waste electronic and electric products (July 1, 2012)	Imported EEE shall be paid the fund; the state sets up the fund for the treatment of e-waste for subsidizing the cost for the recovery and treatment of WEEE	NDRC, MIIT, MEP, Ministry of Finance (MF), State Administration of Taxation (SAT), General Administration of Customs (GAC)

living standards between rural and urban areas, the penetration rate of electronic products is less than 50%, which is much lower in western China. Therefore, for people living in western China, or in rural areas, the demand of electronic products is far from being satisfied. Majority of electronic appliances, such as computers and air conditioners, are often still working, upgradeable or repairable, allowing these obsolete products to still function for some time. These products would be purchased by rural residents. In addition, the disposal fee of WEEE is nonexistence, or much lower than that offered by advanced enterprises. The treatment of WEEE is mainly by primary methods, such as hammering (Wen et al., 2006), manual sorting, open burning (Wong et al., 2007) (Gullett et al., 2010) and acid leaching (Li et al., 2007). The labor condition and environmental conservation are less than satisfactory (Bi et al., 2007).

Wide existence of the informal recycling system has become one of the significant barriers to the formal sector. The supply of WEEE is always insufficient, thus the formal recyclers can hardly afford competitive prices. The treatment costs in the formal system are much higher than the individual. Consequently, to promote the formal recycling system, the government has issued incentive polices and offered financial support for the WEEE industry.

3.2.2. The formal recycling system

In China, resources scarcity, rapid industrialization and urbanization make the supply of some critical metals challenging. Effective recovery of WEEE is indispensable not only for the environmental conservations, but also for utilization of resources and alleviating pressure of the critical metals supply risks. Since Chinese government has been paying great attention, national and local pilot programs, along with voluntary collective initiatives have been launched by manufacturers and distributors, and specialized companies participating in the WEEE recycling industry have been put into action.

In recent years, the development of WEEE formal recycling system has achieved remarkable progress. In 2008, less than 20% of WEEE were collected by specialized companies in Beijing, among which only about 10% were disassembled for the recovery of materials (Wang et al., 2011). However, in 2013, according to the report by the China Household Electric Appliance Research Institute (CHEARI, 2013), about 40% of WEEE were funneled into the formal system. The flows of WEEE recycling and disposal in China is shown in Fig. 4.

Since December 2003 when national pilot programs for waste resources were promoted in China, NDRC has designed 34 national

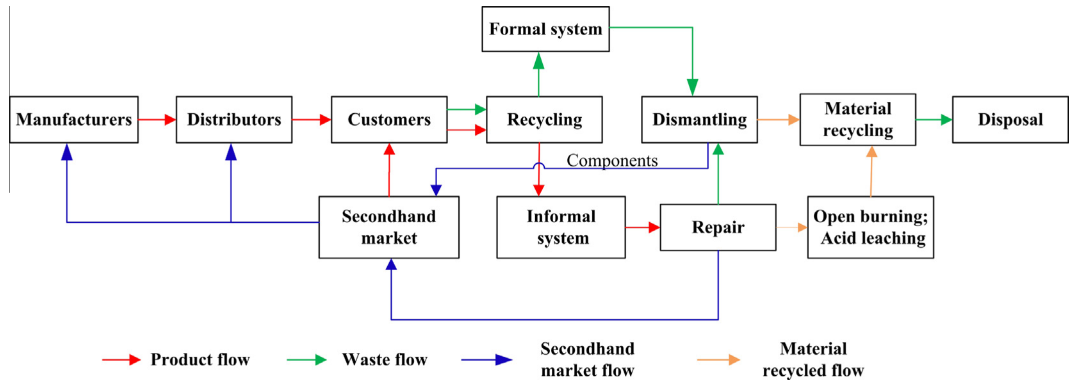

Fig. 4. Flows of WEEE recycling and disposal in China.

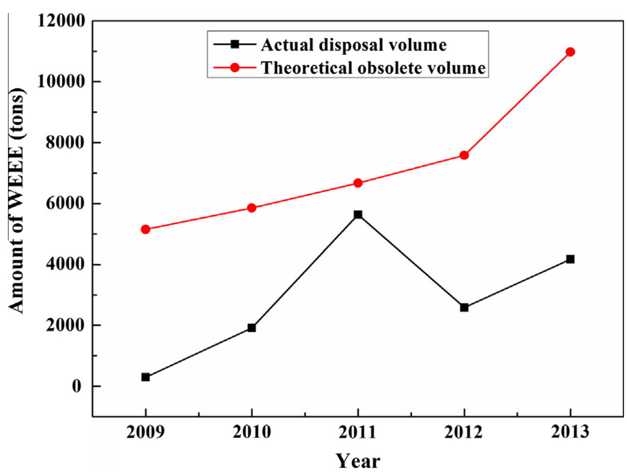

Fig. 5. Theoretical obsolete volume of WEEE and disposal volume by formal companies from 2009 to 2013. (Date source: (CHEARI, 2013)).

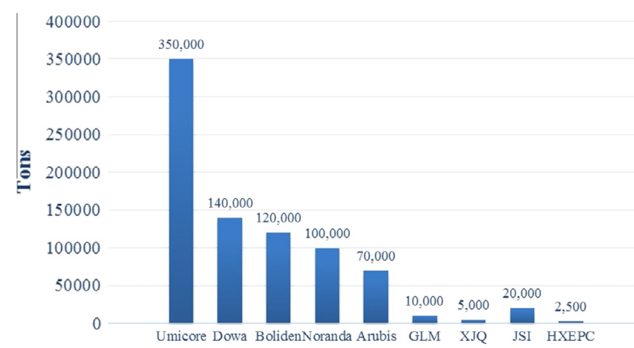

Fig. 6. WEEE disposal capacity of specialized companies. Dowa GLM: Shenzhen GEM High-tech Co., Ltd., XJQ: Shanghai Xin Jinqiao Environmental Co., Ltd., JSI: Jiangxi Self-independent Co., Ltd., etc., HXEPC: Huaxin Green Spring Environmental Protection Industry Development Co., Ltd. Only PCBs are calculated by GLM, XJQ, JSI, and HXEPC. (Date source: http://en.worldscrap.com and the websites of corresponding enterprise.).

pilot programs mainly in developed cities and coastal cities, among which fourteen are for the WEEE recycling, nine for metal recycling, three for discarded household appliances recycling and the rest for other types of recycling (NDRC, 2005). The NDRC claims that the pilot programs must analyze the recycling costs for improving related technologies and processes (Yang et al., 2008). Up to now, China pilot projects have been scaled up. For example, the disposal capacity of the Huaxing Environmental Protection Group Company, one of the directed pilots in Beijing, has boomed from 106,000 units in 2007 to 2,400,000 units in 2014 (HXEPC, 2015a).

In 2009, to tackle the economic crisis and boost domestic demands, China carried out a pilot program for replacement of household electrical appliances with a 10% subsidy, namely the “old-for-new” policy (SCC, 2009). The first period of the pilot started in 9 cities from June 2009 to May 2010, expanding to 28 cities in June 2010 and ending in December 2011. This policy developed a practical collection channel and funds operation mechanisms. Consumers, collection transporters and recycling companies could receive subsidies for the first time. Up to December 2011, the total of 95.3 million units of old electronic appliances were recycled (XHN, 2012). Fig. 5 shows the disposal and theoretical volume of WEEE from 2009 to 2013 (CHEARI, 2013). Obviously, this practice plays a key role in the foundation of China’s e-waste recycling system. Stimulated by the “old-for-new” policy, many manufacturers launched voluntary initiatives for establishing WEEE collection systems, such as Suning Appliance Co., Ltd., Haier Group, Changhong Electric Co., Ltd, aiming to establish a collective take-back scheme for the end-of-life electronic appliances. Meanwhile, the professional recycling enterprises scaled up sharply due to the adequate supply of WEEE. By the end of January 31, 2011, the government ended the “old-for-new” policy. However, the disposal volume by the formal sector decreased dramatically. The recycling system got into trouble again and the supply of WEEE turned to be insufficient.

Along with the development of national pilot programs and the “old-for-new” policy, many specialized enterprises devoted to the WEEE recycling industry have been created. After the end of the “old-for-new” policy, the government has issued new policies to subsidize WEEE treatment facilities to change this situation. In 2011, the NDRC issued Regulations on Recovery Processing of Waste Electrical and Electronic Products, which primarily aimed at regulating the recycling of WEEE, as well as comprehensive utilization of resources and environment protection. In 2012, Administrative Measures for Levy and Use of Treatment Fund for Waste Electronic and Electric Products provided the subsidy standard for WEEE dismantling. Under the impetus of related policies, the formal recycling and disposal of the WEEE industry came back on track. By the end of 2014, there have been 106 specialized companies on the fund subsidy list, and can dispose over 100 million units of WEEE. However, only 40 million units were disposed in 2014 (MEP, 2015).

Shenzhen GEM High-tech Co., Ltd. is one of the state-of-the-art high technology enterprises, specialized in resource recovery and recycling, found in 2001. GEM devote all attention to exploit “urban mines”, and are committed to recycle 500,000 tons of e-wastes, used batteries, and wasted Co and Ni scraps annually.

So far, the WEEE collection network of GEM covers nearly 100 cities in Hubei, Jiangxi and Hunan provinces. GEM has established the first e-waste recycling system with the combination of recycling boxes and recycling shops in China. In accordance with the principle that WEEE are provided by volunteers for free, or for a nominal fee for others, GEM has established its own recycling system (GLM, 2015).

To increase the recycling rate of WEEE, a "Business-to-Consumer" (B2C) recycling model was proposed by the Huaxin Green Spring Environmental Protection Industry Development Co., Ltd. (HXEPC, XJP, 2013). People prefer to sell their obsolete electronic products to individuals. One of the reasons is that there are no formal appointed sites to recycle WEEE, or it is just for convenience. The B2C model can relieve this situation to some extent. Consumers can register their information of WEEE online, volunteer to donate or get a reasonable price, while the recycling company will provide "door-to-door collection" service offline. Similar recycling models can be popularized around the whole country.

As shown in Fig. 6, the handling ability of China's professional companies are obviously dwarf compared to developed countries. In developed countries, due to the well-established recycling system, WEEE are collected by appointed organizations or departments and transported to professional companies for treatment. Therefore, WEEE market is highly centralized. For this reason, WEEE are treated by the pyrometallurgical process for its high efficiency, high metal recycling rates, and suitability for complex feed materials. However, when it comes to China, WEEE recycling activities are quite diverse from an individual to national levels. More than 60% of WEEE are treated by the informal sector, and the rest are distributed to hundreds of qualified companies, as shown in Fig. 7 (CHEARI, 2013). On the one hand, the market concentration of WEEE is far behind of the advanced world level. On the other hand, this diversity is attributed to the insufficient supply of WEEE, leading to the low utilization of workers and equipment. Hence, these companies prefer to choose flexible recycling technologies with relatively low investment.

3.3. Technical system

3.3.1. Informal technologies

Widely immature recycling activities by the informal system are the main problem compared with developed countries. Informal sector prefers to choose private processes, such as acid leaching and open burning, for the recovery of metals from waste WEEE, resulting in serious health risks and environment pollution.

Acid leaching is used to recover precious metals from WEEE. However, the spent acid, which is rich in heavy metals and leachates from the WEEE dumpsites, was disposed on land or in water, posing serious threats to local environment and human health (Premalatha et al., 2014). At Guiyu, the largest informal recycling localities in China, soils were contaminated by acid leaching activities, and rice crop soils showed total polychlorinated dibenzopdioxin and dibenzofurans (PCDD/Fs) concentrations that were approximately 15,300 and 2160 times higher than the ecological screening level for total PCDD/Fs (Sepúlveda et al., 2010). Concentrations of heavy metals, such as Ag, Cd, Cu and Ni were significantly elevated in rivers within Guiyu (Premalatha et al., 2014). In addition, workers were facing adverse working conditions, such as released gases, acid solutions and toxic smoke.

Open burning is another typical unsound treatment. Dioxins were generated due to the combustion of brominated flame retardant (BFR) in the PCBs. The concentrations of atmospheric dioxins in Guiyu ranged from 64.9 to 2365 pg m^{-3}, while the safety concentration is below 0.6 pg m^{-3} (Li et al., 2007). Reports have also showed that levels of Cr, Cu and Zn in dust particles were elevated (Deng et al., 2006). The mean blood lead levels (BLLs) in children of Guiyu (15.3 μg dL^{-1}) exceed the Chinese mean (9.29 μg dL^{-1}) value by a large margin, thus posing a potentially serious threat to children's health (Song and Li, 2014; Zheng et al., 2008).

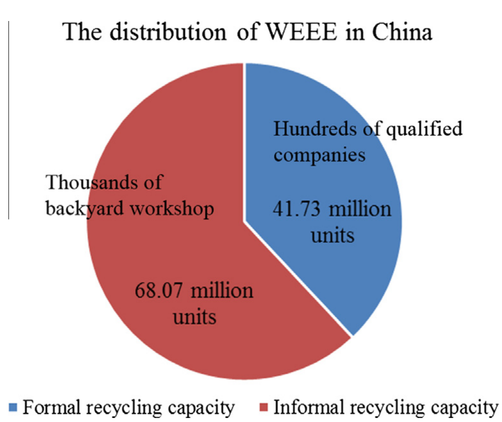

Fig. 7. The distribution of WEEE in China. (Date source: (CHEARI, 2013)).

3.3.2. Formal recycling technologies

These specialized companies can be generally divided into two - kinds, depending on their recycling technologies of WEEE. One is focused on the pre-treatment of WEEE, generally including dismantling, crushing, and physical separation. HXEPC, XJQ and GLM are the typical ones. The other kind is mainly for the final disposal by metallurgical processes, and the representative case is JSI.

The recycling and disposal of e-waste in HXEPC is a national demonstration project in China, as well as a key construction project in Beijing. In 2011, HXEPC has established the disposal base with independent intellectual property rights, including television, refrigerator, washing machine, air conditioner, computer, and PCBs disposal line (HXEPC, 2015a).

HXEPC is equipped with advanced CRT TV/monitor disassembly line, as shown in Fig. 8, which can disassemble 0.46 million TV units annually (HXEPC, 2015b). CRT is hazardous and the key problem lies in the separation of lead-contained CRT glass (Xu et al., 2012). HXEPC developed heated metal wire technology to achieve the proper separation between panel faceplate and funnel glass. Funnel glass containing lead would be treated for lead recovery. Phosphor would be recovered from the faceplate. This integrated separation technology is efficient and environmentally friendly. However, the production of televisions with remanufactured CRT was prohibited since 2005 in China. Therefore, there is a contradiction between the popularization of technology for CRT recycling and the product life cycle.

An integrated recycling process, which ranged from waste classification to product remanufacturing was proposed by GEM for the complete recycling of WEEE, as shown in Fig. 9 (GEM, 2015). Before material separation, WEEE was classified and crushed into particles. This process integrated magnetic, eddy current, cyclone air and corona electrostatic separation to effectively separate metal and non-metal fractions. The entire flow line was finished in an enclosed system. The off gas and dust emissions were strictly controlled by the activated carbon adsorption and dust collector. Metals were recovered from WEEE by physical and mechanical methods, and there was no waste water or residue emission. However, the metal fraction needed to be further separated for metal recovery. The non-metal fraction was used for manufacturing wood plastic composite (WPC) for high value utilization. The WPC was high density, high strength, and low deformation, which was a good alternative for plastic and anticorrosive wood products.

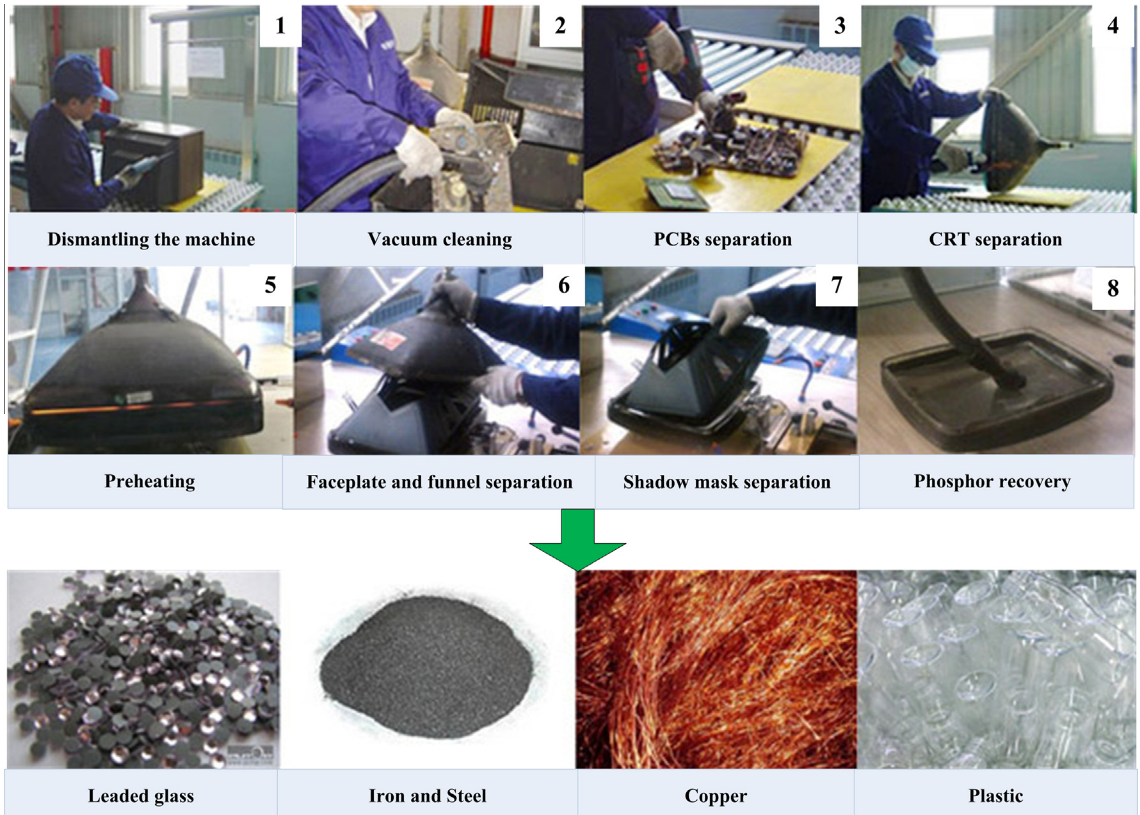

Fig. 8. CRT TV/monitor disassembly line in HXEPC. (From: (HXEPC, 2015b)).

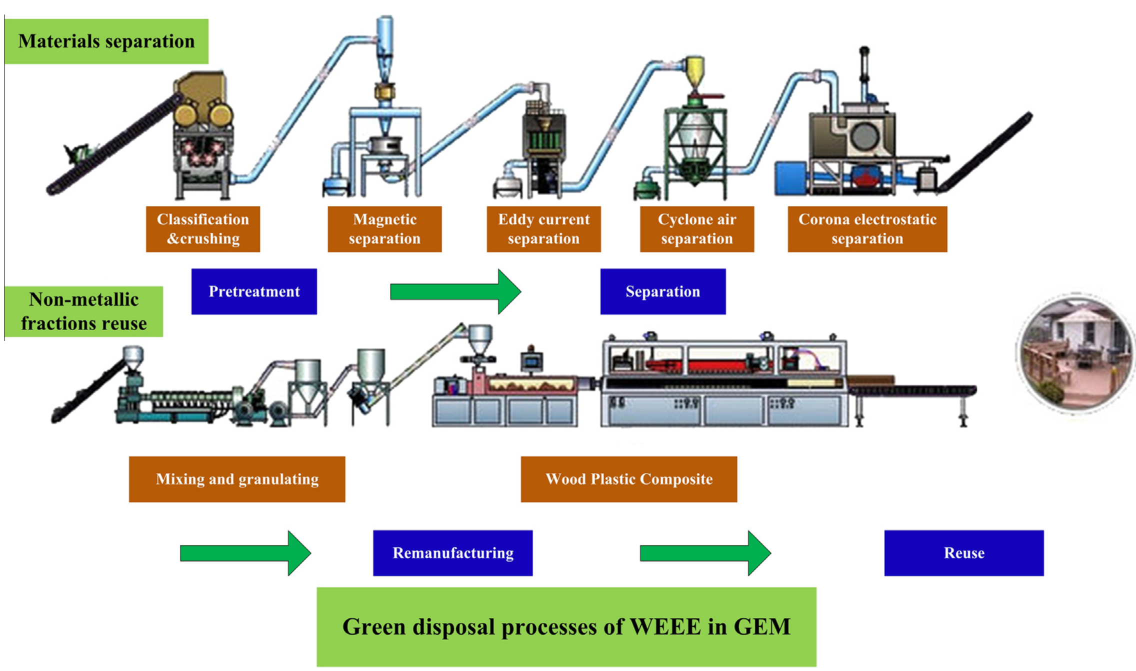

Fig. 9. Flowchart of WEEE green disposal processes at GEM. (From: (GEM, 2015)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

PCBs are valuable materials, and are part of almost all WEEE. The recycling of PCBs is difficult due to their distinctive characteristics, such as complicated structure, toxicity, and high hardness (Ghosh et al., 2015). In China, fluid bed separation, based on density separation, was widely used for waste PCBs recycling by small scale enterprises due to low investment and easy operation (Huang et al., 2009). This method involves wet crushing and water separation. However, the metals recovery rate is about 70% and 30% of metals are lost. The generated wastewater and residues will lead to serious secondary pollution without proper treatment.

Xu and his team members have done lots of work on relevant techniques and equipment for recycling of waste PCBs (Jujun et al., 2013; Wu et al., 2008). They have investigated a set of automatic lines for recycling waste PCBs (Li and Xu, 2010). The whole process contains four parts: multiple scraping, multiple-roll corona electrostatic separation (CES), multiple-roll cyclone air separation, and dust precipitation. The flow process chart of the automatic line is shown in Fig. 10 (Li and Xu, 2010). The average size of materials is finally reduced to 0.6–1.2 mm after multiple shredding. Then the particles are fed to CES for recovery of metal and nonmetal particles. A dust collector is used to precipitate dust resulting from the scraping and material delivery. This process indicates that the recovery rate of metals could reach up to 95%. The metal fractions need further separation. The non-metal powders maintain their original properties and can be used as wood plastic composite (Guo et al., 2009) or phenolic molding compound (Guo et al., 2008). According to their analysis, the automatic line has distinct advantages of lower energy consumption, better technology rationality, and environmental friendliness compared with other production lines (traditional fluid bed production line and processing from developed countries). This process has been installed and applied in some enterprises, such as Shanghai XJQ and Yangzhou Ningda Precious Metal Co., Ltd. XJQ can process about 5000 tons of PCBs by this production line annually.

Usually, the non-ferrous metal fractions from PCBs are recovered via secondary copper smelting processes. The secondary copper smelting is an attractive method for the ability of receiving high levels of impurities, including Pb, Sn, Sb, precious metals and other metals. These impurities are upgraded and remained in the anode slime by the following electro-refining process. The anode slime contains various kinds of elements, which are hard to be separated. Hence, Zhang et al. have studied the complete non-cyanogens wet green process for overall recycling of the anode slime. In their study, the valuable metals (such as gold, silver, platinum and palladium, lead, tin and antimony) were selected and recovered with the waste water recycled, as shown in Fig. 11 (Zhang et al., 2012). The overall metal recycling rate has reached up to 98%. The purity of the cathode copper was up to 99.99% level. The recovery rates of gold, platinum, palladium, silver, lead, tin and antimony were over 98%, 96%, 96%, 95%, 95%, 90%, and 90%, respectively.

In 2013, these professional WEEE recycling companies have recycled 96,300 tons of steel, 19,800 tons of copper, 5200 tons of aluminum and other materials (CHEARI, 2013). In addition, the companies have dismantled over 700,000 units of refrigerators and air conditioners. Consequently, the formal activities avoided the emission of more than 100 tons of refrigerant, which was equivalent to the emission of about 1.0 million tons of CO_2 (CHEARI, 2013). Hence, the WEEE formal recycling activities not only have an impact on resources conservation, but also bring a profound influence on the global environment changes.

3.4. Challenges for WEEE recycling in China

As discussed in Section 3, China has achieved a great progress in legislation, recycling systems and technologies of WEEE. The encouraging legislation indicates the government approach on WEEE recycling. The pilot programs and the "old-for-new" policy have a great effect on forming the official recycling system nationwide. The special fund and subsidies provided by the government stimulate specialized enterprises to actively participate in WEEE recycling activities. The advanced technologies employed in the WEEE recycling industry significantly enhance the resources recovery, reducing the risks for the environment and humans. However, it becomes a challenge due to the unique situation in China, which is distinct from other countries, which have implemented legislation.

First, dynamic and diverse electronic manufacturing sectors in China challenge the implementation of EPR (Yu et al., 2010). One precondition for implementing EPR is that a producer can be identified. China has become the world's largest manufacturer of electronic products and the number of new electronic manufacturers is increasing, while others get bankrupt and go out of business. Therefore, it is difficult for the government to identify all producers and impose responsibility upon them. This is contrast to the US and Europe, owning to a relatively small number of large enterprises with relatively low growth.

Second, due to economic factors, the informal recycling is very profitable in China (Yang et al., 2008). It turns out that the informal collectors pay consumers for WEEE. Therefore, most consumers in China are willing to sell their discarded products to street peddlers, unwilling to participate in the collection systems, which need to pay for the discarded electronic products. This situation can be hardly changed in the present time. This is the reason that the pilot projects in China failed to collect sufficient WEEE: the incentives offered by the formal system are not attractive enough compared to those offered by the informal sector (Yu et al., 2010). In the present stage, it is difficult to change the public opinion of paying fees for their discarded product. Presently, a special legislation referred to the responsibilities of different stakeholders (government, manufacturers, dealers, and consumers) is absent in China. In some sense, it is the basic reason, which leads to the disorder in the WEEE recycling system.

In general, the technical system is determined by the recycling system to some extent. The recycling situation in China leads to the market concentration of WEEE much less than in the developed countries, resulting in the lack of large integrated recycling plants. The application of advanced technologies in large integrated

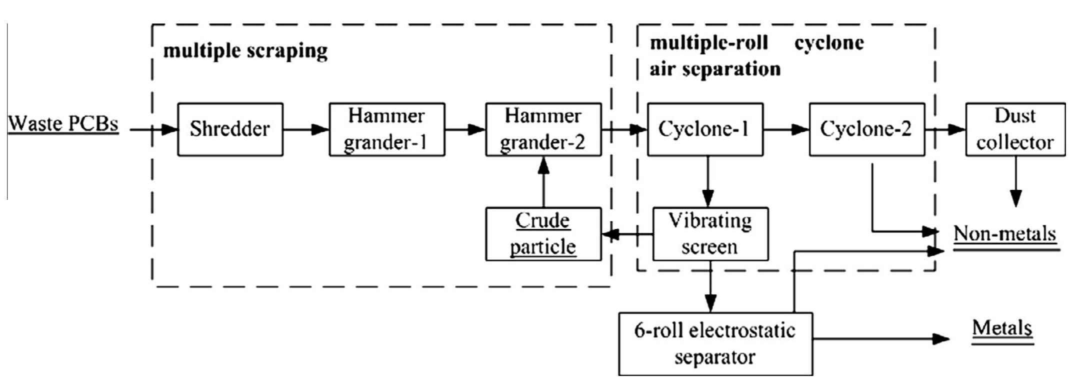

Fig. 10. The flow process chart of the automatic line (Li and Xu, 2010).

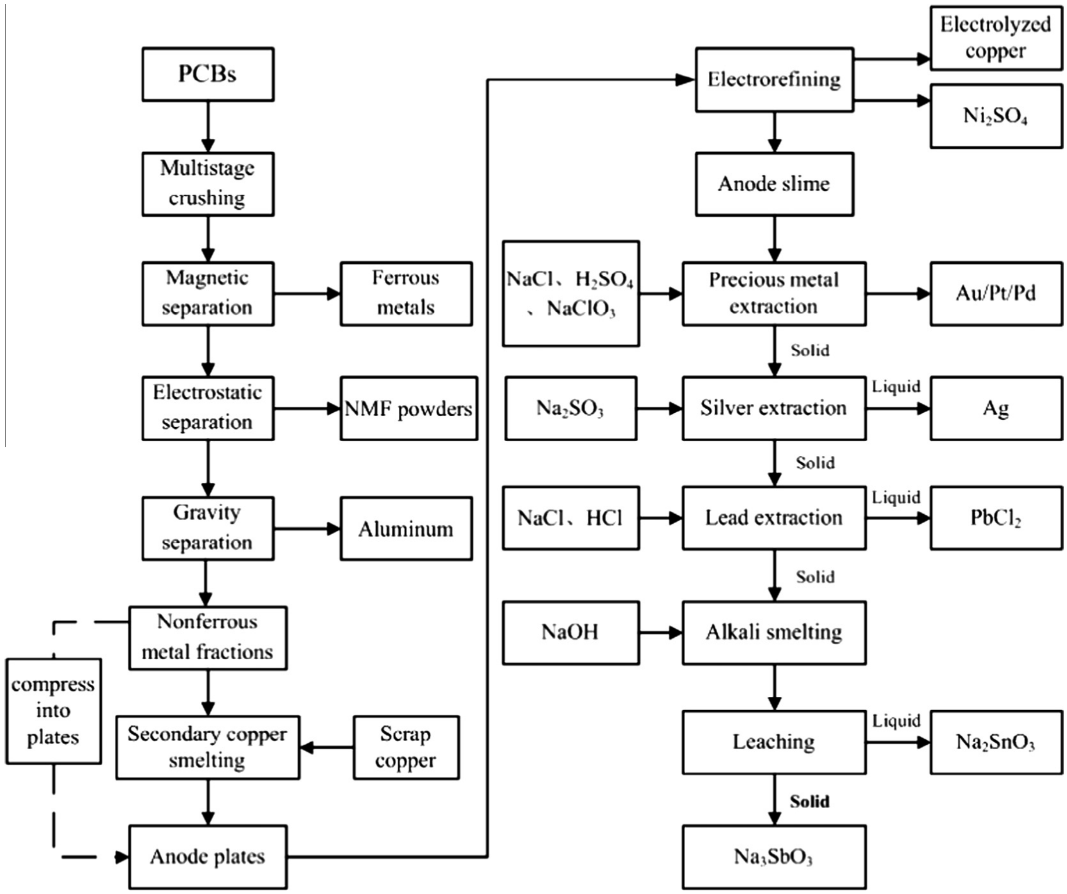

Fig. 11. Complete non-cyanogens wet green process for overall recycling of waste PCBs (Zhang et al., 2012). NMF: non-metallic fraction.

recycling plants significantly enhances materials recovery and reduces the impacts on the environment and humans. However, the inadequate supply of WEEE leads to low utilization rate of facilities, resulting in higher cost than the informal ones. Currently, the most urgent problem is to restrict WEEE entry into the informal recycling sectors and increase the processing capacity of qualified enterprises.

However, most enterprises are focused on dismantling of WEEE to obtain subsidies from the government, ignoring deep processing for materials recovery. Most components dismantled from WEEE are waste PCBs. However, related legislation has not referred to this flow. Furthermore, there is no any fund or subsidy for the final disposal of waste PCBs, leading to the absence of specialized final disposal enterprises. Consequently, waste PCBs finally enter the informal sector. Chinese government has realized this situation and is making efforts to enhance the WEEE recycling technologies. On the 28th of September 2014, National Electronic Waste Recycling Engineering Research Center (EWR-ERC) was formally approved by the National Ministry of Science and Technology (MST, 2014). This center will reach the world's e-waste recycling technology level, promoting the development of China's harmless e-waste recycling and recovery by conquering the key technologies of e-waste recycling, supporting the industry and serving the country.

4. Future of WEEE recycling in China

To this end, future development of WEEE recycling system is put forward, as shown in Fig. 12. Actually, the legal, recycling and technical systems complement each other. First and most important, it is required to establish a reasonable and workable legal system to optimize recycling and technical systems. To realize this goal, specific monitoring administrative institutions are indispensable and the responsibilities of different stakeholders need to be clear. Also, it is necessary to have clear recycling targets for planning and collection activities. The legal system accelerates the formation of mature WEEE recycling system. National and local pilot programs, different stakeholders, including manufacturers or distributers, specialized companies, and customers, are participating in WEEE recycling. WEEE flow into the appointed qualified recycling enterprises and are centralized to be dealt with. Therefore, integrated recycling plants with the advantage of high efficiency are prior to be selected as the final processing methods to deal with large amounts of WEEE.

Generally speaking, the key factor of WEEE recycling in China is collection. For the Chinese government and formal recycling enterprises it is a major challenge and an urgent problem to figure out how to divert more WEEE flow from the informal to formal channels. To optimize WEEE collection, on the one hand, the government, producers, or recycling enterprises need to set up permanent collection infrastructure for WEEE, providing convenience for consumers to return their obsolete products. On the other hand, raise the public awareness of waste management. Another scheme is to transform or integrate existing informal recyclers into the formal ones. The government or the enterprises provide a base salary to individual collectors, encouraging them to participate in the formal recycling business.

As mentioned above, the state-of-the-art integrated smelting and refining facilities are successful in recycling metals from WEEE in some developed countries. The integrated smelting and refining facilities need optimization and an efficient emission

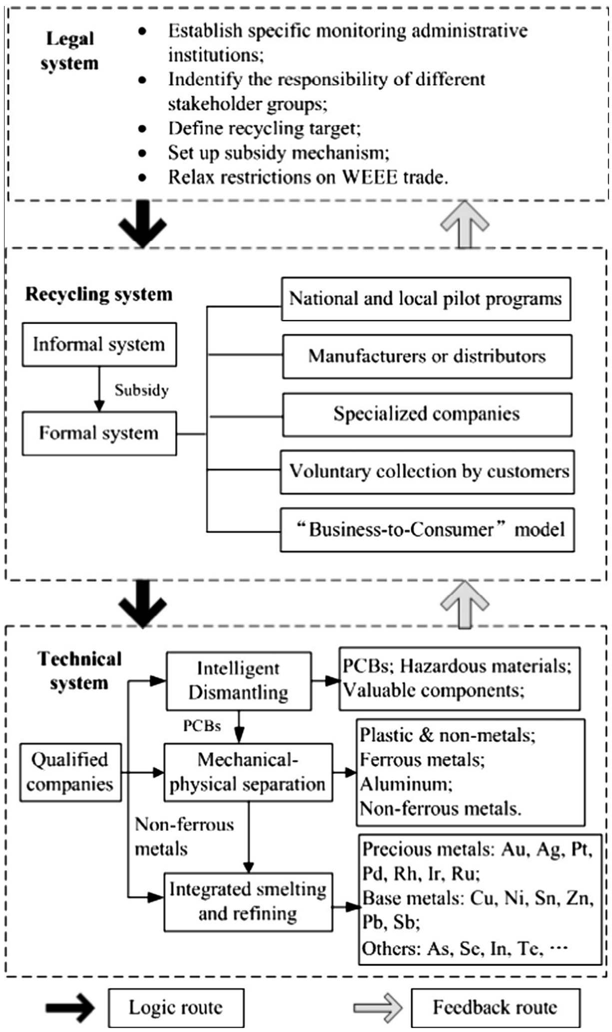

Fig. 12. Future development of the WEEE recycling system in China.

control system. The contaminants should be controlled from the environmental protection standpoint. Thus, the government should encourage and help qualified enterprises to improve the WEEE processing ability by financial subsidies.

In future, with the development of recycling technologies, the technical system will feed the recycling and legal systems. Large integrated recycling plants require sufficient supply of WEEE to raise the utilization ratio of facilities and reduce cost. Thus, a highly centralized recycling system is needed. Once the specialized enterprises profit, like Umicore, they will have the ability to compete with the informal sector. Then the WEEE informal system will disappear step by step. For the legal system, WEEE is an important source of some critical metals, not just the hazardous matter. Related laws and legislation of WEEE management need to keep pace with the recycling technologies. The ban of trans-boundary trade on WEEE should relax restrictions to qualified enterprises in a proper sequence.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2015.05.015.

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