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The Social Cost of Informal Electronic Waste Processing in Southern China

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A B S T R A C T

Large amounts of e-waste are processed "informally" in lower income countries. Such processing releases dangerous pollutants, which increase mortality and reduce cognitive functioning. This paper estimates the social cost of informal e-waste processing in Southern China. This parameter may be "plugged-in" to cost-benefit analyses that evaluate the economic efficiency of policies to reduce informal e-waste processing in China or other lower income countries. It may also be used in the estimation of the social benefits (or costs) of new or proposed e-waste processing policies in higher income countries. We estimate that the social cost of informal e-waste processing in Guiyu is about $529 million. This amount is equivalent to about $423 per tonne (in 2018 US dollars) or $3528 per person, which is over half the gross income per capita of the residents of Guiyu. We also perform sensitivity analysis that varies the estimated mortality outcomes, the value of a statistical life and the amount of e-waste processed.

A R T I C L E I N F O

Keywords:
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1. INTRODUCTION

Economists and policy analysts argue that a primary goal of government policies or programs should be to increase economic efficiency, also called allocative efficiency (Boardman et al.2018). Thus programs should be evaluated in terms of their net social benefits that is the net benefit to society as a whole. Net social benefits equal social benefits minus social costs. Social benefits are based on individuals' willingness to pay while social costs are opportunity costs basically the value of the resources society has to "give up" in order to implement a particular program. For inputs that are bought and sold in well-functioning markets the market price is a reasonable measure of the opportunity cost. However, for many impacts of government programs, there is no market price for example for lives saved or for different forms of pollution. For such social impacts, economists estimate shadow prices, that is, the price that the impact would be in a well-functioning market if one existed.

Viscusi and Masterman(2017a) analyze many estimates of the value of a statistical life (VSL). Recently Vining and Weimer(2019) estimate the social benefit of high school graduation in the United States. TheNational Academies of Sciences, Engineering, and Medicine(2017), Marten et al.(2015) and numerous other researchers have estimated the social cost of carbon dioxide emissions and other greenhouse gas emissions. Other researchers have estimated shadow prices for other impacts including the social cost of injuries and of automobile accidents with different level of severity the social cost of crime the social cost of noise the value of travel time saved and the value of recreation (Boardman et al.2018). Such estimates can be "plugged-in" to cost-benefit analyses (Boardman et al.1997). For example, the shadow price of the VSL can be plugged in to studies evaluating alternative health and safety programs, and the value of a high school diploma can be plugged in to studies that directly or indirectly seek to increase the number of students who graduate from high school. AsVining and Weimer(2019) note, plug-ins not only lower analytic costs, but also promote consistency.

The research question in this paper is: what is the social cost of informal e-waste processing (SCIEWP) in Southern China? This is an understudied topic. Indeed, no previous research has estimated this shadow price. We express the social cost in terms of the total social cost to residents of Guiyu, in terms of dollars per tonne (1000 kg) of e-waste processed and in terms of dollars per person. Estimating this shadow price is important because, as we discuss in the next section, the amount of e-waste is growing rapidly. Furthermore, informal e-waste processing has severe negative impacts on those who process it and on others in the community.1 This issue requires more government attention and intervention. A SCIEWP provides an informed indication of the nature and extent of the problem. This, in turn, can provide a better rationale for government intervention than currently exists. In particular, the SCIEWP expressed in terms of dollars per tonne provides an estimate of the amount society should be willing to pay to reduce informal e-waste processing by one tonne. Our shadow price can be plugged-in to quantitative analyses of alternative government policies that attempt to mitigate this problem. It is particularly applicable to the evaluation of policies in importing countries pertaining to the importation of e-waste, changing e-waste processing methods, or the relaxation or tightening of current environmental policies or regulations. However, it is also important when evaluating the social benefits (or costs) of environmental policies in higher income countries, for example, those pertaining to the extent to which producers are responsible for identifying and ensuring the implementation of end-of-life management policies for their products.

In order to derive the SCIEWP, we focus on e-waste processing in Guiyu, a town in Guangdong province. At the time of our research, Guiyu and surrounding regions constituted the largest e-waste processing site in the world. Research byWu et al.(2010) andZhuang(2017) suggests that this area processed approximately 1.25 million tonnes of e-waste annually.

Our methodology follows standard practice in cost-benefit analysis for more information see Chapter 1 inBoardman et al.(2018). In this paper only the residents of Guiyu have standing. Impacts on residents of other jurisdictions are not considered. In the conclusion, we discuss the implications of this assumption. Our analysis consists of three main steps. The first step which is discussed in Section2, identifies the main impacts of informal e-waste processing. We focus on mortality and lost productivity. The second step, which is discussed in Section3, estimates the impact of informal e-waste processing on mortality. The third step, which is discussed in Section4, is to estimate the social cost of e-waste processing in Guiyu. We obtain an estimate of the VSL of residents of Guiyu and, by combining this parameter with our analyses in Section3 we monetize the mortality impacts of e-waste processing in Guiyu. Then we estimate the social cost of lost productivity due to children's impaired cognitive abilities and add it to the mortality cost to compute the social cost of e-waste processing in Guiyu. Finally we derive our shadow price estimate in terms of dollars per tonne of e-waste processed and in terms of dollars per person. Section4also includes sensitivity analysis where we vary the estimated mortality outcomes the VSL and the amount of e-waste processed in Guiyu. Section5 concludes the paper with a review of our results a discussion of some limitations of our analysis and potential policy applications.

Our main conclusion is that the social cost of informal e-waste processing in Guiyu is about $529 million and the SCIEWP in Southern China is about $423 per tonne (in 2018 US dollars). Most of the information used to compute the excess levels of pollutants in Guiyu date from about 2010. Thus our estimates of the social cost of e-waste processing and the SCIEWP can be thought of as an estimate of the costs borne by the cohort of individuals living in Guiyu in 2010. Since that time government policies in China have changed and, in fact, informal e-waste processing in Guiyu has decreased. Thus, the social cost of e-waste processing in Southern China is different now. However, our estimate of the social cost per tonne is still likely to be applicable in the evaluation of policies pertaining to areas where informal e-waste processing is similar to the conditions that existed in Guiyu in about 2010. Of course, whenever shadow price estimates are applied to other jurisdictions or time periods, they must be adapted to the specific circumstances.

2. E-WASTE GENERATION AND PROCESSING, AND THE RESULTANT HEALTH IMPACTS

The amount of e-waste generated worldwide is increasing rapidly. Schluep et al.(2009) estimated that worldwide generation of e-waste in 2009 amounted to over 40 million tonnes. By 2016, the figure ballooned to 45 million tonnes, or 6.1 kg per inhabitant, an 18 percent increase from 2014 (Baldé et al.2017) . In Europe, e-waste production has grown 16–28 percent every five years, three times faster than the growth in aggregate municipal waste (UNEP2007).Bald é et al.(2017) predicts e-waste generation to increase to 52.2 million tonnes (6.8 kg per inhabitant) by 2021.

E-waste generation is increasing in higher per capita income countries, primarily due to increasing obsolescence rates of electronic devices. CPU lifespans have decreased from 4–6 years in 1997 to only two years in 2005 (Needhidasan et al.2014). As the price of electronic devices continues to fall, replacements become more cost efficient than repairing, thus the lifespans of electronic devices continue to decrease (Konoval2006).

In low income countries, e–waste production is increasing due to the increased use of electronic devices. In the Asia-Pacific region, personal computer penetration grew at a compounded annual growth rate of 26 percent in the fifteen years leading up to 2005. Africa, the Middle East, Eastern Europe and South America have experienced similarly dramatic increases, and the installed base of computers and electronics in these regions will increase further as incomes rise and technological advances make electronic devices cheaper.

Some of the e-waste generated in advanced countries is processed in those countries. However, national e-waste generation rates have outpaced e-waste collection rates. In Canada in 2014, 20 percent of the e-waste generated was processed through recycling programs, while the remaining 80 percent entered landfills or were informally processed overseas (Kumar and Holuszko2016) . The amount of e-waste processed in lower income countries continues to grow Lundgren(2012, p. 14) estimates that exporting e-waste to lower income countries is ten times cheaper than it is to recycle it in the United States.

E-waste is composed of more than 1000 different substances, including ferrous metals and non-ferrous metals, plastics, glass, wood and ceramics (UNEP2007). Some of these substances are economically valuable, including reusable plastics and glass, and trace amounts of gold, silver and copper. However, e-waste also contains toxic substances like flame-retardant plastics and heavy metals like lead, mercury, cadmium and chromium. In Guiyu, the majority of e-waste recycling sites are small-scale, family-based workshops which use manual disassembly, open burning and acid leaching (Liu et al.2011;Guo et al.2014). This informal processing releases poisons that leach into the soil and groundwater and emit toxins during incineration. The most serious consequence is premature mortality and morbidity.

As shown in Table1, informal e-waste processing is much less safe than best available technologies (UNFCCC2012). The unsafe practices used in Guiyu make citizens vulnerable to the excessive pollutant emissions from many substances. This paper focuses on pollutants that are ubiquitous in the recycling process and probably have the largest impact on health and mortality: lead, dioxins and furans as well as particulate matter.

Table 1. Comparison of E-waste Recycling Processes Using Presently Applied Technologies and Best Available Technologies.

	Presently Applied Technologies	Best Available Technologies
1	Functioning components (like cables, power supplies) are removed for reuse.	E-waste is manually separated into reusable components and end-of-life parts.
2	Deflection and focusing coils are removed by breaking off the neck glass.	The e-waste is processed in an enclosed mechanical system which segregates the materials using a four step process: a. E-waste is shredded into small pieces of two inches in size. b. The e-waste pieces are placed into a magnetic separator where ferrous metals are collected. c. The non-ferrous metals pass through an eddy current separator where the materials are sorted. d. The dust generated is collected in a bag filter and sent to the metallurgical refining unit for processing.
3	The monitor is manually dismantled to extract steel, aluminum, and copper parts.	The e-waste is now sorted into five types of materials: glass, plastics, aluminum, ferrous metals and non-ferrous metals. a. Ferrous metals are sold directly to steel plants. b. Aluminum is sold directly to smelters to be reused for commercial purposes. c. Plastics are segregated into recyclable and non-recyclable fractions, and processed accordingly.
4	Cables and other components are incinerated in the open to recover copper.	Non-ferrous materials are recycled in a controlled manner (smelting, electronic refining).
5	CRT glass and residues are crushed and disposed in an uncontrolled manner, without regard for emissions.	Hazardous materials are removed from the glass and transferred to external recyclers for proper processing.

Source: Adapted from UNFCCC (2012).

2.1. The Health Impacts of Lead

Due to its malleability and resistance to corrosion, electronic devices often contain lead. In e-waste, the primary source of lead is found in monitors of CRTs and the solder of printed wire boards(Jang and Townsend2003 Vann et al.2006). Human exposure to lead is exacerbated through primitive recycling processes which emit dust and contaminates soil, food or water (Wang and Zhang2006; Leung et al.2006;Liu et al.2011). Children are frequently involved with e-waste processing and play with the electronic devices at the worksites (Guo et al.2014). They are particularly vulnerable because their bodies absorb lead more readily than adults (Huo et al.2007). Exposure to lead can lead to a diverse array of health effects, including an increased risk of cardiovascular disease, cancer, and renal disease. Elevated blood lead levels affect the physical development of children and may cause adult osteoporosis (Yang et al.2013).Liu et al.(2011) also documented alterations to the temperament of children due to lead exposure.

2.2. The Health Impacts of Dioxins and Furans

Minh et al.(2003) found that open waste dumping sites like those in Guiyu are significant sources of dioxins (technically, polychlorinated dibenzo-p-dioxins) and furans (technically, polychlorinated dibenzofurans). These substances are sometimes referred to as polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F). Dioxins can take many forms, the most toxic of which is 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD). Elevated levels of this pollutant have been found in workers exposed to e-waste recycling (Leung et al.2007;Chan et al.2007). Chan et al.(2007) provides a comprehensive study of the presence of dioxins and furans in e-waste recycling towns.

Significantly high levels of these compounds were found in the human milk, placenta and hair samples of residents living close to the Taizhou e-waste recycling site, which is close to Guiyu. In fact, the concentrations of PCDD/Fs in the human milk of Taizhou mothers are ranked second highest in the world.

Dioxins and furans lead to an increased risk of cardiovascular disease, cancer, and diabetes. Chan et al.(2007) notes that postnatal exposure to dioxins adversely affects infants' thyroid hormone systems and immunological functions. Health impacts of 2,3,7,8-TCDD include an elevated risk of circulatory diseases (Steenland et al.1999;Flesch-Janys et al.1995;Bertazzi et al.1989) and cancer mortality (Fingerhut et al.1991).

2.3. The Health Impacts of Particulate Matter (PM)

The presence of particulate matter (PM) has become a major concern in China, especially in large urban areas like Beijing, Shanghai and Chongqing. The informal recycling process incinerates e-waste, which leads to the emission of PM, mainly due to the combustion of plastic materials (Gu et al.2010).

Major health impacts of PM include cardiovascular diseases and respiratory complications, leading to increase medical expenses and decreased productivity (Matus et al.2011). China has historically exhibited above average PM levels. In the 1980s, China's PM levels ranged between 200 μg/m3 and 317 μg/m3, which is significantly higher than WHO's standard of 20 μg/m3 (Matus et al.2011).

3. ESTIMATING THE DEATHS DUE TO INFORMAL PROCESSING OF E-WASTE IN GUIYU

Estimating the additional deaths in Guiyu due to informal processing of e-waste requires three steps. Step (1) estimates the excess pollutant levels (also called excess body burden) in Guiyu, that is, the difference between the typical level of a pollutant in the body of a person living in Guiyu (or in the air) and what the level would be in the absence of e-waste processing. Step (2) relates the excess body burden of a pollutant in Guiyu to expected increases in mortality rates. Step (3) multiplies the increase in the mortality rates by the population of Guiyu to obtain an estimate of the number of deaths in Guiyu due to increased pollution.

Our data requirements are fairly substantial. Specifically, we require data on the level of a pollutant in Guiyu, the level of that pollutant in China and the relationship between the excess level of the pollutant and mortality. We are unable to estimate the mortality effect of a pollutant if data are missing on any one of these dimensions. As a consequence, our analysis considers only the impact of lead, dioxins, furans and particulate matter, which are major contributors to mortality.

3.1. Excess Pollutant Levels (Excess Body Burdens) in Guiyu

This section estimates the excess body burdens of various pollutants for residents of Guiyu. Again, we focus on lead, dioxins, furans and particulate matter. By definition, the body burden associated with a pollutant is the amount of that pollutant in a human body or, in the case of air pollution, it is the amount of pollution in the air. Informal e-waste processing causes body burdens to rise. The effect of e-waste processing on the level of pollution in Guiyu can be measured by the excess body burden of residents in Guiyu which equals the difference between the body burdens of residents in Guiyu and the body burdens of residents of China in similar towns but with no e-waste processing, that is, the base case. In practice, we generally use the average levels for China as the base case. We argue that if there were no informal e-waste processing in Guiyu, then the body burden for a typical resident of Guiyu would equal the body burden of the average resident of China and the excess body burden in Guiyu would equal zero. Positive values of the excess body burden in Guiyu are caused entirely by informal e-waste processing and not by any other processing industry. The main justification for this assumption is that 60 to 80 percent of the families in Guiyu have engaged in informal e-waste processing (Huo et al.2007). There were no other major processing industries in Guiyu. A former resident is reported to have said: "Ev/ery household was engaged in that business and we just did it at home and on the street" (Zhuang2017).

Lead: The body burden of lead is measured by blood lead levels (BLL) in terms of micrograms of lead per deciliter of blood (µg/dL).Huo et al.(2007) performed field studies on the blood lead levels in children in Guiyu. Their high, medium and low estimates of the BLL of children in Guiyu are shown in the first row in Table2. No study has measured the BLL of adults in Guiyu. Although adults might have different BLL to children we have no reason to believe that they would be higher or lower and therefore we use theHuo et al.(2007) figures as estimates of the average BLL in Guiyu. 2 We estimate the average BLL for people in China by using a composite of three studies: a set of estimates calculated by the World Health Organization (Chen et al.2001), and two studies measuring adult BLLs in urban China (Qu et al.1988,1993). These studies indicate an average BLL of 8.39 µg/dL in Chinese adults. Taking the difference between the midpoint estimate of the BLL in Guiyu (15.30 µg/dL) and the average for residents of China (8.39 µg/dL), we obtain a midpoint estimate of the excess body burden of lead in Guiyu equal to 6.91 µg/dL.

Table 2. Excess Body Burdens in Guiyu: Comparison of Body Burdens in Guiyu with the rest of China.

Pollutant	Low Estimate	Best Estimate	High Estimate	Source
Lead (BLL)				
Guiyu	4.4	15.30	32.67	Huo et al. (2007)
China		8.20		Qu et al. (1993)
		8.98		Qu et al. (1988)
	4	8.00	12	Chen et al. (2001)
Blood levels of lead for China	4	8.39	12	
Excess Body Burden of Lead (µg/dL)	0.4	6.91	20.67	
Dioxins and Furans (Body Burden)				
Guiyu	5.26			Chan et al. (2007)
Guiyu		10.68		Ma et al. (2008) and Geeraerts et al. (2015)
China	0.75	1.25	1.75	EPA (2002)
China		1.05		Sun et al. (2010)
Body burden for China		1.15		
Excess Body Burden of Dioxins and Furans (TEQ/BW)	4.11	9.53		
Particulate Matter				
Guiyu		103.50		Deng et al. (2006)
China		86.24	61.48	Pandey et al. (2000)
China		98.00		WHO (2011)
Excess Body Burden of Particulate Matter Exposure (µg/m^3)	5.50	17.26	42.02	

Our estimates of the BLL of residents of Guiyu and the average BLL for China, which are used to compute the excess body burden of lead, come from different studies that were conducted at different times. Our BLL estimate for Guiyu comes fromHuo et al.(2007). We use this study because it is the only study that measures the BLL in Guiyu. In order to compute the excess body burden (or excess BLL) it would be preferable to have a study that measured the BLL for China in 2007 or just earlier. However, we do not know of such a study. Instead, we draw on three studies that were published in 1988, 1993 and 2001, and take the average of their average BLLs. Thus, we conduct a meta-analysis. In meta-analysis it is common to draw on studies from quite different time periods. The key issue for our study is whether the average of the average BLLs of these studies is a reasonable estimate of the average BLL in China in 2007. There are three reasons to suppose it is. First, all of these studies were well-conducted they were taken from cities representative of China and appeared in well-respected journals. Second the three estimates are quite similar which enhances the validity of these studies. Third, there is no compelling reason to believe that the average BLL in China increased or decreased during the period that all of these studies were conducted.

Dioxins and Furans: The body burden of dioxins and furans can be measured by their toxic equivalent quantity (TEQ) (in nanograms) per kilogram of body weight (BW) that is in terms of TEQ/BW. Since dioxins and furans have different levels of toxicity TEQ expresses the combined concentration of dioxins furans and PCBs in terms of the most toxic dioxin the 2,3,7,8-TCDD.

Ma et al.(2008) and Geeraerts et al.(2015) measured exposure to dioxins and furans in Guiyu in a number of ways. AddingMa et al.'s (2008) measures of the population's dietary intake of PCDD /Fs (0.00053 TEQ/BW per day),Ma et al.'s (2008) measures of air inhalation (0.00254 TEQ /BW per day), and Geeraerts et al.(2015) measure of soil /dust ingestion and dermal exposure (0.000499 TEQ/BW per day) gives an estimate of daily exposure to dioxins and furans of 0.00357 TEQ/BW. We convert this aggregate measure into an estimate of body burden of dioxins and furans using the following formula fromEPA(2002):

$$\text{Body Burden of dioxins and furans} = \frac{Daily\ Exposure \times half\ life \times f}{ln(2)} \quad (1)$$

where Daily Exposure is the daily exposure to a dioxin or furan half life is the half life of the compound, f is the fraction of it absorbed and ln is the natural logarithm. Using theEPA's (2002) estimates of the half-life of 2,3,7,8-TCDD (2593 days) and of the fraction of dose absorbed (0.8), we estimate the body burden is 10.68 TEQ/BW.

Chan et al.(2007) studied the breast milk of expecting mothers in Taizhou, a similar town to Guiyu with e-waste recycling activity, although less than in Guiyu.Chan et al.'s (2007) estimates range between 1.8 TEQ/BW and 8.71 TEQ/BW with an average of 5.26 TEQ/BW. Because e-waste recycling activity is less common in Taizhou than in Guiyu, the estimates for Guiyu are likely to be low.

To estimate the body burden of dioxin/furan exposure for an average Chinese person, we draw onEPA(2002) andSun et al.(2010).EPA(2002) obtained an average estimate of the body burden of TCDDs in higher income countries of 1.25, with a low of 0.75 and a high of 1.75. Dioxins and furans are completely man-made and are only produced in processes involving incineration. Therefore, body burdens in lower income countries track those in higher income countries quite closely (unlike other pollutants like lead).Sun et al.(2010) estimated that the average TCDD in the breast milk of mothers in northern China was approximately 1.05. Taking the average of these two estimates yields a body burden estimate of 1.15 for the average person in China. Thus, our best estimate of body burden of dioxins/furans in Guiyu is 9.53 TEQ/BW, with a low estimate of 4.11 TEQ/BW.

Particulate Matter: The body burden of air pollution can be measured using the concentration of particulate matter with diameter 10 microns or less (PM10).Deng et al.(2006) collected air samples at Guiyu and found 62.1 µg/m3 of PM2.5. We convert PM2.5 levels to PM10 using a factor of 0.6 (Aunan and Pan2004) to obtain an estimate of 103.50 µg/m3 of PM10. To calculate the levels of exposure to particulate matter for the average Chinese resident, we draw primarily on Pandey et al.(2000), who developed a model to estimate PM10 levels in Chinese towns and cities with populations greater than 100,000. A weighted average of these levels in 379 Chinese cities gives an average estimate of the body burden of particulate matter for China equal to 86.24 µg/m3. Thus, our best estimate of excess body burden in Guiyu due to particulate matter equals 17.26 µg/m3.

To obtain a high estimate of the excess particulate matter in Guiyu we use a subset of 19 Chinese towns from Pandey et al.(2000) that had fewer than 200,000 residents. The weighted average of PM10 levels in these towns was 61.48 µg/m3, which yields a high estimate of excess particulate matter in Guiyu of 42.02 µg/m3. To obtain a low estimate, we examined the World Health Organization Outdoor Air Pollution Database, which contains international air pollution data from 2003 to 2010 (WHO2011). It shows that the air pollution of a typical Chinese municipality with no e-waste processing activities is about 98.0 µg/m3. This figure likely overestimates the air pollution of a typical town with no e-waste processing activities because it includes the extremely high air pollution levels in megacities like Beijing and Tianjin. Thus, our low estimate of excess body burden due to particulate matter equals 5.50 µg/m3.

3.2. Increases in Mortality Rates

This section describes how we estimate the increases in mortality rates due to the excess levels of different pollutants in Guiyu. This process is fairly complicated and requires many steps. To facilitate understanding, we explain the process and, at the same time, illustrate computation of the increased mortality level for lead. The application of the various steps is summarized in Table3. The first few rows contain the parameters associated with our best estimates of mortality rates, which are followed by our low estimates of increased mortality rates and finally our high estimates of increased mortality rates.

In order to calculate the increases in mortality rates, we require an estimate of the risk ratio in Guiyu. By definition, a risk ratio, RR, equals the ratio of the mortality rate in an area of high pollution to the mortality rate in some other less polluted area, the base case.3 The increased probability of death due to higher pollution (expressed as a percentage) equals the RR minus unity times 100.4

No study has estimated the RRs associated with any pollutant in Guiyu. Therefore we begin with the RR for a particular pollutant estimated previously in a different setting, which we refer to as a reference study. In selecting the most appropriate RR (and reference study) we take into account the quality of the analysis and the similarity between the situation in Guiyu and the particular setting that was used in the reference study.

Lead: Many studies estimate the RR of various diseases due to lead exposure. Here, we focus on studies by Schober et al.(2006) and Lustberg and Silbergeld(2002) that provide RRs for all-cause mortality rather than just one type of disease and that study a population that spans across all ages and both sexes. Schober et al.(2006) found that individuals with BLLs above 10 μg/dL had a RR of 1.59 compared to those with less than 5 μg/dL. This is our best estimate for the RR because it comes from a population with BLLs close to those in Guiyu. This estimate is shown in column 2 of Table3. For our low and high estimates, we draw on Lustberg and Silbergeld(2002) and Schober et al.(2006) using their studies' RRs of 1.46 and 1.24, respectively, as shown in column 2 of Table3.

If the body burden in the reference study were equal to the body burden in Guiyu, then we could use the RR in the reference study as an estimate of the RR in Guiyu. The reason is that the RRs of the pollutants we focus on depend only on the relationship between pollution and human mortality. This relationship does not vary from one place to another or from one time to another. However, the level of pollution in Guiyu may differ from the level of pollution in the polluted area in the reference study or the average level of pollution in China may differ from the pollution in the base case of the reference study. It is necessary to adjust the RR from the reference studies to account for these potential differences. For this purpose, we compute the excess body burden ratio (BBR), which equals the ratio of the excess body burden in Guiyu to the excess body burden in a reference study, such as Schober et al.(2006). Thus, a RR taken from a reference study in a polluted area with less (more) higher pollution levels than in Guiyu will be adjusted up (down), holding other factors constant. Furthermore, if the level of pollutant in the base case (relatively unpolluted areas) of the reference study is higher (lower) than the average level in China then the RR is adjusted down (up), holding other factors constant.

Table 3. The Number and Social cost of Excess Deaths from e-waste in Guiyu.

Pollutant	Initial Risk Ratio (RR)	Excess Body Burden in Reference Study	Excess Body Burden in Guiyu (from Table 2)	Excess Body Burden Ratio (BBR)	Increased Probability of Death in Guiyu	Guiyu Mortality Rate	Increased Mortality Rate in Guiyu	Excess Deaths in Guiyu	Social Cost of Excess Deaths ($ millions)
Best Estimates									
Lead	1.59	9.20	6.91	0.75	44.29	1.04	0.32	478	311
Dioxins and Furans	1.15	16.10	9.53	0.59	8.88	0.78	0.06	96	62
Particulate Matter (acute)	1.00	1.67	17.26	10.36	0.62	0.72	0.00	7	4
Particulate Matter (chronic)	1.05	16.67	17.26	1.04	5.18	0.76	0.04	56	36
Total							0.42	637	414
Low Estimates									
Lead	1.46	19.50	6.91	0.35	16.29	0.84	0.12	176	114
Dioxins and Furans	1.00	16.10	9.53	0.59	-	0.72	0.00	-	0
Particulate Matter (acute)	1.00	1.67	17.26	10.36	0.52	0.72	0.00	6	4
Particulate Matter (chronic)	1.04	16.67	17.26	1.04	4.14	0.75	0.03	45	29
Total							0.15	226	147
High Estimates									
Lead	1.24	3.70	6.91	1.87	44.80	1.04	0.32	484	314
Dioxins and Furans	1.30	16.10	9.53	0.59	17.76	0.85	0.13	192	125
Particulate Matter (acute)	1.00	1.67	17.26	10.36	0.72	0.73	0.01	8	5
Particulate Matter (chronic)	1.06	16.67	17.26	1.04	6.21	0.76	0.04	67	44
Total							0.50	751	488

For our best estimate of the Guiyu mortality rate due to lead, we use Schober et al.'s (2006) estimate of the RR equal to 1.59. The excess body burden in this reference study is obtained by subtracting the median BLL of individuals who had BLLs above 10 μg/dL, which was 11.8, from the median BLL of those with BLL less than 5 μg/dL, which was 2.6, giving an excess BLL of 9.20 μg/dL. This amount is shown in column 3 of Table3. For our low estimate we draw on Lustberg and Silbergeld(2002) who found that individuals with BLLs between 20–29 μg/dL had a RR of 1.46 compared to individuals with BLLs of below 10 μg/dL, implying an excess body burden of 19.50. The RR associated with our high estimate comes fromSchober et al.(2006) who found that individuals with blood lead levels of 5–9 µg/dL had a RR for all-cause mortality of 1.24 compared to those with less than 5 µg/dL, implying an excess body burden of 3.70, as shown in column 3 of Table3.

Given the excess body burden in a reference study, shown in column 3 of Table3and our previously estimated excess body burdens in Guiyu, shown in column 4 of Table3, we obtain the BBRs by dividing the latter (column 4) by the former (column 3). Thus, our best estimate of the BBR for lead is 0.75, which is shown in column 5 of Table3, with low and high estimates of 0.35 and 1.87, respectively.

Residents are more likely to die in polluted areas. As mentioned above, the probability that a resident of a polluted area in a reference study is more likely to die than a resident of the base area equals the RR minus unity times 100. In order to compute the probability that a resident of Guiyu is more likely to die than the average resident elsewhere in China we multiply this amount by the BBR.5 Thus, exposure to lead in Guiyu is likely to increase the probability of death by about 44 percent, as shown in column 6 of Table3, with a range between 16 and 45 percent.

The mortality rate in Guiyu, taking into account the high levels of lead, is calculated by adding unity to the increased probability of death (expressed as a rate) and multiplying by the average mortality rate in China, which equals 0.72 (WHO2019). 6 These amounts are shown in column 7 of Table3. Our best estimate of the mortality rate in Guiyu taking into account the excess lead exposure equals 1.04 with a range of 0.84 to 1.04.

Finally, we estimate the increased mortality rate in Guiyu due to excess lead exposure by computing the difference between the increased mortality rate in Guiyu (column 7) from the average mortality rate in China, which is 0.72.7 Our best estimate of the increased mortality rate due to excess lead exposure for the cohort of Guiyu residents in 2010 is 0.32, as shown in column 8 of Table3, with a range of 0.12 to 0.32.

Dioxins and Furans: A number of studies estimate RRs for dioxins and furans (Ketchum and Michalek2005;Flesch-Janys et al.1995;Pesatori et al.1998;Steenland et al.1999). Out of all these studies only Ketchum and Michalek(2005) provide a RR for all causes of death, rather than just a specific type of disease or condition. This article analyzed the health of more than 1200 U.S. veterans of the Vietnam War who had skin contact with dioxin-based herbicides. It found that all-cause mortality increased significantly with a RR of 1.15 and a range between 1.0 and 1.3.

Our mid-point estimate of the excess body burden of dioxins/furans in Guiyu, which we calculated above, is 9.53 TEQ/BW. The population studied in Ketchum and Michalek(2005) exhibited an excess body burden of 16.1 TEQ/BW, which results in a BBR of 0.59. Adjusting our initial RR by the BBR yields an increased probability of death due to exposure to dioxins and furans of 8.88 percent, which translates into an excess mortality rate of 0.06.

Particulate Matter: Mortality due to exposure to particulate matter can come from acute or chronic conditions. The RR is much higher for chronic conditions than for acute conditions.

Therefore, we compute the increased mortality due to particulate matter separately for these two conditions.

For mortality from acute conditions we draw on a study by Bickel et al.(2005) who found a RR of 1.0006 amongst 500,000 adults in metropolitan areas of the United States with a range between 1.0005 and 1.0007. Our estimate of the excess body burden of particulate matter in Guiyu is 17.26 µg/m3 as calculated above. The population studied in Bickel et al.(2005) was exposed to air with excess PM10 pollution levels of 1.67 µg/m3 resulting in a BBR of 10.36. We estimate an increased probability of death due to PM10 exposure from acute conditions in Guiyu of 0.62 percent, resulting in an excess mortality rate of 0.004.

For chronic mortality we used a study byPope et al.(2002) which derives a RR of 1.05 with a range between 1.04 and 1.06. The population studied inPope et al.(2002) was exposed to air with excess PM10 levels of 16.67 µg/m3. Again using our estimate of excess burden due of particulate matter in Guiyu, we obtain a BBR estimate of 1.04. We estimate an increased probability of death due to PM10 exposure from chronic conditions in Guiyu of 5.18 percent, resulting in an excess mortality rate of 0.04.

3.3. Estimated Deaths Due to Informal E-waste Processing

The expected excess number of deaths in Guiyu due to informal e-waste processing is computed by multiplying the increases in the expected mortality rates, shown in column 8 of Table3 by the population of Guiyu in 2010 which was about 150,000. Consequently we expect 637 more deaths in our studied cohort of individuals in Guiyu than would occur without informal e-waste processing. Most of the deaths were due to lead poisoning.

4. THE SOCIAL COST OF INFORMAL PROCESSING OF E-WASTE IN GUIYU

This section first discusses the appropriate estimate of the value of a statistical life in Guiyu. Using this estimate, we then estimate the social cost of the mortality that results from the impacts of on health of pollutants emitted during informal e-waste processing. Section2 estimates the effect of lead poisoning on children on their future earnings. Section3 contains our estimates of the social cost of informal e-waste processing and presents our sensitivity analysis.

4.1. The Value of a Statistical Life in Guiyu and the Social Cost of Increased Mortality

Estimation of the social costs associated with increased mortality requires an estimate of the value of a statistical life (VSL) applicable to the residents of Guiyu. Fortunately a number of studies have derived estimates of the VSL in China over the last 20 years. Based on a meta-analysis of these estimates and some new research, we derive an estimate of the VSL in Guiyu.

One may obtain an estimate of the VSL in two ways. One way is to draw on previous studies that estimate willingness to pay for reductions in mortality risk using participants in Guiyu or from people with characteristics similar to residents of Guiyu. These estimates are based on stated preference methods such as contingent valuation or on revealed preference methods such as a wage-risk study (Boardman et al.2018).

A second way uses benefit transfer to adjust estimates of the VSL derived from another country usually the United States. This method is sometimes referred to as the scaling approach. Most importantly these studies adjust (i.e., scale) for income differences. A key parameter is the income elasticity of the VSL EI which is defined below for small discrete changes in income:

$$_{I}E = \frac{\%\Delta VSL}{\%\Delta I} \tag{2}$$

where, %ΔVSL equals the percentage change in the VSL, and %ΔI is the percentage change in income. If an individual is willing to pay a larger (smaller) proportion of their income for a small reduction in fatality risk as their income increases, then this elasticity is greater (less) than unity. Assuming that this income elasticity is constant, E, and is the same in Guiyu as in the US, and given an estimate of the VSL in the United States, denoted VSLUS, then the VSL in Guiyu denoted VSLG can be estimated thus, as suggested by Hammitt and Robinson(2011):

$$VSL_G = VSL_{US} \times \left(\frac{I_G}{I_{US}}\right)^E . \tag{3}$$

Table 4. VSL estimates for China and Guiyu.

Study	Yuan	USD	USD (2018)	Source or Notes
Willingness to Pay Studies:				
Zhang (2002)	970,000		409,946	World Bank (2007)
Hammitt and Zhou (2006)	385,000		162,711	World Bank (2007)
Wang and Mullahy (2006)	775,000		322,944	World Bank (2007)
Wang and Mullahy (2006)		150,619	157,585	Hoffmann et al. (2017)
Krupnick et al. (2006)	1,400,000		547,392	World Bank (2007)
Hammitt and Zhou (2006)		10,500	15,826	Robinson et al. (2019)
Hammitt and Zhou (2006)		75,095	78,568	Hoffmann et al. (2017)
Guo et al. (2006)		24,000	32,750	Robinson et al. (2019)
Guo and Hammitt (2009)		184,366	268,890	Robinson et al. (2019)
Guo and Hammitt (2009)		107,789	112,774	Hoffmann et al. (2017)
Qin et al. (2013)		188,000	205,616	Robinson et al. (2019)
Liu and Zhao (2013)		117,186	122,606	Hoffmann et al. (2017)
Ohdoko et al. (2013)		1,464,412	1,532,139	Hoffmann et al. (2017)
Yang et al. (2016)	3,729,492		1,114,620	Hoffmann et al. (2017)
Wang and He (2014)		332,310	347,679	Hoffmann et al. (2017)
Hoffmann et al. (2017)	1,470,000		517,207	
Average			371,828	
Benefit Transfer Studies:				
Viscusi and Masterman (2017b)		1,364,000	1,444,325	E = 1.0.
The current authors			1,534,301	Updated GNI/capita; E = 1.0
The current authors			1,269,740	Updated GNI/capita; E = 1.1
The current authors			857,675	Lower Guiyu income; E=1.1
Based on Anqing, a relatively small city.				

Table4 lists previous estimates of the VSL in China. For some studies, we consulted the original studies while for other studies, we drew on surveys by the World Bank(2007),Ho ffmann et al.(2017) and Robinson et al.(2019). In order to make the amounts comparable, each estimate has been converted to 2018 US dollars, the most recent year for which data are available. Amounts initially expressed in Yuan are first converted into 2018 Yuan using World Bank data on annual inflation rates in China and then converting these amounts into 2018 US dollars at purchasing power parity.8 The amounts initially expressed in US dollars are converted to 2018 US dollars using the US CPI-U index from the US Labor Bureau of Labor Statistics.9

The willingness to pay studies in Table4 are based on a number of different methods including contingent valuation, dichotomous choice methods and wage-risk studies. In general, more recent studies obtained higher estimates than earlier studies. The Viscusi and Masterman(2017b) benefit transfer estimate assumes a VSL of $9.631 million for the US in 2015 dollars, an income elasticity of the VSL of 1.0 and computes the ratio of GNI per capita in China to that in the United States using the World Bank's estimates calculated using the Atlas method.10 As shown in Table4 we re-estimate the VSL using the same method as Viscusi and Masterman(2017b) but with more recent GNI per capita data. The estimated VSL rises by almost $100,000.Viscusi and Masterman(2017b) suggest that the income elasticity of the VSL for lower income countries is in the range of 1.0 to 1.2. Assuming this elasticity equals 1.1 yields an estimated VSL of just less than $1.27 million for China. This amount is 134 times the average GNI per capita in China which is generally regarded as reasonable. Huang et al.(2015) and Guo et al.(2014) surveyed residents of Guiyu and found that most households are lower middle to middle income households. Assuming, therefore that the average income in Guiyu is 70 percent of the average income in China, then our best estimate of the VSL in Guiyu using the benefit transfer method is about $850,000 as shown in the final row in Table4.

Almost without exception, the estimates based on willingness to pay are smaller than those based on benefit transfer sometimes by a large amount. The main argument in favor of the willingness to pay estimates is that they are based on the stated preferences or behavior of residents in the relevant country. However the estimates can vary considerably depending on how they are converted to 2018 US$. For example Hoffmann et al.(2017) and Robinson et al.(2019) provide different values for the Hammitt and Zhou(2006) study, and the Guo and Hammitt(2009) study. Viscusi and Masterman(2017b) argue against the willingness to pay studies on the grounds that in non-US countries they likely suffer from publication selection bias. Considering these factors leads us to a VSL for Guiyu of $650,000.

Multiplying our estimates of the number of excess deaths due to a pollutant by $650,000 yields the social cost attributable to each pollutant which is shown in the tenth column of Table3. Lead has the largest social cost, followed by dioxins and furans. Our best estimate of the mortality costs due to pollution in Guiyu is $414 million with a range between $147 million and $488 million.

4.2. The Impact of E-waste Processing on Cognitive Functioning and Earnings

E-waste processing leads to lead poisoning in children, which has negative impacts on their cognitive functions and, in turn, decreases their productivity and reduces their earnings (Muennig2009). Grosse et al.(2002) suggests that the change in lifetime earnings due to excess BLLs, ΔE, can be calculated using:

$$\Delta E = \Delta BLL \times \left(\frac{\Delta IQ}{\Delta BLL}\right) \times \left(\frac{\frac{\Delta E}{E}}{\Delta IQ}\right) \times E \tag{4}$$

where E equals the present value of lifetime earnings, ΔBLL measures the excess blood lead levels, ΔIQ/ΔBLL reflects the change in IQ points per unit of excess BLL and (ΔE/E)/ΔIQ measures the percentage change in earnings per IQ point change. As discussed earlier Huo et al.(2007) estimated the BLL of children in Guiyu was 15.3 µg/dL. The average lead levels of children in China were 9.29 µg/dL (Wang and Zhang2006). Therefore the excess BLLs of children in Guiyu were 6.01 µg/dL with a range from 0.61 µg/dL to 7.25 µg/dL. We use Grosse et al.'s (2002) estimate of both the ΔIQ/ΔBLL ratio, which equals 0.257 IQ points per µg/dL with a range of 0.185 to 0.323, and the percentage change in earnings per unit change of IQ, which equals 2.00 percent with a range of 1.76 percent to 2.37 percent. The average annual income per capita in Guiyu is about $6514.11 The present value of the average income equals $139,108 assuming that the average person works for 40 years and earnings are discounted at 3.5 percent per annum. By substituting these parameter values into Equation (4), we obtain an estimate of the lost earnings from lead poisoning of $4297 per child. The proportion of children (aged under 14) in China is 17.88 percent.12 This suggests that there are about 26,820 (17.88 × 150,000) children in Guiyu, implying the present value of the cost of their reduced earnings equals about $115 million, with a range of $73 million to $172 million.

4.3. Social Cost and Sensitivity Analysis

Our best estimate of the social cost of informal e-waste processing for the cohort of Guiyu residents in 2010, computed by adding the cost of the earnings losses to the mortality costs, is $529 million. Estimates of the total amount of e-waste processed annually in Guiyu range from 1 million tonnes (Zhuang2017) to 1.5 million tonnes (Wu et al.2010). Taking the average, we estimate approximately

1.25 million tonnes of e-waste were processed in Guiyu in 2010. Dividing the social cost of informal e-waste processing by this amount gives an estimate of the social cost of informally processing per tonne of e-waste. Thus, our best estimate of the shadow price of processing e-waste in Southern China is about $423 per tonne.

Earlier we showed our main the results varying the mortality outcomes, but holding the VSL and the amount of e-waste processing constant. Table5shows our estimates of the shadow price with the mortality outcomes varying as above, the VSL ranging between $400,000 and $900,000, and the e-waste processed varying between 1 million and 1.5 million tonnes per year. This analysis yields a range of estimates of the shadow price of e-waste processing from $109 to $847 per tonne.

5. LIMITATIONS AND CONCLUSIONS

Electronic waste has become a prevalent issue in the twenty-first century. While unprecedented developments in technology have contributed to major economic and social developments the disposal and processing of its main by-product namely e-waste, has adversely affected many people. Informal processing of e-waste results in the emission of various pollutants which ultimately find their way into the bodies of local residents and have severe negative consequences. In order to evaluate policies to deal with this problem in terms of their net social benefits it is essential to have an estimate of the shadow price of informal social waste processing.

This study estimates the social cost of the effects of pollutants that are emitted during informal e-waste processing. We focus on the effects of lead, dioxins and furans and particulate matter. These pollutants lead to increased incidence of cancer cardiovascular disease renal disease cerebrovascular disease cognitive deficits kidney malfunction and respiratory infections and ultimately increase mortality. We also consider the effect of lead pollution in children and the resultant impairment of their cognitive development and reductions in their incomes. These impacts are the most serious.

Our analysis estimates that the social cost of e-waste processing for the cohort of Guiyu residents in 2010 is $529 million, expressed in 2018 US$. This amount is equivalent to $3528 per person, which is over half the gross income per capita of the residents of Guiyu. This amount is likely to be higher for people engaged in e-waste processing than for people who are not. However, those not engaged in processing still suffer considerably. The overwhelming majority of the total social cost stems from the increased mortality that results from elevated levels of lead in the blood.

Our best estimate of the shadow price of e-waste processing is $423 per tonne for the cohort studied. Research by Li et al.(2006) and Bald é et al.(2017) suggests that in 2010, the year of our data, about 12 million tonnes of e-waste was recycled informally in China. If so, our analysis implies that the total social cost of informal processing in China was about $5 billion, assuming that other informal e-waste processing sites in China were similar to those in Guiyu.

Table 5. Sensitivity Analysis: The Shadow Price of Informal E-waste Processing ($/tonne) Varying Mortality Outcomes, VSL and the Amount of E-Waste Processed.

Mortality Outcomes	**VSL**		
	$ 400,000	**$ 650,000**	**$ 900,000**
E-waste processed: 1,000,000 tonnes			
Best	370	529	688
Low	164	220	277
High	472	659	847
E-waste processed: 1,250,000 tonnes			
Best	296	423	551
Low	131	176	221
High	377	528	678
E-waste processed: 1,500,000 tonnes			
Best	247	353	459
Low	109	147	184
High	315	440	565

Our analysis has a number of limitations. First, we do not measure the social cost of some impacts on residents of Guiyu. In particular, we do not consider the mortality effects of toxic heavy metals besides lead, such as cadmium, chromium or copper. Also, we did not consider the effect of informal e-waste processing on morbidity. This limitation is primarily due to lack of reliable published data. Thus, our methodology probably underestimates the total social cost of e-waste processing. Second, only the residents of Guiyu have standing. Therefore, we do not consider the effects of pollution generated in Guiyu on other jurisdictions. For example, we do not consider the effect of windborne particulate matter generated in Guiyu on residents of adjacent towns. In fact, it is possible that some of the particulate matter in Guiyu actually originated elsewhere, and, therefore, these effects may offset one another. Informal e-waste processing also releases carbon and other greenhouse gasses. These impacts are not included in our analysis because the amounts of these pollutants released in Guiyu have a very small effect on the residents of Guiyu. However, they do affect global warming. If standing were global, then the impacts of carbon and other GHG emissions should also be included. Third, our estimate assumes that the status quo is maintained over time. In fact, government policy in Guiyu has changed the levels of emitted pollution since 2010. In 2013 local authorities set up the National Circular Economy Pilot Industry Park (the Park), which became fully operational in 2015. Since that time, many e-waste processors have been shut down and the remaining workshops were ordered to move to the Park.13 Many informal processing businesses were consolidated into 29 larger companies. The local government has also remediated heavily polluted land. In 2014 the Chinese premier declared “War on Pollution” and, near the end of 2017, the Chinese government banned importation of 24 types of waste, including e-waste. All of these initiatives have reduced the levels of pollutants in Guiyu. One likely consequence is that exported e-waste (and other waste) is diverted away from China to other countries with fewer restrictions.Brooks et al.(2018) estimate that 111 million metric tons of plastic waste will be displaced from China by 2030 as a result of this new policy.

Despite the limitations of our analysis, our estimate of the social cost of informal e-waste processing may encourage governments in jurisdictions with informal e-waste processing to adopt and enforce better (i.e., more economically efficient) environmental policies. As mentioned above, our estimate is based on conditions in Guiyu in about 2010 and therefore it is most relevant to jurisdictions with similar characteristics. When it is used in other jurisdictions it should be modified to reflect the particular circumstances.

Our estimate may also be used to inform the e-waste processors themselves not only of the dangers they face and the cost to themselves, but also the cost to others of their processing methods. Educational programs aimed at e-waste processors may encourage adoption of safer processing methods.

E-waste is a global problem. Waste banned from one country is likely to end up in another country. To provide a long-term sustainable solution e-waste must be reduced from exporting high income nations. Our shadow price might influence recycling policies and the implementation of those policies in such countries. Although Canada, for example, bans the export of e-waste, less than 20 percent of e-waste is recycled in Canada. Furthermore, better implementation of regulations in high income countries pertaining to producers’ end-of-life management of their products may have social benefits. Our estimates may also influence both producers of electronic products and citizens who use them of the importance of disposing of e-waste in an environmentally responsible way.

Our research makes two other contributions. First it highlights the negative consequences of exposure to lead. Major improvements in societal well-being can be achieved by limiting lead exposure. For example initiatives to minimize occupational exposure and inhalation of lead through the use of face masks and better ventilation in e-waste processing workshops could be social welfare improving. Additionally, investment in education programs that encourage parents to monitor and restrict their children’s hand-to-mouth behavior could be socially beneficial. Second it discusses in one place a broad set of consequences of informal e-waste processing. Previous research has measured the volumes of e-waste and the levels of dangerous pollutants in informal e-waste processing areas (see, for example Bald é et al.2017;Schluep et al.2009;Lepawsky and McNabb2010). Often, though, each of these studies focuses on only one type of pollutant. Our research considers multiple pollutants.

Thus, it provides a more comprehensive picture of the impacts of e-waste processing.

Conflicts of Interest:

The authors declare no conflict of interest.

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