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The application of best available technology in dealing with Ontario's waste electric and electronic equipment : a case study

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THE APPLICATION OF BEST AVAILABLE TECHNOLOGY IN DEALING WITH ONTARIO'S WASTE ELECTRIC AND ELECTRONIC EQUIPMENT: A CASE STUDY

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ABSTRACT

THE APPLICATION OF BEST AVAILABLE TECHNOLOGY IN DEALING WITH ONTARIO'S WASTE ELECTRIC AND ELECTRONIC EQUIPMENT: A CASE STUDY

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This study seeks to inquire into the impacts of pursuing a comprehensive Waste Electrical and Electronic Equipment (WEEE) program similar to the system in the European Union in the Province of Ontario. *O. Reg. 393/04 WEEE* seeks to establish a weight-based system of recycling end-of-life (EOL) electronics. BAT revenue projections would make for a profitable endeavour across the first five years of the program, with reductions in pollution and operating costs from primary ore refinement. Sensitivity analysis reveals that the BAT scheme profitability exceeds the "do nothing" option across all price ranges (including worst case scenarios), while, at the same time, results in increased susceptibility to market volatility. A cost-effectiveness study showed that the investment in a new integrated smelting operation would still be more cost-effective than the "do nothing" option. This study points to the need for further research into market incentives regarding the amount of collected electronic waste.

ACKNOWLEDGEMENT

I would like to acknowledge the advice and assistance of Dr. Paul Missios for bringing this enterprise into focus. I would also like to thank Dr. Ronald Pushchak for placing his faith in me, as well as the insistence of Dr. Kathryn Woodcock that I could do better in life with the resources at my disposal.

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INTRODUCTION

WHAT IS E-WASTE?

Electronic waste is alternatively labeled "e-waste", or by the acronym WEEE (Waste Electrical and Electronic Equipment). Electronic waste encompasses a broad and growing range of electronic devices, ranging from large household appliances such as refrigerators and air conditioners to smaller devices such as cellular phones, personal stereos, consumer electronics and computers (Li et al., 2007). However, it should be noted WEEE does not consist of equipment used in the transmission of electrical power such as transformers, junction boxes, hydro lines, etc. WEEE contains over 1000 different substances, many of which are toxic (lead (Pb), cadmium (Ca), mercury (Hg), arsenic (As), trivalent chromium (Cr(III)), hexavalent chromium (Cr(VI)), etc.) and have the potential for creating serious pollution upon disposal (Li et al., 2007). For these reasons, some authors advocate the treatment of WEEE as a hazardous waste rather than a mere subset of the normal waste stream (e.g., Morf et al., 2007).

INTERNATIONAL LEGAL SPHERE

International Law is characterized by its essential nature as what is often termed "soft law"; that is, it consists of "nonbinding instruments: codes of practice, recommendations, guidelines, standards, and declarations of principles" (Joyner, 2005, 211). Soft law may be contrasted with domestic law, or "hard law", which is composed of "legally binding document[s]" (Rochester, 2006, 63). The *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal* (1989) is the principal document in the international legal sphere by which parties to the treaty are duty bound to regulate the international traffic of hazardous substances. Further supplementary documents were drafted in order to fill gaps within the existing text of the *Basel Convention*. For example, stipulated in the *Conference of Parties Decision II/12* (March 1994), Organization for European Cooperation and Development (OECD) countries are required by treaty to not ship their hazardous wastes to non-OECD countries. Similar provisions exist under the *Bamako Convention* (1991) which prohibits the dumping of hazardous waste from the developed world onto African nation states. A loophole with the Basel Convention allows for the shipping of hazardous waste when it is "required as a raw material for recycling or recovery industries in the State of import" (Arts & Gupta, 536-537). In spite of these measures, notorious violations of the *Basel Convention* have occurred. Illegal shipments of waste are a frequent occurrence in the European Union (EU), often under the false pretence of representing legitimate recycling industry activities. According to Lloyd's of London, some 51% of waste leaving EU ports is illegal (Lloyd's List, 2006). A further complication of the situation occurs by virtue of the fact that one of the largest consumer nations in the world (the United States) failed to ratify the *Treaty*, even though it is a signatory to it.

One of the key principles of the *Basel Convention* (1989) and its supplementary array of legal documents was to prevent the *developed* world from dumping its hazardous wastes upon the *developing* world, which intuitively is least equipped to deal with hazardous wastes. Unfortunately, in large part these measures have failed, both in terms of reducing the volume of waste or bringing about substantive measures to address this predicament. WEEE has presented a unique problem in the control of the movement of hazardous substances across international borders and has become increasingly acute in recent years (US EPA, 2007). In the developed economies of North America, the EU and the Far East (Japan, S. Korea, etc.), much of the WEEE portion of the waste stream is either landfilled, recycled or languishes uncollected. Improper disposal of WEEE in unregulated landfills poses the danger of leaching heavy metals into soils. A large portion of what is collected for recycling more often than not is exported to one of three destinations: China, Sub-Continental Asia (India, Pakistan) or Western Africa (Nigeria, Ghana, etc.). The pretext for the export of much end-of-life (EOL) electric equipment is its reuse as "used computers"; however, approximately 75% of these goods are in fact "unusable junk" (Osibanjo & Nnorom, 2007). Much of this "unusable junk" then enters what economists term the "non-formal" economy where it is processed by rudimentary means such as cyanide leaching, mercury amalgamation, and electrolytic gold-stripping in order to extract the few grams of gold, silver or copper in a PC, which is then sold on the local scrap metal market. This particular cycle of economic activity has severe environmental consequences, such that virtually every strata of the local environment is contaminated with dioxins and furans. Preventing this trend has been the aim of governments in the developed world, as well as manufacturers concerned about EOL responsibility.

A substantial increase in domestic participation is implicit in the proper control and management of the WEEE problem. Product design, including full-cycle "cradle-to-grave" design, as well as the advancement of recycling technologies and processes, are all emphasized as important in achieving proper domestic management of WEEE (Meech, 2006; Hammond & Beullens, 2007; Bakar & Rahimifard, 2007; Kongar & Gupta, 2006; Kopacek & Kopacek, 2006; Segebade et al., 2007; Lofthouse, 2007; Schlummer et al., 2006; Ahluwalia & Nema, 2006). Nevertheless, despite advancement in these areas, systematic improvements in OECD countries must be made to address the domestic WEEE problem and bring about responsible recycling practices. The dire situation of the problem may be gleaned from a few statistics. For example, a 2007 study by the U.S. Environmental Protection Agency (EPA) cited that, of the 1.9-2.2 million tons of WEEE generated in the US in the year 2005, some 1.5-1.9 million tons were discarded in landfills while only 0.345-0.379 million tons were recycled (U.S. Environmental Protection Agency, 2007). Similar problems exist with collection and recycling in advanced economies such as Japan, Korea and the European Union (Tong & Wang, 2004; Li et al., 2006; Liu et al., 2006a; Liu et al., 2006b; Terazono, et al., 2006, Oguchi et al, 2008; Lee et al., 2007; Huisman et al., 2007; Selin and VanDeveer, 2006; Hagelüken, 2006a; Hagelüken, 2007). Between the years 1999 to 2002, the amount of WEEE in the EU went from 1 megaton to over 6 megatons (Segebade et al., 2007). It is estimated that 80% of the world's computer e-waste is exported to Asia and that 90% of these exports were illegal, under the guise of "recycling" (Bi et al., 2007). As mentioned before, the improper disposal of WEEE in landfills has been implicated in significant leaching of hazardous heavy metals and toxic elements such as mercury (Hg), beryllium (Be), indium (In), lead (Pb), cadmium (Cd), arsenic (As), antimony (Sb), etc. (Canning, 2006; Hagelüken, 2006b; Lincoln et al., 2007). Although the total amount of WEEE in the waste stream can be as high as 8%, this single stream represents a total of 40% of the lead and 70% of the heavy metals entering global landfills (Babu et al., 2007). Another source puts the contribution of leached heavy metals from WEEE between 50 and 80% (Osibanjo & Nnorom, 2007).

Some companies within the European Union have been at the forefront of creating significant advancements to address the management of WEEE with regard to BAT. For example, Umicore (UPMR) of Belgium possesses advanced smelting facilities which melt down constituent computer parts and resell the refined metals for profit on the international metal markets, all within the pollution emission standards of the EU and the Flemish state (Hagelüken, 2006a). Facilities such as Umicore can achieve up to 95% efficient recovery of seventeen ferrous and non-ferrous metals, metalloids, and the non-metal selenium, whereas efficiency in third-world non-formal economies typically achieves only about 20% efficiency (Keller, 2006). This may be increasingly important in a world posed with substantially dwindling supplies of resource metals such as indium (Gordon et al., 2006; New Scientist, 2007; Geology.com, 2008). However, the capital costs of building such a facility were $1billion US, with an additional $500 million US in metallurgical and environmental technologies (Hagelüken, 2006a). It should be noted that no facility such as Umicore exists in Canada (PHA Consulting Associates, 2006).

Advanced studies have also been undertaken in the EU, in particular with one noteworthy document, *2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE): Final Report* (Huisman et al., 2007). This study entails an in-depth analysis of the costs and logistical problems in administering a comprehensive WEEE recycling program across the 27 member union. No comprehensive document exists for Canada which includes, as in (Huisman et al., 2007), an examination of the full Life Cycle Analysis (LCA) of the environmental consequences of pursuing a comprehensive WEEE recycling program. The document also goes on to promote system-wide standards and classifications across all EU borders; a registration system is advocated to keep track of the movements of electronic waste; and a reporting mechanism for producers and manufacturers. None of these elements are under current consideration in Canada, and information is usually managed in a strictly "proprietary" manner. Moving towards this goal should be an endeavour and a basis for future research.

ELECTRONIC WASTE IN THE DEVELOPING WORLD

Contrary to the Basel Convention, substantial amounts of Waste Electrical and Electronic Equipment (WEEE) from OECD countries (Lloyd's List, 2006) find their way to India (Streicher-Porte et al., 2007; Babu et al, 2007, Keller, 2006; Amit & Sareen, 2006), China (Tong & Wang, 2004; Li et al, 2006; Liu et al., 2006a; Liu et al., 2006b; Terazono et al, 2006), and Africa (Osinganjo & Nnorom, 2007). Within China and India, a non-formal economy exists where precious metals such as gold (Au), silver (Ag), palladium (Pd), and platinum (Pt) are extracted from imported WEEE in rudimentary and often makeshift manners incorporating methods such as cyanide leaching, mercury amalgamation, and electrolytic gold-stripping (Keller, 2006; Hagelüken, 2006b). Other secondary but less valued metals such as copper (Cu) and zinc (Zn) are also extracted from WEEE. The extracted metals are then sold to local scrap dealers or precious metal markets.

The formal sector is usually precluded from being involved in the metal extraction process in China and India. Streicher-Porte et al., (2007) stated the reason for this is owing to the low concentration of metals within PCs and metal prices on the open market. Streicher-Porte et al. further states,

> In India [...] almost all recycling of PC components is carried out by small enterprises using processes with low capital costs and not complying with state regulation regarding taxation, environmental protection or safety standards (p. 328).

The obvious reason for the maintenance of low capital costs is the maximization of profit at the expense of the environment, and worker health and safety.

Toxicology of Electronic Waste: A Case Study in China

Plastics, such as polyvinyl chloride, polybutylene terephthalate, polyethylene, acrolonitrile-butadiene-styrene, and epoxy-resin, are the basic materials used to manufacture electrical and electronic equipment. These plastics always contain chlorinated and brominated flame retardants (BFRs), which are added as stabilizers and plasticizers to enhance performance. Therefore, during the pyrolysis or combustion of electronic waste such as TV sets, circuit boards and electronic cables, congeners of polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), and polybrominated dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs) are formed and emitted into the atmosphere (Li et al., 2007). Laboratory examination of the emissions resulting from the burning of e-waste indicates serious consequences (Gullet et al., 2008). The products of combustion include fly ash, which is full of deleterious levels of lead, as well as congeners of both PBDD/Fs and PCDD/Fs. Consequently, according to numerous toxicology studies surfacing through the years 2006-2007, these economic activities have resulted in widespread dioxin poisoning in parts of Guiyu, China (Guangdong Province) where these non-formal economic activities are concentrated. Air emissions are heavily laden with PCDD/F and PBDD/F from open burning of printed circuit boards and other elements of WEEE (Li et al., 2007). Further studies of emissions reveal the presence of five to six ring polycyclic aromatic hydrocarbons (PAHs) such as Benzo(a)Pyrene (BAP), and heavy metals such as chromium, copper and zinc (Deng et al., 2006). Elevated lead levels were found in the children of Guiyu (Huo et al., 2007); elevated levels of lead are associated with developmental disorders in children (Shannon & Graef, 1996). Naturally, it comes as no surprise that the workers at these sites are also inundated with polybrominated diphenylethers (PBDEs), with one congener alone (BDE-209) found to be 50-200 times higher than in any previously recorded occupationally exposed group (Bi et al., 2007). Polycyclic aromatic hydrocarbons are produced by the open burning of printed circuit boards (PWBs) and plastics such as vinyl chloride; these have been found in significant levels in soil sediments in the form of dioxin, furans and brominated flame retardants, as well as some levels of PCBs or polychlorinated biphenyls (Leung et al., 2006). Combustion residues consisting of PCDD/F and PBDE were found in soils extending as far away from Guiyu as 10km (Leung et al., 2007). Local vegetation has also been found to contain PBDEs (Yang et al., 2008). PBDE congeners were also found in the fish and sediments of the Nanyang River, a tributary running through the area of Guiyu (Luo et al., 2007). Body loadings of PCDD/Fs at a waste site in Taizhou, Zhejiang Province are very high, with levels found in breast milk exceeding World Health Organization (WHO) standards by 25 and 11 times respectively (Chan et al., 2007). The electronic waste dismantling industry is thought to be a factor in the increased levels of PBDEs discovered in the Pearl River, which empties into the Pearl River estuary situated between Hong Kong and Macau (Guan et al., 2007). According to Tong & Wang (2004), attempts to domestically manage China's internal problem with imported WEEE have not been successful to date: "...increasing strict [state] controls have failed to curb the growth of e-waste recycling in coastal China" (p. 614). This non-formal, environmentally deleterious process of precious metal extraction will probably continue into the foreseeable future, as the costs of environmental controls in China are prohibitively high for competing companies in the formal economy (Liu et al., 2006a). This problem is also projected to be more acute in the near future. Levels of WEEE in China between 1999 and 2004 increased from 10.7 million tons to 33.1 million tons (Li et al., 2006). This is projected to increase a further four-fold in the years 2005 to 2020 across all categories (Liu et al., 2006b).

Scope and Aims of Thesis

Scope and Limitations

The scope of the thesis is to examine the economic limitations and some environmental implications for pursuing BAT applications within the province of Ontario, with emphasis upon the first five years of the proposed plan across five categories as specified by Ontario Electronic Stewardship (OES). The model applied will be based upon an existing WEEE supply model derived from OES (Ontario Electronic Stewardship, 2008), as well as the application of BAT to the end product coming from OES recycling infrastructure.

The techniques which were employed in this study began with process-based Material Flow Analysis (MFA), which is described in this succinct summary:

> Process-based MFA studies deliver indicator values for a system's characteristics (e.g. recycling rates), performance (e.g. resource efficiency, rates of resource depletion) and impacts (e.g. range of available resource deposits or landfill capacities) (Streicher-Porte et al., 2007, p. 327).

MFA will be used in determining the total efficiency of the system resulting in final refined recycled metals. Economic modeling was also utilized, in particular markets of scale and scope in order to determine the sources and size of potential revenue flows. A sensitivity analysis was conducted in order to determine whether the investment in BAT would respond negatively to market volatility with regard to metal prices. Game theory will also be employed in order to forward policy initiatives which address some deficiencies in the OES strategy (see Outlook).

The data sources used in this study may be divided into three major categories: technical reports, commodity markets data, and volume projections. Technical reports include peer-reviewed papers, conference papers, reports issued by private consultants, universities and governmental bodies. Commodity markets data consist of real-time (current) market prices from global markets, historic trends in metal prices (as to be found in trade journals such as *Platt's Metals*, online brokerages such as Metalprices.com, or those of governmental bodies such as the United States Geological Survey), as well as market prices for recycled WEEE components which can be found on the internet (e.g., RecycleNet Corporation www.recycle.net is an online brokerage). Lastly, volume projections are taken from OES reports which are corroborated or analyzed in conjunction with Waste Diversion Ontario's *Municipal Datacall* reports.

The limitations of this study naturally revolve around the reliability of source data. In particular, two major areas of focus require mentioning. First, the revenues derived for this study are based on the realization and maintenance of perfect collection rates (i.e., 100%), these volumes being provided by OES, as well as minimal losses during the recycling process (such as dismantling, assay, and smelting). As such, this introduces an element of idealization into the final results, especially since collection rates have the highest impact on total gross revenues. Nevertheless, while it is assumed throughout this work that a 100% collection rate is realized, in the Cost-Effectiveness chapter a break even analysis was conducted which found that minimal collection rates of 86.1% would be necessary for a seventy year project horizon. Secondly, technical reports about the content of the metals in WEEE were sparse and at times their data anomalous. This necessitated the elimination (at the author's discretion) of data which would overextend total gross revenues, to the effect of a preference for conservative estimations. In the case of two metals (platinum and indium), there were no data available whatsoever. Other issues also remain, such the necessity for robust pricing in the metal commodities markets and the maintenance of a low inflation policy in order to realize profit potential. The overall analysis here does not include operating costs such as labour, power, transportation, etc.; however, the BAT asset's capacity (by volume) far exceeds that of the volume of available waste in Ontario. Also, the emissions data used to derive production savings in terms of coke and CO_2 are incomplete. These and other issues will be discussed in further detail in chapters Possible Revenue Derived From e-Waste Volumes, Sensitivity Analysis, and Cost-Effectiveness Analysis.

AIMS AND SCIENTIFIC QUESTIONS

The central aim of this thesis is to present a concise and specified investigation of the current electronic waste problem in the province of Ontario with regard to its potential for economic exploitation. Three central questions are at the heart of this undertaking:

1) What are the possible revenues from the application of BAT to Ontario's electronic waste, specifically derived by OES's projected volumes?
2) What are the market conditions by which such an undertaking would operate? To that end, a sensitivity analysis will be employed.

3) Is such an undertaking cost-effective in terms of the long-term outlook as a waste stream and as a resource?

The unifying hypothesis derived from these three questions is whether there is sufficient presence of recoverable elements in WEEE to justify the investment in capital necessary to construct BAT and whether a BAT system can be viable, given fluctuations in the market for recoverable elements. A core assumption of this hypothesis is that the investment in BAT is based on the non-existence of any smelting infrastructure. That is to say that no case will be considered whereby elements of BAT will be retrofit onto existing smelting operations in Canada. Furthermore, the cost of investing in BAT will be spread across several decades to facilitate a viable business strategy. As well, the BAT asset will have an indefinite lifespan as it is assumed that proper maintenance measures will be taken. A second core assumption of the hypothesis will be the realization of perfect collection rates and minimal losses during the actual recycling process.

PROCEEDING AND STRUCTURE OF THESIS

The structure of the thesis will be to answer each of the above questions by chapter and discuss the findings thereof in terms of economic speculation and analysis. Specific methodology and quantification will be employed within each subject area. A generalized summary will be found at the end of the paper under Conclusions.

RECYCLING

BEST METHODS TECHNIQUES

UMICORE OF BELGIUM

Within the text of the *Waste Diversion Act* and *O. Reg. 393/04 WEEE,* there is no mention of Best Available Technologies (BAT). Nevertheless, with regard to electronic waste, this does not imply they are non-existent.

Umicore of Belgium is a publicly traded corporation which uses integrated smelting operations to achieve an overall efficient recovery (>90%) of over seventeen metals inherent in the WEEE stream, with precious metals such as gold, silver, platinum and palladium retrieved at efficiencies exceeding 95%. Substantial investments in technological improvements make this particular facility a "Best-Available Technologies" example in the processing of complex secondary materials (Hagelüken, 2006a). A mass-balance study conducted by Umicore found the external mechanical separation techniques (such as eddy-currents for aluminum separation, magnetic separators for ferrous elements, gravity separation, etc.) of printed circuit boards (PWB) can contribute to a loss of up to 20% of recoverable metals (Hagelüken, 2006a). This is dues to the limitations of the separation process attributable to an overlap of physical properties, dust and very fine fractions (Hagelüken & Art, 2007). Metallurgical (smelting) operations have the benefit of 'liberating' individual metals from the waste stream

(Hagelüken & Art, 2007). This is achieved through smelting, copper leaching, electrowinning, and precious metals refining. All emissions meet standards for both the EU and the Belgian state. This is not to suggest that alternate means of metal extraction do not exist. Certainly, alternative methods have been developed to extract metals from e-waste, methods such as aqua regia (Sheng & Etsell, 2007), selective leaching (Oh et al., 2003) and vertical vibration (Mohabuth et al., 2007). The main component of the pyrolysis of plastics contained in electronic waste is an oil made mostly of aromatic compounds with small concentrations of halogen compounds (Hall et al., 2006; Vasile et al., 2007). However, thermal treating of electronic waste presently represents the best method for the extraction of precious metals and to render potentially hazardous substances inert (Scharnhorst et al., 2007; Vasile et al., 2006).

For the purposes of illustration, the system envisaged by OES is juxtaposed with the contrasting BAT system at Umicore (Figure 1). As stated by Hagelüken & Art (2007), overall system efficiency is determined by the product of efficiencies at each stage in the recycling process (see Possible Revenue Derived From e-Waste Volume chapter). Thus, the OES process invariably involves shredding PWBs as an expedient step towards data security, while BAT at Umicore guarantees that this is done (data security) at the point of feedstock recycling (i.e., the smelter). This is why the shredding element is included in the OES line, although naturally this is outsourced to a recycling firm. Other hypothetic loses are 10% due to dismantling, 20% at the assay stage and 10% at the smelting stage. Thus, as may be seen from the diagram, at a collection rate of 50% the contrasting systems achieve an overall efficiency difference of 6% owing to

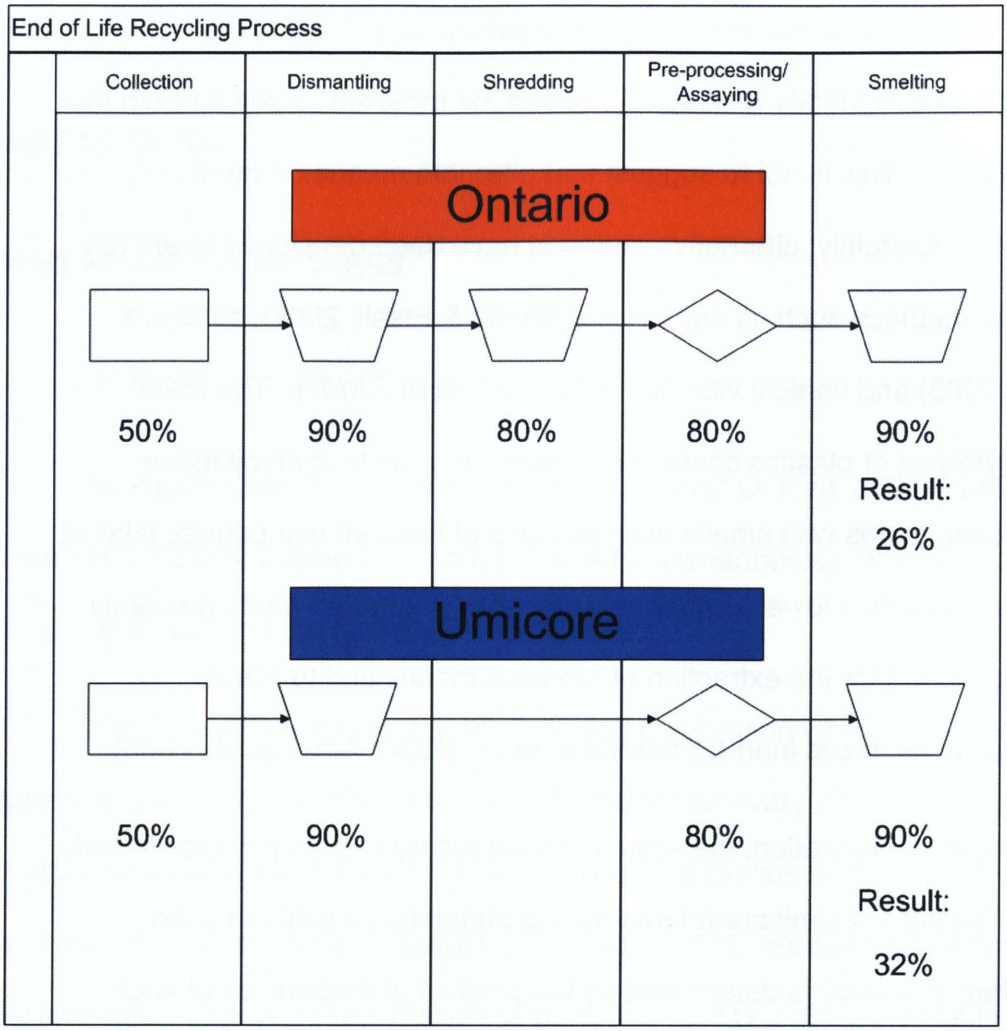

Figure 1. A comparison between two hypothetical recycling systems. The above system incorporates shredding measures such as proposed by OES while the one below is a BAT system somewhat similar to Umicore of Belgium. Adopted from Hagelüken (2006b).

the reduction of efficiency inherent in mechanical separation. An additional systemic deficiency may be gleaned from this diagram: that overall systemic efficiency is contingent upon the realization of significant collection rates.

Beyond the containment of hazardous substances and the elimination of systemic inefficiencies, there is economic reasoning for smelting PWBs. This lies in the fact that metals from naturally occurring ores are far less present in the environment than they are in WEEE. For instance, gold usually occurs at concentrations of 1-5ppm in ores (Patron Mining AG, n.d.), but as high as 230ppm in the electronic waste stream (Hagelüken, 2006). Kang & Schoenung (2005) also cite the United States Geological Survey as quoting the incidence of gold in WEEE is forty times higher than in naturally occurring ores. Older computers from the 1990s contained as much as four grams of gold; however, over time this has declined to just over one gram. Yet, for the foreseeable future, the levels of metals in computers should stay constant (Streicher-Porte et al., 2007). Another economic motive behind recovering metals from WEEE is the reduction of overall energy consumption to one tenth the amount otherwise necessary to produce refined metal products derived from mined ores, at no loss to quality or performance characteristics (Vanbeillen & Chintinne, 2007).

The waste plastics derived from the recycling process have been used as a fuel and as a reducing agent (Kang & Schoenung, 2005). Plastics themselves are a very effective substitute for coke as a reducing agent, with a proportional energy exchange of 1.3 tons of plastics to 1.0 tons of coke (Kang & Schoenung, 2005). However, this should only be done in the presence of adequate environmental controls. Like refuse-derived-fuels (RDF), they must have their hazardous elements removed and neutralized (Schlummer et al., 2007). Unfortunately, at this time this market is underdeveloped and, thus, is not part of this study.

Recycling efficiencies have been determined based on observable studies. Truttmann & Rechberger (2006) cite Nassour (2004), with recycling efficiencies of 85% for copper, 95-99% for iron (Fe), 85%-95% for non-ferrous metals and 95% for plastics and non-metals. BAT recycling levels are derived from Hagelüken (2006a) and will be the basis for determining revenues.

DATA COLLECTION

Data were collected from a network of sources. Chief among these are the data on the amount of metals available for extracted from the printed circuit boards (PWBs) and the various other elements of the waste stream. Data on these metals were derived from technical papers by Hagelüken (2006a) and Huisman (2008).

Municipal Datacall provided the current volume figures within Ontario. This database is maintained by Waste Diversion Ontario (WDO) for the years 2002-2007. These figures are discussed below. Furthermore, OES provides total volume flows based upon averaged unit weights and the total number of expected units (PCs, monitors, printers, etc.)

INTERPRETATION

SYSTEM DESCRIPTION AND PROCEDURES

Much of the variation in the levels of metals within observed electrical equipment can be explained by the fact that the actual manufacturing of electronic equipment is outsourced to firms which then use markets of scale to reduce costs (Osibanjo & Nnorom, 2007). Thus, variation in content is a significant factor in the distribution of materials entering the waste stream. Another process which affects the overall inefficiency is the improper sorting and diversion of recycling content; thus, an automobile which is full of electronics equipment rarely enters the proper waste stream (Hagelüken, 2007b). Figure 1 illustrates some difficulties with the overall recycling scheme. As was discussed above, shredding computer circuit boards causes inherent losses in the overall recycling process. On the other hand, feedstock recycling used in BAT removes this inherent inefficiency altogether. To reiterate, the primary weakest link in the chain—namely, collection rates—has the greatest effect on the overall efficiency rates. As mentioned elsewhere, collection levels are inherently weak owing to improper market instruments. Quantification of the efficiency levels achieved is given below.

ONTARIO

To address the deficiency of regulation regarding the handling of WEEE, the Government of Ontario drafted *O. Reg. 393/04 WEEE,* which is scheduled to come into effect on April 1, 2010. The regulation is supplementary to the Ontario *Waste Diversion Act* (2002) and seeks to increase the levels of WEEE recycling through targeted measures. A not-for-profit governing body, Ontario Electronic Stewardship (OES), was established in order to administer this regulation. OES is made up of manufacturers, retailers, for-profit and not-for-profit recyclers, and refurbishing foundations. During the initial phase of the program, five categories of waste will be targeted, namely computers, monitors, printers, peripherals and televisions. Like similar regulations promulgated to deal with the WEEE problem (such as European Union *Directive 2002/96*), weight-based targets are employed in order to measure program success. Unfortunately, as noted by Huisman et al. (2004), Hagelüken (2006a) and Huisman et al. (2007), weight-based targets may not be an ideal policy strategy as they typically lack content differentiation. For example, under such a weight-based target scheme, a kilogram of a carcinogen such as cadmium is treated with the same gravity as a kilogram of concrete. This has the potential to distort the success of a recycling program in terms of how much hazardous material has been diverted from landfills and export, especially since OES will compensate collectors $165/ton of collected WEEE. At the same time, weight-based measures have the possibility of understating the revenue potential of the electronic waste stream. Furthermore, the agenda set by *O. Reg. 393/04 WEEE* is, "to obtain the highest environmental benefit in an economically efficient manner" (Ontario Electronic Stewardship, 2008, 52). From the onset, this raises the question whether carrying out a program under such a mandate would result in environmentally desirous outcomes. OES has earmarked $62.1M CAN[1] to cover the

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[1] Except where indicated, all figures are in US dollars.

first year of its operations. Year 1 budget includes $950,000 CAN[2] in Research and Development; however, contrary to Best Methods Practices (BMP), no provisions are made for investment in new infrastructure (the belief—on the part of OES--is that existing infrastructure already meets demand).

For the interim, Ontario does not plan to handle cell phones, even though these present a significant source of lead leachate in landfills (Lincoln et al., 2007). Advanced processing institutes already exist in Sweden where the precious metals are extracted and the plastics are used in heat generation (Canning, 2006). OES has indicated that other consumer electronics will be included in Phase 2 of the OES program plan, to be developed after acceptance of the Phase 1 plan.

Projected Volumes

In Ontario, the projected volume of electronic waste is governed primarily by levels estimated by Ontario Electronic Stewardship (2008). These figures have been provided [Figure 2] with cross-correlations to figures from other studies, including Waste Diversion Ontario (2005), PHA Consulting Associates (2006), and Waste Diversion Ontario *Municipal Datacall* database (2002-2007). The lines labeled "Available", "Reuse", "Collection Targets", and "Recycling Targets" were all derived from Ontario Electronic Stewardship (2008). A simpler version is given in Table 1, in order to prevent ambiguity with Figure 2, and a translation into the number of units involved is given.

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[2] $600,000CAN in "common" research and $350,000 in "material-specific" research

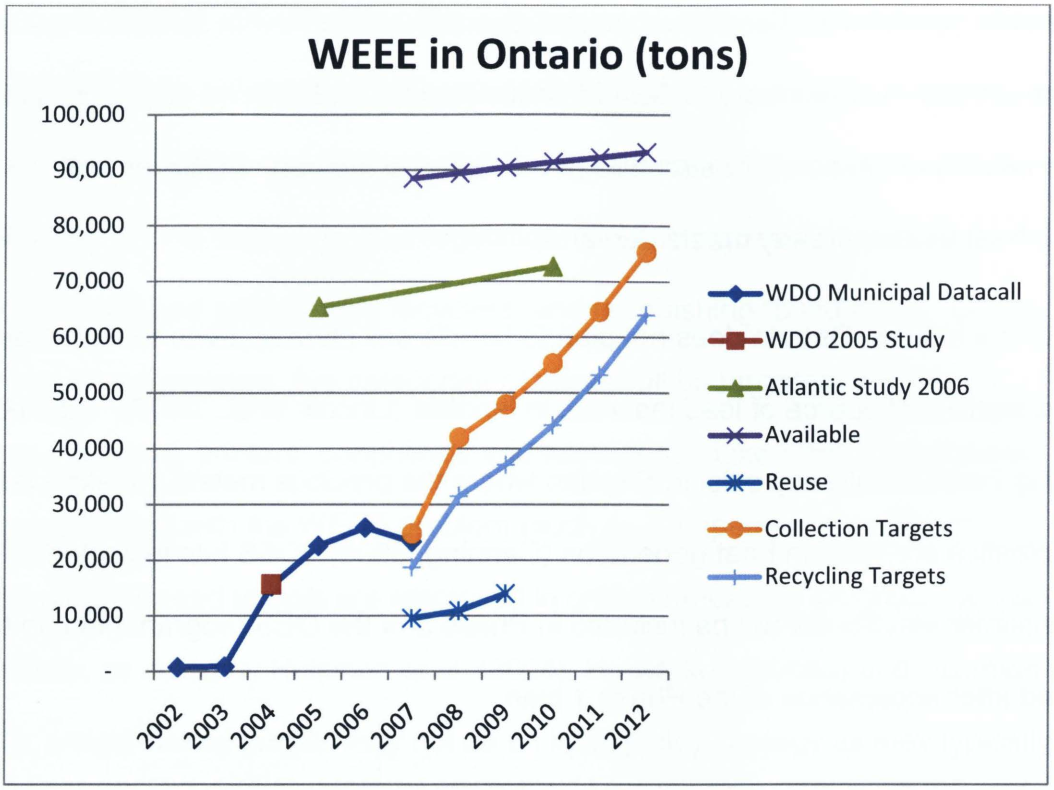

Figure 2. Projected volume of WEEE provided by OES with WDO *Municipal Datacall* figures for the years 2002 to 2007. WDO Municipal Datacall and WDO 2005 correspond to actual collection levels of e-waste. Atlantic Study 2006 and Available correspond to projections of available e-waste, the latter from OES (2008). Reuse, Collection Targets and Recycling Targets are all theoretical targets as provided by OES (2008).

The figures provided represent tons of available WEEE (Ontario Electronic Stewardship, 2008) and units are based on averaged weights per single item.

Table 1

Projected WEEE Volume

Draft O. Reg. 393/04

	Baseline Year	Year 1	Year 2	Year 3	Year 4	Year 5
	2007	2008	2009	2010	2011	2012
Tons	88,523	89,424	90,395	91,364	92,285	93,216
Units	11,531,900	11,667,500	11,858,800	12,041,200	12,175,500	12,311,000

DISCUSSION

As may be gleaned from Figure 2, the levels of collection are projected to eventually meet the actual available levels of electronic waste sometime in the future beyond 2012 (growth is projected by OES to be 25% per annum). Only one figure was cited by WDO in the 2005 study and this correctly correlates to the *Municipal Datacall*. It might be worth noting that the projected volumes are, in fact, larger than in the previous study conducted in 2006 for Atlantic Canada (PHA Consulting Associates, 2006). However, the realization of collection levels close to the actual available amounts of e-waste may in fact be idealized. Note the levels of e-waste collected by WDO actually drop for the year 2007. Furthermore, a substantive portion of the actual collection levels is really comprised of heavy household appliances and not what is typically characterized as electronic waste (certainly not within the text of *O. Reg. 393/04*)[3]. For example, in the year 2007, 17,887 tons out of 23,306 tons, or 76.7%, were comprised of heavy household appliances. This brings to light the difficulties in achieving targeted collection rates which arise from both the lack of coordination in setting categories for collection and collaboration among different bodies entrusted with the task of collecting waste.

[3] Typically large household appliances (dishwashers, dryers, etc.) are considered "white goods" based on their lower implications for environmental damage, as compared with "brown goods" which have much more serious cause for concern.

POSSIBLE REVENUE DERIVED FROM E-WASTE VOLUMES

METHODOLOGY

Starting with a process-based MFA, a model can be derived for the total revenues (*R*) as governed by the following equation:

$$R = \sum_{i=1}^{5} V_i p_i c_i r_i$$

where: *R*=total annual revenue ($US) across categories *i*,

V=volume of WEEE (kg/year)

p=price ($US/kg),

c=correction factor ($0 \leq x \leq 1$),[4] and

r=recycling efficiency rate ($0 \leq x \leq 1$).

The recycling efficiency rates are derived according to rates provided by Hagelüken (2006a) and Huisman et al. (2007) and according the method described in Figure 1. The recycling efficiency rate may be defined as the product of the recoverable efficiencies at each stage of the recycling process. Therefore, the general equation determining overall efficiency is given as,

$$r = e_c e_d e_s e_p e_{sr}$$

[4] The correction factor *c* is used to normalize otherwise incongruent units, such as converting ton to kg.

where: e_c=collection efficiency

e_d=dismantling efficiency

e_s=separation efficiency

e_p=pre-processing/assaying efficiency

e_{sr}=smelting recycling efficiency

Collection efficiency (e_c) is the percent of available EOL electronics received by recycling processors, be they public, private or not-for-profit, and not diverted to landfills, foreign destinations, or put into storage. Dismantling efficiency (e_d) refers to the amount of recoverable materials not lost during the dismantling of EOL electronics by recycling processors, as through breakage or improper sorting. The separation efficiency (e_s) is the amount of recoverable materials not lost during the mechanical processing of WEEE (i.e., shredding or magnetic separation). As well, pre-processing/assaying efficiency (e_p) refers to the amount of recoverable material not rejected during the assaying stage. Lastly, smelting recycling efficiency (e_{sr}) is the amount of recoverable material not lost during the feedstock recycling process. For example, using figures cited in Figure 1 and using an e_{sr} for silver (Ag) of 0.95 from Hagelüken (2006a) this would give:

$$r = e_c e_d e_s e_p e_{sr}$$

$$= (1.0)(0.9)(1.0)(0.8)(0.95)$$

$$= 0.684$$

Note, the separation efficiency e_s is set to 1.0 (or 100%) as this stage does not take place under BAT. The revenue projections are calculated according to the baseline and first five years of the OES plan using volume projections of "available" WEEE (note: not "collected," "recycled" or "refurbished"), which is why the collection rate efficiency is set to 1.0 (or 100%). Furthermore, it is assumed since the actual text of the *O. Reg. 393/04* specifies PWBs will not be landfilled (thus, losses in dismantling will be negligible and no PWBs will be rejected through assay) and that there will be no further losses to the system except at the smelting stage. This may be misguided on the part of OES since assaying prior to the smelting stage makes for the possibility of rejecting certain PWBs. Keller (2006) noted one recycler in the formal Indian market purportedly sells his dismantled PWBs directly to Umicore owing to losses between 44 and 83% at the pre-processing stage.

QUANTIFICATION

The tentative revenue projections calculated incorporating the above methodology in Microsoft Excel is illustrated in Figure 3. "MIN" and "MAX" correspond to those which would be available through BAT, while those labeled "Revenues with no BAT" correspond to the value of these assets if they were traded on the open recycling market with a 15% turnover, 5% over expectations for recycling industries (Ontario Electronic Stewardship, 2008). The solid areas under "MAX", "MIN" and "Revenues with no BAT" are meant to convey the fact that potential revenues may decline

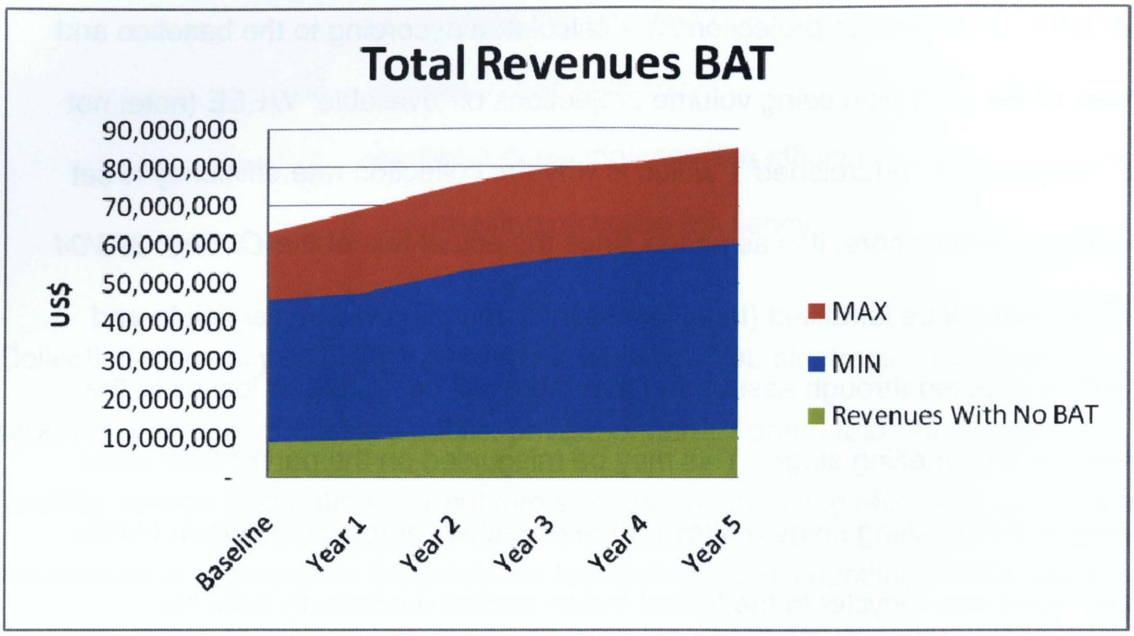

Figure 3. A comparison of projected revenues derived from PWBs using BAT as compared with revenues due to trading processed recyclables.

according to decreases in collection efficiencies or e_c. As mentioned in the Introduction, prices for each category under the "Revenues with no BAT" were derived through online brokerages such as RecycleNet Corporation. The difference between MIN and MAX is contingent upon the mixture of content in the WEEE stream, specifically the number of LCD versus CRT monitors and PWBs to PCs. Overall, this represents a net increase in profit potential of roughly four hundred to almost six hundred percent, the exact figures of which are given in Table 2.

Table 2.

Total Revenues BAT (US$)

	AVAILABLE					
	Baseline	Year 1	Year 2	Year 3	Year 4	Year 5
PWB	13,762,868.24	14,971,473.23	18,115,203.10	20,511,756.83	21,238,276.72	25,052,227.50
PC	21,797,882.37	23,704,144.99	28,674,909.92	32,495,995.15	33,654,234.86	39,686,214.38
Printers	14,587,795.40	14,726,726.79	14,448,864.02	14,587,795.40	14,309,932.63	13,476,344.32
Monitors (CRT)	1,533,391.27	2,074,588.19	1,954,322.20	1,844,078.39	1,733,834.57	1,633,612.92
Monitors (LCD)	11,059,647.87	14,963,053.00	14,095,629.64	13,300,491.56	12,505,353.47	11,782,500.67
Televisions	10,886,700.22	10,788,178.05	12,758,621.52	14,261,084.68	15,344,828.59	14,827,587.18
Peripherals	4,942,415.30	4,942,415.30	5,491,572.55	5,308,520.13	5,674,624.97	5,674,624.97
MIN	45,713,170.42	47,503,381.54	52,768,583.40	56,513,235.42	58,301,497.49	60,664,396.89
MAX	63,274,441.16	69,124,518.11	75,469,597.66	79,953,886.92	81,488,974.53	85,447,271.52

Revenues With No BAT

Net	8,175,600.00	8,666,450.00	9,679,350.00	9,989,450.00	10,399,800.00	10,955,700.00
Profit (15%)	9,401,940.00	9,966,417.50	11,131,252.50	11,487,867.50	11,959,770.00	12,599,055.00

The concentrations of metals in each category of WEEE were derived from figures provided in individual studies. For example, Hagelüken (2006a) provides this information for various consumer electronics products reproduced in Table 3. Similar data were derived from other authors, including Huisman et al. (2007), Keller (2006) and Streicher-Porte et al. (2007). Nevertheless, there are deficiencies with the data which the author was able to retrieve; these will be examined in the Discussion section.

Net revenues derived from BAT can also be augmented by the levels of coke production saved and credits accrued against CO_2 emissions into the atmosphere. Hagelüken (2008) provides most of the details of how this may be calculated using integration of lifecycle inventories (LCA) derived from *ecoinvent 2.0* (Swiss Centre for

Table 3.

Sample data for metal and other material concentrations in various electronic devices

		1 cell phone 1999	2 cordless phone 1999	3 portable audio 2000	4 DVD 2001	5 DVDR 2002	6 calcu-lator	7 TV-boards	8 PC-boards
Weight	g/unit	125	175	515	3050	4350	n/a	n/a	n/a
Cu	%	13	10	21	5	6	3	10	20
Al	%	1	2	1	2	4	5	10	5
Fe	%	5	13	23	62	57	3	28	7
Plastics	%	57	41	47	24	25	61	28	23
Glass	%	2	n/a	n/a	n/a	n/a	13	6	18
Others[5]	%	21	32	8	6	7	14	15	22
Ni	%	0.1	0.1	0.03	0.05	0.1	0.5	0.3	1
Pb	%	0.3	0.8	0.14	0.3	0.4	0.1	1.0	1.5
Sn	%	0.5	0.9	0.1	0.2	0.2	0.2	1.4	2.9
Ag	ppm	1340	1350	150	115	170	260	280	1000
Au	ppm	350	120	10	15	25	50	17	250
Pd	ppm	210	95	4	4	5	5	10	110

Note: Adapted from Hagelüken (2006a).

Life Cycles Inventories). This strategy was adopted for some metals in this study (Sn, Ag, Au, Pd and Cu) and some preliminary results in the Discussion section following the Interpretation below.

[5] Made up of various substances left in the balance of the unit's weight.

Interpretation

The revenues represent the recovery of metals from printed circuit boards across four categories of WEEE (computers, printers, monitors, and televisions). As well, revenue derived from peripherals is related to the amount of copper in the wiring, which represents the largest source for revenue potential from peripherals. The revenue potential of CRT glass from this model has been discarded, as CRTs are projected to disappear from the waste stream by the years 2011-12 (Kang & Schoenung, 2005). As well, there is no efficient means for the recycling of liquid crystals as found in the LCD monitors and laptop computers (Huisman et al., 2007). Other markets for material recovery, such as metals in rechargeable batteries (cadmium) or plastics recycling, are not well understood at this time or are too premature in their development for either study or elaboration. For example, plastics derived from cellular phone WEEE are used as alternative fuels for the generation of electricity in Sweden (Canning, 2006); however, there is as yet no discernable formal market or price structure by which to track this economic activity. Similarly, there is a fundamental lack of data on metals like cadmium in electronic waste, which is largely used in rechargeable batteries; this is in spite of the usage of cadmium in steel production (Papp, 2000).

Discussion

The net benefits to the environment through the application of BAT are relatively small in comparison with the net economic benefits. Although a total reduction of

60,860 to 88,439 tons of coke usage would be realized, this would only result in production cost reductions of \$16.4M to \$23.9M (US) across the five years of the OES plan.[6] In terms of total emissions, this could produce a decrease of 174,060 to 252,935 tons of carbon emissions (CO_2) which corresponds to carbon credits in the range of \$2.48M to \$3.60M (US) at the current Verified Emission Reductions (VER) rate of \$15.80US/ton from the European Climate Exchange of London (ECX EUA).

The total revenue derived from such a waste stream is dependent upon the overall collection rates. The overall success of existing collection programs varies from country or region and within individual categories of waste. Jofre & Morioka (2008) report rates of overall collection in Japan at between 50-80% across eight different categories; however, more recently Oguchi et al. (2008) report this to be less than 56% across nine target categories. Similarly, in South Korea the collection rate was found to be 40% (Lee et al., 2007). Peralta & Fontanos (2006) put it at 50% in the Philippines. As cited earlier, the EPA (2007) reports the rate at less than 18.2% across the entire United States. The European Union experience is mixed, owing primarily to the number of its member states. For example, Savage et al. (2006) report the recycling performances in both Norway and Sweden in 2002 exceeded the 4kg/capita target collection rates by a factor of two (i.e., ≥8kg), while Belgium met the 4kg/capita target and the ICT Milieu program in the Netherlands reported little success at 0.58kg/capita. Existing programs running in provinces of Canada report progress in the collection of WEEE (Electronic Stewardship Association of BC, 2007; Saskatchewan Waste

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[6] Current coke price forecast for 2009 is \$300CAN/ton (Western Canadian Coal, 2008).

Electronic Equipment Program, 2008; Alberta Recycling Management Authority, 2008). However, there are no performance statistic levels provided in their documentation. Nevertheless, using older available data from 2006 from PHA Consulting Associates, their performance falls below 50% of available levels, with the sole exception of the number of monitors collected in British Columbia.

There is also a measurable degree of fluctuation in the level of metals found in PWBs across all categories. In some instances (such as PWBs, CRT and LCD monitors), there were three or more studies from which data could be retrieved (Huisman, 2004; Hagelüken, 2006a; Keller, 2006; Morf et al., 2007; Streicher-Porte et al., 2007; and Huisman et al., 2007). In the instances of PCs, Peripherals and TVs, there were two or more studies available (Socolof et al., 2001; PHA Consulting Associates, 2006; Babu et al., 2007; Morf et al., 2007; Hagelüken, 2006a; Hagelüken, 2007, September; and Huisman et al., 2007). Lastly, in the Printer category, only one study was available (Huisman et al., 2007). Unfortunately, the simple presence of multiple studies does not automatically denote a situation which is free of problems and quandaries.

Overall, there were two problems with the supplied concentrations of metals in WEEE. The first was missing data. For example, while the concentration of copper and gold in PWBs would be known, there would be no data on the amount of bismuth or palladium. In some cases (such as the PC category), this meant relying on data provided from one source only. Similarly, most studies made no mention of certain rare metals such as indium or ruthenium. Secondly, some of the data available stood out as suspect due to either their idiosyncratic nature or the fact that the confidence interval exceeded the data range (even though this was due to a lack of large data sets). For example, if the concentration for copper in PWBs is given as follows: 20% (Hagelüken, 2006a), 17% (Morf et al., 2007), and 18% (Huisman et al., 2007), this yields an average concentration of 18.3% copper per unit of PWB. The corresponding sample standard deviation is 1.5 with a 95% confidence interval of ±3.8.[7] Given the relative size of the sample (N=3), this would be acceptable. However, in the same category (PWB), the same three authors provide the following concentrations of tin: 2.9% (Hagelüken, 2006a), 2.7% (Morf et al., 2007), and 0.48% (Huisman et al., 2007). This set yields an average of 2.0% copper per PWB, with a sample standard deviation of 1.3 and a 95% confidence interval of ±3.3. In this case, the figure for tin supplied by Huisman et al. (2007) seems anomalous; however, the author's preference in this study was to err on the side of caution and, thus, this anomaly by was accepted for inclusion. On the other hand, in situations where the anomalous figure was too high, the author preferred to err

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[7] A Student's *t*-test was employed. Here, the average ($\bar{X}$) is given by,

$$\bar{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$

The sample standard deviation (σ) is given by,

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(X_i - \bar{X})^2}{N-1}}$$

And, the confidence interval (CI) is given by,

$$CI = \pm t \frac{\sigma}{\sqrt{N}}$$

Where t is derived from tables according to the degrees of freedom (d_f) and the desired percentage (in the above case this is 2 and 95%, respectively).

on the side of caution by eliminating the figure altogether and thus, prevent overestimating revenues.

In the end, the author's preferences for data augmentation resulted in surprisingly little variation in the overall revenue projections. In fact, only two categories were affected, namely PWBs and TVs. With PWBs this meant a reduction in potential revenue of 3.6% across all years of the program, while for TVs this meant a potential revenue increase of 31.5% across all years of the program. The overall effect these alterations would result in a 6.4% to 7.1% percent reduction in potential MIN revenues and a 4.9% to 5.9% reduction in potential MAX revenues across all years of the program.

Sensitivity Analysis

Methodology

Historic metal prices were collected from conventional sources on the subject, with particular emphasis on the journal *Platt's Metal Weekly*, the U.S. Geological Survey, and Metalprices.com, an internet brokerage. *Platt's Metal Weekly* and U.S. Geological Survey data may be reviewed in the Appendix; however, it should be noted here that the U.S. Geological Survey data was used strictly for comparison with data from *Platt's Metal Weekly* and subsequently was not employed. Once the prices were collected from the period 1995-2008, they were put in a spectrum from historic Low to High and collated into 5% intervals so that shifts in prices (plus or minus) occurred simultaneously, for all metals.

Once the 5% intervals have been entered into a matrix, they are then substituted into an Excel spreadsheet with the according operating scheme. One operating scheme is for BAT and a second for an operating scheme as proposed by Rouyn-Noranda (Xstrata) of Quebec (Moore, 2008). Once these have been calculated, they are illustrated in graphic form for comparison.

QUANTIFICATION

The results of the sensitivity analysis showed three key findings. Historic trends in metal prices were collected from the years 1995-2008 as prices during this period were not distorted owing to prevailing 'mild' ($<4\%$) inflation rates (Powell, 2005). The metal prices were divided into percentiles (Q) according to the entire price spectrum (Low to High) by five percent intervals (i.e. Q_5, Q_{10}, Q_{15}, etc.). The first stages of the sensitivity analysis showed, by their slopes in Figure 4, that the majority of the price volatility inherent in the recoverable elements is borne out of the metalloid arsenic and the metals lead, tin and copper, respectively.

Figure 5 displays metals which historically sell on the market at higher prices; not surprisingly, gold and palladium are the most stable in this set, with indium and silver indicating higher levels of volatility. It is worth noting for the sake of clarity that all the metals in Figure 4 would compress into the minute space to the left of indium and silver lines in Figure 5. Each five percent Q interval was then substituted into the revenue matrix such that all the elements (metals) covaried. In the first case, this revealed that the revenues derived from closing market prices for September 18, 2008 (MIN_BAT and MAX_BAT) were below the median range of price volatility, this despite the recent slump in the market owing to the financial sector crisis of 2008 onward (Figure 6a). That is, the expected revenues of September 18, 2008 can be found between the first intercept at MIN Revenue_SA and MIN_BAT and the second intercept at MAX Revenue_SA and MAX_BAT, or between the price percentiles Q_{44} and Q_{48} (Figure 6b). Nevertheless, the graph also shows the level of revenues derived from BAT even under

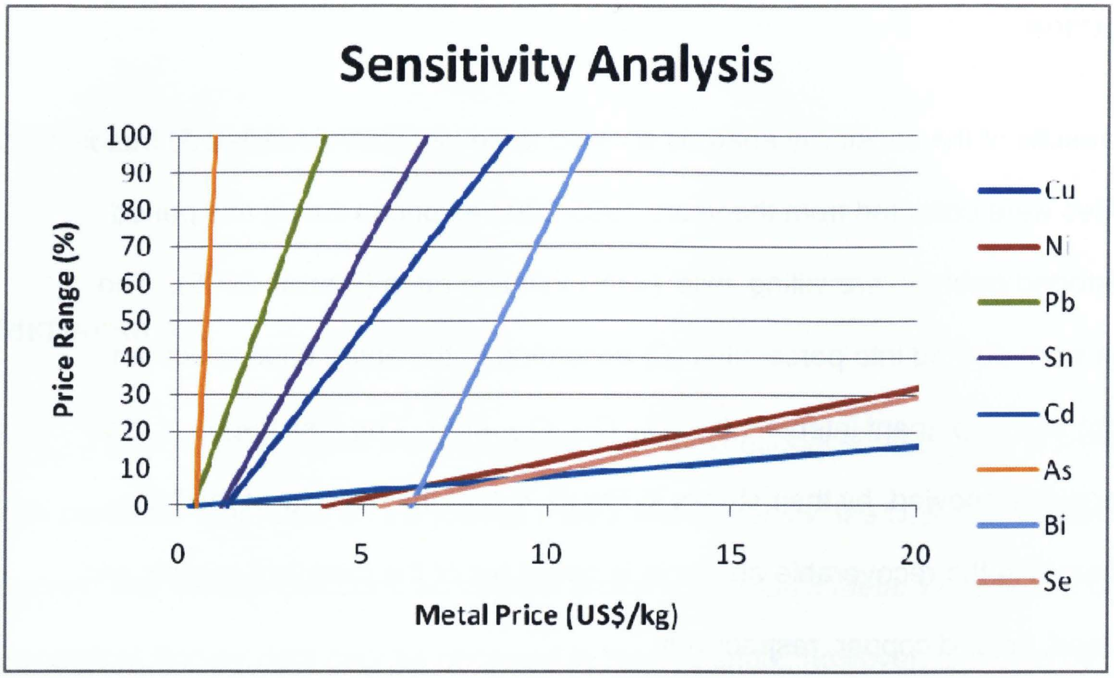

Figure 4. *A comparison of the relative volatility of metals, the metalloid arsenic and non-metal selenium recycled from WEEE indicating arsenic, lead, tin and copper as the most volatile (respectively).*

a worst case scenario (the so-called "perfect storm", though in all likelihood merely a hypothetical situation) would yield higher revenues than the scheme by which OES proposes (No BAT).

Recently, Xstrata of Switzerland announced plans to expand its facilities at its copper smelter in Rouyn-Noranda, Quebec, to handle 100,000 tons of WEEE by 2010 (Moore, 2008). However, Xstrata has indicated it will only be extracting the copper and precious metals (gold, silver and palladium). If applied to the WEEE streams in Ontario (Figure 7), this strategy would realize potential revenues of MIN_SA R-N(X) and MAX_SA R-N(X). The lower slope as compared to the MIN_SA and MAX_SA indicates

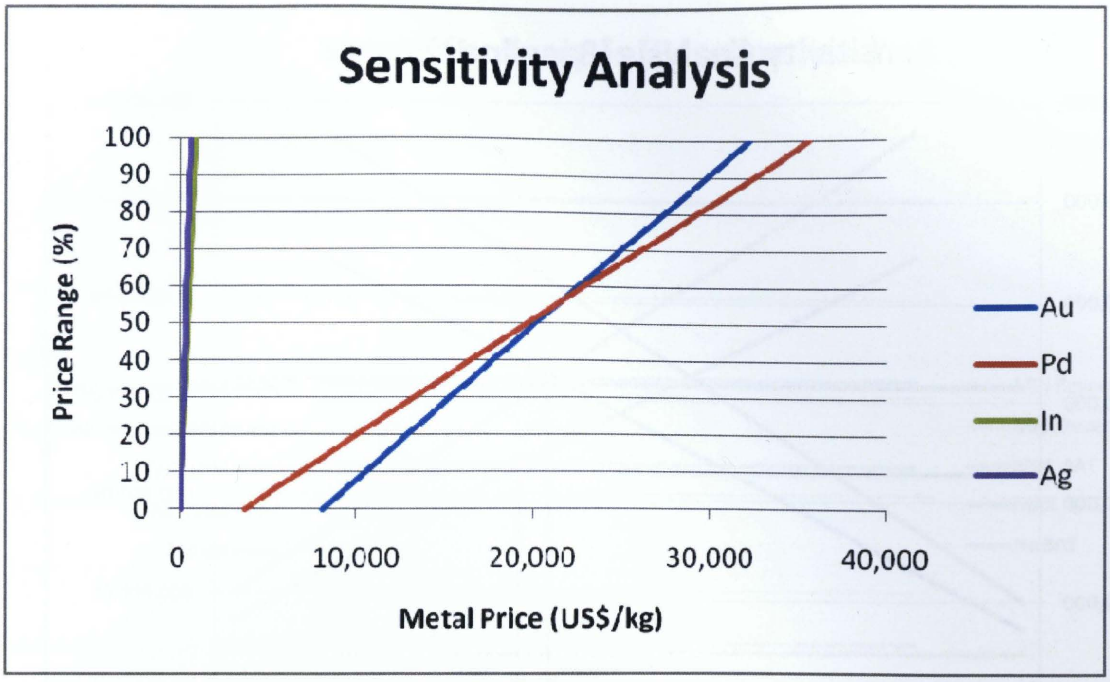

Figure 5. *A comparison of the relative volatility of metals recycled from WEEE indicating indium and silver as the third and fourth most volatile metals.*

there is less inherent volatility with the Rouyn-Noranda strategy; however, not surprisingly their profit potential is, for the most part, less than that which would otherwise be realized under BAT. Also of note is that the minimum profit potential for BAT meets and exceeds that of the maximal profit potential for the Rouyn-Noranda scheme at the 30th percentile (Q_{30}).

The most substantial difference between the BAT and Rouyn-Noranda scheme re between 76.8% (MAX) to 87.9% (MIN) of the difference between the BAT and Rouyn-Noranda schemes, while selenium makes up to 7.9% (MIN) to 11.4% (MAX) of the venues is due to the recovery of nickel and selenium through BAT. Nickel makes up difference between the two schemes. The remaining recoverable elements have less in

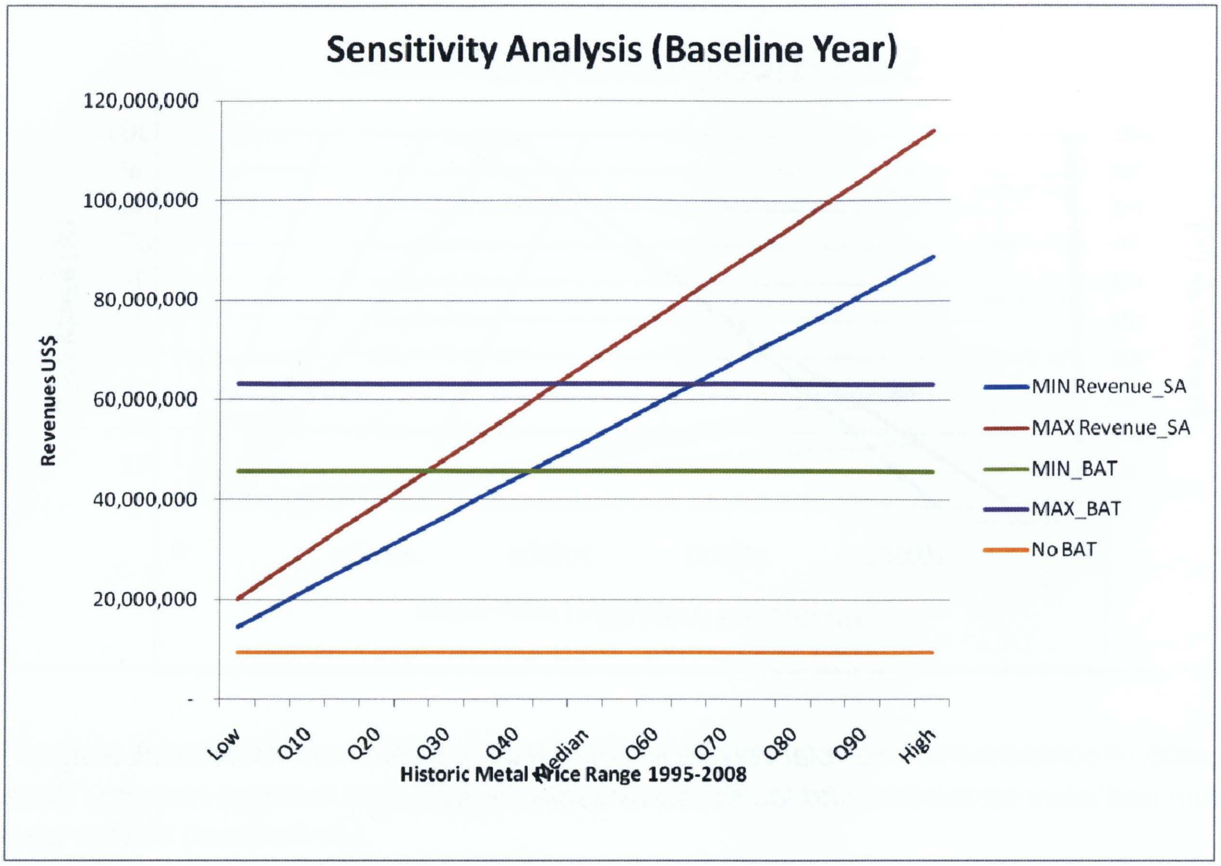

Figure 6a. *Sensitivity Analysis for the Baseline Year of the OES scheme showing the volatility of expected revenues given historic fluctuations in metal prices.*

terms of recoverable potential: antimony between 1.9% (MAX) and 3.5% (MIN); lead between 0.5% (MIN) and 9.4% (MAX); cadmium between 0.1% (MAX) and 0.2% (MIN);indium at 0.3% (MAX); and, lastly, bismuth at less than 0.1% (MAX and MIN).

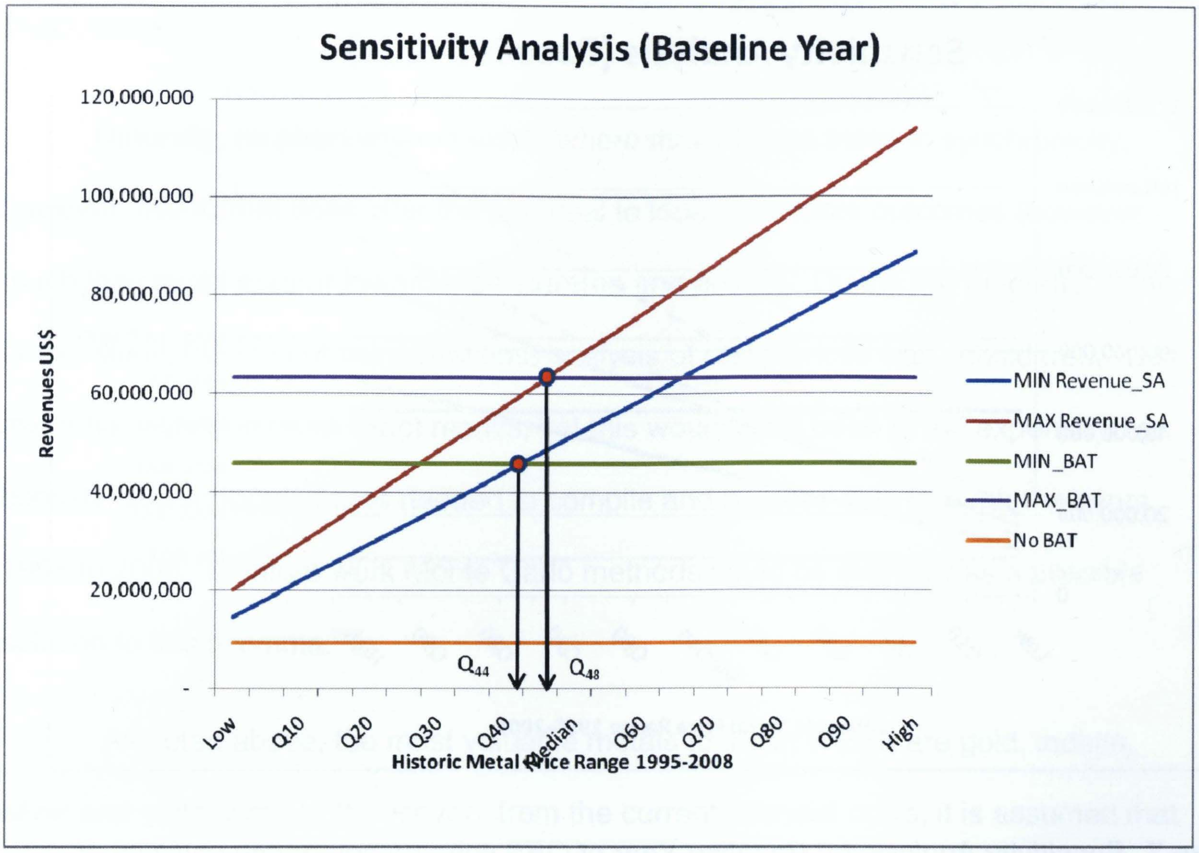

Figure 6b. *Sensitivity Analysis for the Baseline Year of the OES scheme showing the intercepts between MIN Revenue_SA and MIN_BAT as well as MAX Revenue_SA and MAX_BAT occurring at* Q_{44} and Q_{48}, *respectively.*

INTERPRETATION

The main hypothesis tested here is whether there is a sufficiently significant presence of precious metals in WEEE to contribute to overall volatility and whether a BAT system might be feasible even under market fluctuations. Under the BAT system, higher market prices reflect higher revenue potential and, consequently, these higher market prices in turn will affect the project's net present value (NPV). In the case of the

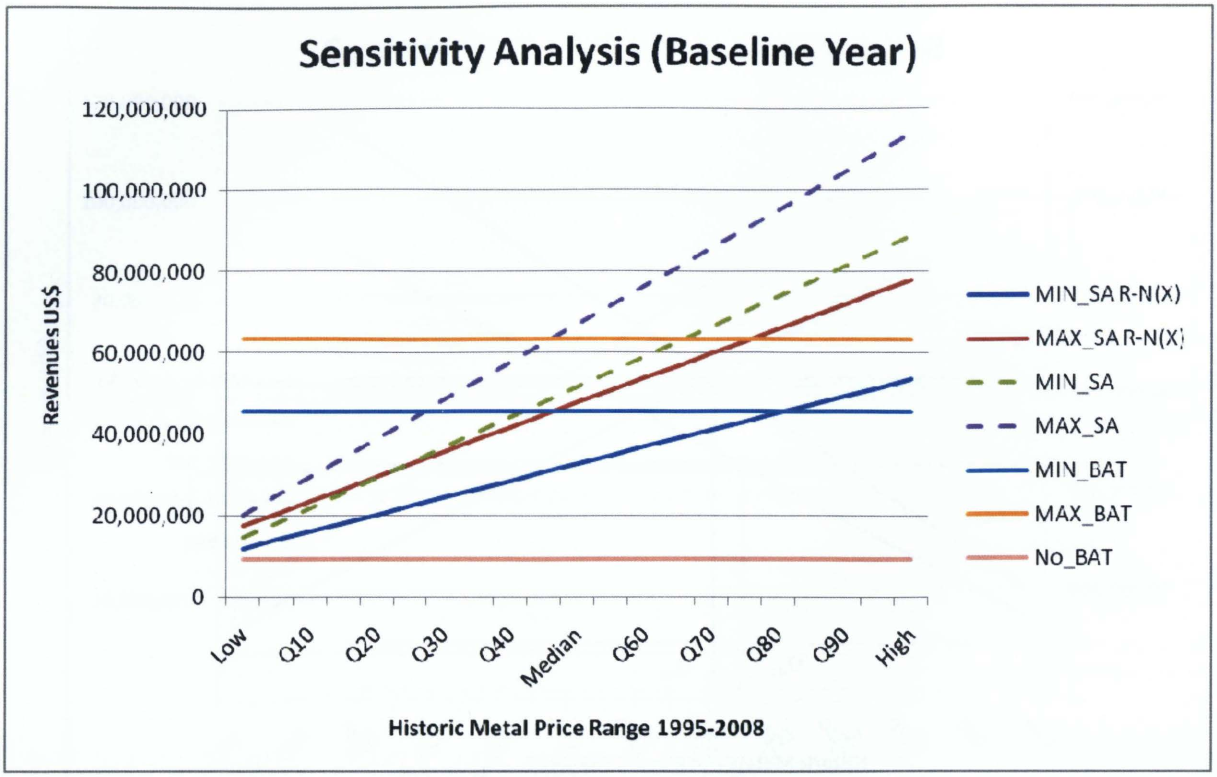

Figure 7. *Sensitivity Analysis for Baseline Year of OES scheme comparing volatility of inherent in BAT scheme versus Rouyn-Noranda (Xstrata) scheme.*

latter, this will be discussed in more detail in the next chapter. However, it may be stated briefly here that the NPV is the total present value of future cash flows and this is a useful tool to compare different schemes in a decision making analysis. Nonetheless, for historically low prices, the difference between the BAT scheme and the Rouyn-Noranda strategy in terms of revenue and NPV would become less obvious.

DISCUSSION

Naturally, no phenomenon exists where metal prices move in synchronicity; however, this format does offer the potential to look at possible outcomes (however much they might appear towards the extreme end points). During the theoretical stage of this study, the idea of using real time analysis of metal prices was considered. This might have yielded more exact results, yet this would have been at the expense of a considerable amount of time needed to compile and process data through the years 1995 to 2008. In future work Monte Carlo methods could be explored as a possible solution to this dilemma.[8]

As noted above, the most valuable metals found in WEEE are gold, indium, silver and palladium. With recovery from the current financial crisis, it is assumed that prices will bring back stability to the revenue sources. On the other hand, pursuing a strategy whereby only the most profitable metals are extracted could prove to be a mistake; that is, as prices increase, there could be as much as a 45.9% to 65.6% increase in revenues. Hence, a planning strategy must incorporate the projected market fluctuations predicated by a decreasing supply of raw materials weighed against the costs borne in constructing infrastructure.

The stress put on resources by population increases and economic expansion can only result in the necessity for the expansion of existing recycling frameworks. Already, an acute shortage problem in the supply of indium, ruthenium and other rare

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[8] Thanks to a member of the Oral Examination Committee, Dr. Andrew Laursen, for this suggestion.

metals is caused by the drive towards more LCD usage (New Scientist, 2007). Furthermore, the exact problem of finite resources is succinctly elucidated by the following short passage from Gordon et al., (2006):

> Providing today's developed-country level of services for copper worldwide (as well as for zinc and, perhaps, platinum) would appear to require conversion of essentially all of the ore in the lithosphere to stock-in-use plus near complete recycling of the metals from that point forward (p. 1209).

Gordon et al. (2006) go on to state cautiously that the technology for 100% recycling efficiency does not exist, nor is there any guarantee of substitute materials. Given this trend, the movement towards BAT in recovery of metals from WEEE might become inevitable. However, the more protracted is the movement to BAT, the technology investment will become more expensive and the cost of resources (e-waste in particular) will also increase. In the latter case, the cost of e-waste on the open market has changed very little during the course of this two year study, owing in particular to low demand, limited infrastructure to process it and perhaps little understanding of the potential for the exploitation of the resource.

Cost-effectiveness Analysis

Methodology

At this stage a cost effectiveness study of the BAT proposition was carried out under a set of basic assumptions. First, a smelter's lifespan is at least forty years; however, this can extend "forever" (Pereira, 2006) with proper maintenance (e.g., Umicore has been in operation since 1887, albeit in different forms). Thus, investment in this sort of technology will be a long-term enterprise, the cost of which is paid over several years. Hence, if the total cost of a smelter such as Umicore is $1.5B US (Hagelüken, 2006a), obviously this is not an asset which will be paid out in one lump sum principal (*P*). Rather, the cost will be reduced to annual payments or annuities (*A*), as by the following equation:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$

where: *i* is the lending rate, and

n is the number of years.

The term $\frac{i(1+i)^n}{(1+i)^n-1}$ is also known as the present worth factor (PWF) and is denoted by the syntax of (P|F, i, n). PWFs are set in a number of standardized tables in engineering economics textbooks according to interest rates, the years investing, type of interest (compound) and so forth. The Bank of Canada's December 2008 institutional lending rate is approximately 1.5% and the project's estimated lifecycle will be at least seventy years. This results in approximate net annual payments of $34.8M US to be offset by revenues from maximum and minimum revenue streams. Naturally, for extended lifecycles of greater than seventy years the payments (*A*) would decrease.

QUANTIFICATION

The overall results are given in Table 4. With an interest rate of 4%, this would give a Net Present Value (NPV) for BAT ($96M and $212M) which exceeds that of the NPV for the OES recycling scheme ($57.8M). Thus, using September 18, 2008 figures, the higher NPV for BAT indicates a cost effective scheme. At the beginning of this study, one of the key goals was to determine whether it would be necessary to adjust Canada's traditional discount rate (10%), which is the rate required by the Treasury Board for discounting future costs and benefits from public projects (e.g., see Treasury Board of Canada Secretariat (2007)). As is determined, however, this does not seem to be necessary (see NPV Discount 10%) as, in either case of the maximal or minimal, revenue possibilities exceed that of selling recycled materials.

A breakeven analysis was then conducted to find the conditions under which there would be no difference between a BAT scheme and a scheme without BAT. This was found to be a project with a horizon of at least 52 years, which is slightly less than the project horizon of 70 years used earlier and at full collection rates. Similarly, when

Table 4.

Cost effective analysis for OES strategy versus BAT strategy.

Year	No_BAT	MIN	MAX
0	9,401,940.00	10,954,638.42	28,515,909.16
1	9,966,417.50	12,744,849.54	34,365,986.11
2	11,131,252.50	18,010,051.40	40,711,065.66
3	11,487,867.50	21,754,703.42	45,195,354.92
4	11,959,770.00	23,542,965.49	46,730,442.53
5	12,599,055.00	25,905,864.89	50,688,739.52
Present Worth Factor (P|F,i,N)	0.9615	0.9615	0.9615
	0.9246	0.9246	0.9246
	0.8890	0.8890	0.8890
	0.8548	0.8548	0.8548
	0.8319	0.8319	0.8319
	0.7903	0.7903	0.7903
Present Worth	9,039,965.31	10,532,884.84	27,418,046.66
	9,214,949.62	11,783,887.89	31,774,790.76
	9,895,683.47	16,010,935.69	36,192,137.37
	9,819,829.14	18,595,920.49	38,632,989.39
	9,949,332.66	19,585,392.99	38,875,055.14
	9,957,033.17	20,473,405.02	40,059,310.85
NPV Interest 4%	57,876,793.37	96,982,426.92	212,952,330.16
NPV Discount 10%	$47,531,283.99	$78,123,183.69	$173,409,457.13

the collection rates were at least 86.1% of the available levels (and with a 70 year project horizon), a breakeven scenario occurs.

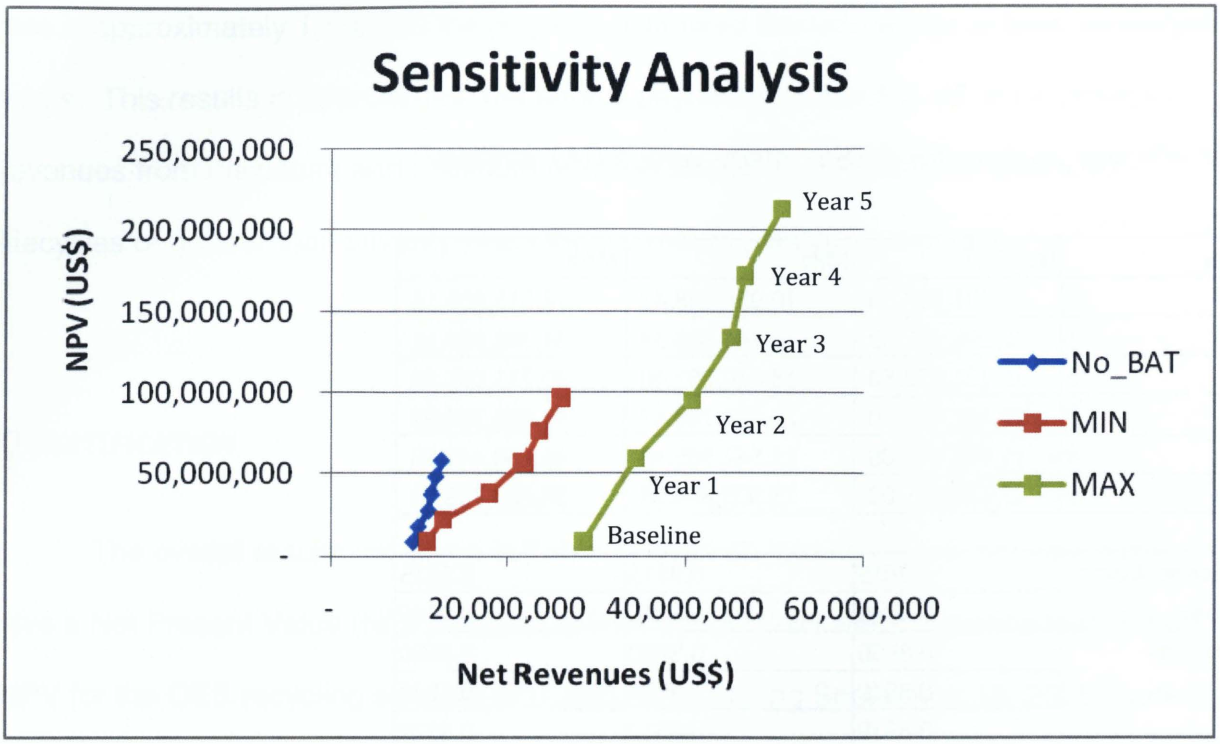

Figure 8. *Sensitivity Analysis comparing NPV and Net Revenues for each scheme.*

Using the data derived from the above cost-effectiveness analysis, a reexamination of the sensitivity analysis can be conducted. In this case, the NPV versus total revenues may be compared for each scheme. The result of this is shown in Figure 8 where the years of program (Baseline, Year 1, Year 2, etc.) are denoted by the square markers (■). The order of slopes from high to low in this diagram is No_BAT, followed by MAX and MIN, respectively. While the MAX or MIN BAT scheme reveals a more rapid realization of similar NPV than No_BAT, there is also an obvious lack of potential which characterizes the No_BAT scheme. That is, its potential to achieve higher NPVs is limited. As mentioned earlier, OES plans to realize 25% per annum increases in its recycling rates. Should OES not realize this target, there will be marked decreases in the NPV, and the difference between a BAT scheme and a scheme without BAT will widen.

INTERPRETATION

These results could be taken to interpret a situation where no existing infrastructure exists. However, given that infrastructure currently exists in the form of smelting operations (copper, nickel, etc.) within Canada, the cost of building a structure with BAT is reduced considerably. However, the adaptation of BAT is concomitant upon the realization of fully-integrated smelting operations as a core feature and, secondly, the higher standards of air pollution control such as cascade air scrubbers.

The sensitivity analysis conducted in Figure 8 indicates there is a preference for a BAT scheme over a scheme devoid of BAT. However, the realization of higher revenues as shown for MAX—when compared to MIN—reflects higher NPV as a function of the amount of metals recovered from WEEE at an increasing rate over future years in the program plan, as was similarly discussed in the Sensitivity Analysis chapter. A more simplified way of summarizing would be to say that NPV is a function of revenues which in turn are a function of the volume of WEEE collected.

DISCUSSION

It should be noted the above results operate under the assumption of metal prices at or near the median range (as discussed in the Sensitivity Analysis chapter).

Runaway inflation would naturally dampen the robustness of the results. The principle *P* results in an annuity that is fixed at $34.8M; however, that need not imply that deferment or paying ahead of schedule could not occur. Furthermore, certain operating costs such as labour and energy were removed from the analysis as these could not be ascertained against the BAT asset. That is, roughly only 30% of the input materials at Umicore involve purely electronic waste (Umicore, 2006), which represents some 300,000 tons per annum (Hagelüken, 2008). However, even with maximum levels of available WEEE in Ontario given over to such a scheme, it is but a fraction of the BAT's capacity (probably less than 10%). Such a realization supports the suggestion of Huisman et al. (2008) for the consolidation of recycling services in North America, both across provincial and international borders (i.e., within the NAFTA zone). A unifying WEEE recycling strategy is currently under consideration in Quebec and the Atlantic Provinces (Nova Scotia, New Brunswick, Newfoundland, Labrador, and Prince Edward Island).

CONCLUSIONS

During this study a number of problems arose in different stages of the undertaking. Perhaps the most important area of deficiency was the number of peer-reviewed studies which indicate with a marked level of precision the level of metals in any category of WEEE.[9] The majority of papers on the subject typically couch their figures in generalities such as "ferrous metals", "plastics", or "glass". More studies on the metallurgical content of WEEE would render more robust results as confidence intervals taken early on in the study were not ideal, in particular owing to the small set size. In part, the International Electrotechnical Commission (IEC) sets performance standards for electronic equipment, yet leaves the specific materials of manufacture up to the industry. Consolidated standards would go a long way to address the disparity of data on WEEE content, although the author contends this would be at the expense of industrial flexibility. Also, data on efficiency losses due to mechanical separation, assaying and smelting operations are often anecdotal or site-specific (Babu et al., 2007). As a considerable amount of this data is provided by industrial insiders, independent verification should be conducted.

The improper disposal of WEEE presents unique challenges to any waste management regime. That aside, the utilization of smelting in order to recover metals from WEEE requires advanced pollution control systems in order to control the escape

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[9] The Swiss Federal Institute of Technology maintains *econinvent2.0*, a database of many life-cycle analyses (LCAs), including electronic waste. However, the prohibitive cost of the data (€1800) makes their inclusion in this study beyond the author's resources.

of materials such as cadmium, lead, halogens, etc. However, the smelting industry in Canada has had difficulties in this area even with recent efforts to combat this deficiency (Canadian Institute for Environmental Law & Policy, 2005). For example, the two largest polluters in Canada are Inco, MB and Hudson Bay Mining & Smelting, MB (Pollution Watch, 2005). Adoption of BAT should be a condition of the mandate of rigorous emission standards, rigorously employed and monitored. This would entail broadening the scope of participation in policy promulgation amongst the various concerned parties.

MAIN FINDINGS

REVENUE ANALYSIS

Projected revenues from the smelting of PWBs far exceed those of merely processing and trading electronic waste. The net revenues (EBIT) consistently exceeded those of the OES scheme by an order of four to six times for each year of the first phase of the program. Thus, for the baseline year, a non-BAT scheme would expect revenues of $9.4M, while a BAT program would expect between $45.7M and $63.3M. The revenues are derived from the expectation of 100% collection rates and systemic losses only occurring at the smelting phase, the latter because of the OES demand that no PWBs be landfilled. However, data deficiencies exist with regard to Phase 1 category content. These deficiencies point to a need for standards of manufacture and studies into systemic throughput.

Sensitivity Analysis

A sensitivity analysis revealed that most of the inherent volatility in the BAT processing of WEEE is in lower priced metals, with the precious metals group exhibiting relative stability. However, in spite of market fluctuations, a scheme which promotes investment in BAT is, even under historic low market prices for metals, likely to exceed that of a scheme without BAT. Nevertheless, metal prices for 18 September, 2008 used to derive revenues for the baseline year indicate that expected revenues are operating under market conditions between the 44th (Q_{44}) and the 48th (Q_{48}) percentile. Thus, the implication is that the figures were derived under moderate market robustness. However, substituting BAT solutions which compromise the total amount of recoverable metals is a weak proposition. Companies such as Rouyn-Noranda (Xstrata) which propose merely extracting precious metals (gold, silver, and palladium) and copper can expect that their maximum revenues under the market conditions of 18 September, 2008 would be expect to exceed that of BAT by 45.9% to 65.6%. Future predictions of resource scarcity could only increase this margin.

Cost-Effectiveness Analysis

A cost-effectiveness analysis of the investment in BAT revealed that investing in BAT yields a net present value which would outstretch a scheme which does not invest in BAT ($57.8M), in spite of incurring annual payments of $34.8M for the cost of infrastructure over seventy years. The breakeven analysis showed that a project horizon of at least 52 years or 86.1% collection rates is necessary for there to be no difference between the BAT scheme and the without BAT scheme. Investment in BAT does not necessitate alteration of the discount rate (10%) as set by the Canadian Treasury Board. A sensitivity analysis conducted on the different schemes using data derived from the cost-effectiveness analysis revealed a preference for BAT, based upon revenues against NPV.

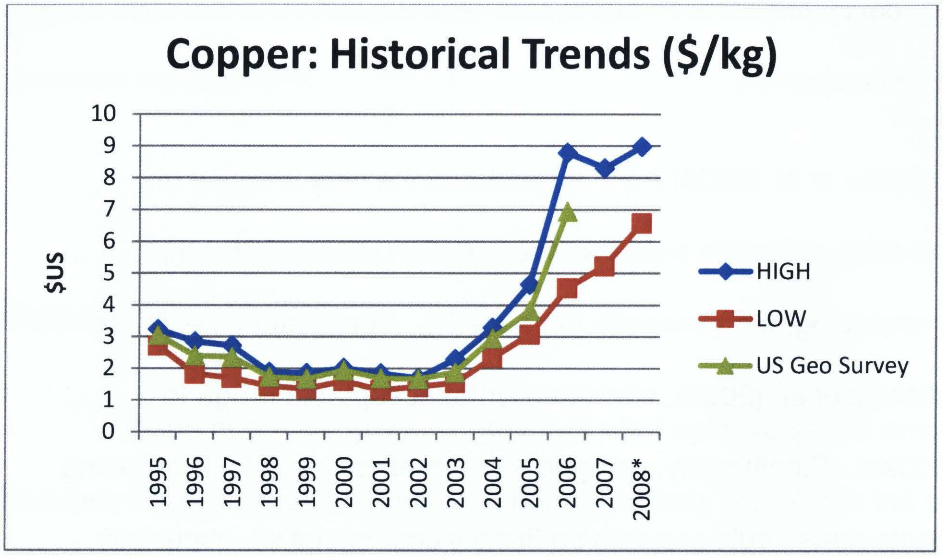
OUTLOOK

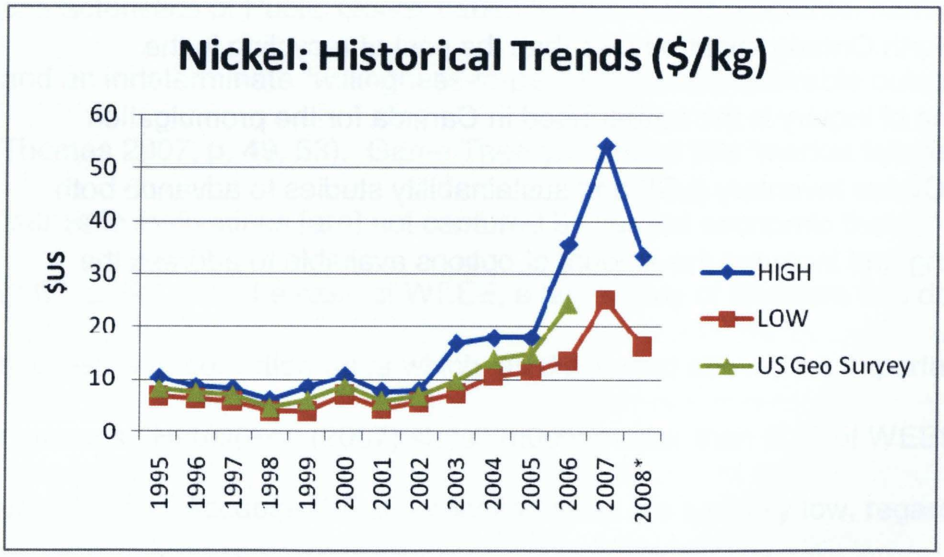
Outside of private property, much of what constitutes the environment is "public." Because Public Goods are owned in common, "any decision in the public sphere encounters great difficulties with the incentives of individuals and public agents to do what is socially desirable" (Kurz, 1994, p. 1189). The non-rival and non-excludable characteristics of Public Goods cause two particular problems, namely "free-ridership" and an indeterminate "willingness-to-pay" for socially desirable outcomes (Callan & Thomas 2007, p. 49, 53). Game Theory ascribes this "market failure" to the fact that "altruistic motivations [are] not captured by current economic theory" (Nixon & Saphores 2007, p. 549). In the case of WEEE, a large body of literature has documented a lack of success with collection rates which, as discussed above, are important for BAT revenues. Hagelüken (2007) states much greater than 50% of WEEE remains uncollected. Because WEEE collection rates are typically low, regardless of country or geography, some have proposed an advanced fee to be paid at the point of purchase. However, Nixon & Saphores (2007) found Californian consumers were not willing to pay adequately for the environmentally responsible recycling of their WEEE. Consequently, as a policy objective, it may be reasonable to pursue a deposit system as these have seen respectable results in some markets. Experimental economics research, of which Game Theory is a subset, could yield some insights into what deposit scheme might be deemed worthy of further investigation.

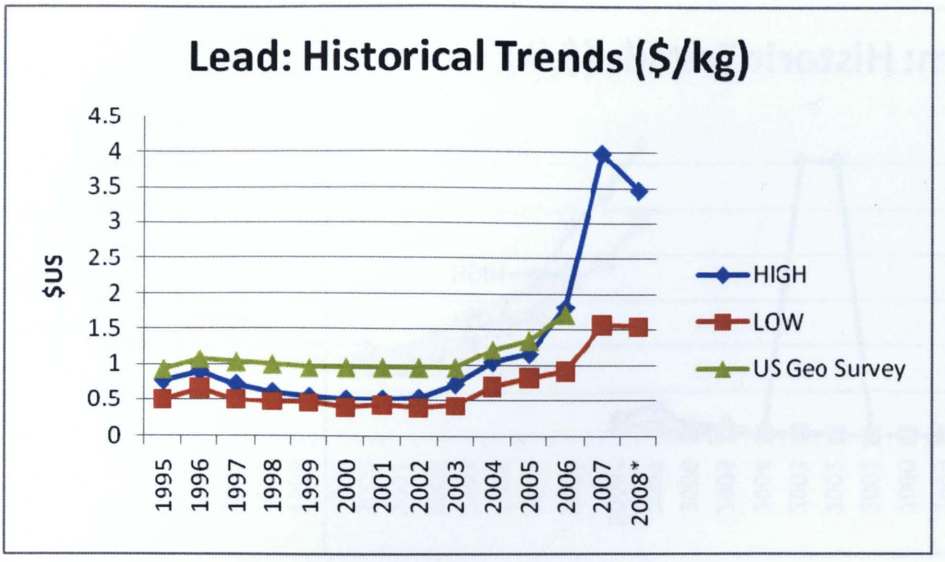
Some such as Hirschier et al. (2005) have argued that the very premise of recycling electronic waste does not make sense as the pollution incurred (through transportation, energy, processing, etc.) exceeds the benefits. Similar sentiments are expressed by Barba-Gutiérrez et al. (2008), who specify the acceptable range to a recycling depot at 200-300km. Significantly, bringing a comprehensive WEEE recycling program to Ontario's remote parts could prove to be fiscally cost-intensive, especially since the Ontario strategy proposes to trade its WEEE on the WEEE market in southern Ontario. For example, the cost created by the environmental damage of landfill in remote areas such as North Ontario might be less than the cost of recycling in the South. Implicit in this line of inquiry is the further need in Canada for the promulgation of and access to a Life Cycles Inventory (LCI) and sustainability studies to advance both the level of understanding and increase the amount of options available to address the current WEEE dilemma.

APPENDIX—HISTORICAL TRENDS IN METAL PRICES

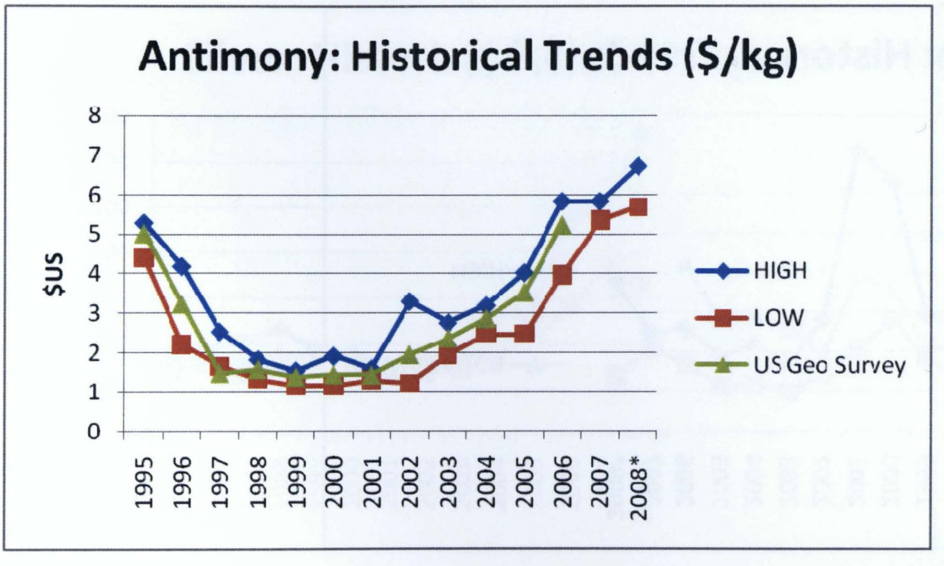
All data used in this section was derived from *Platt's Metal Weekly* and the U.S. Geological Survey.



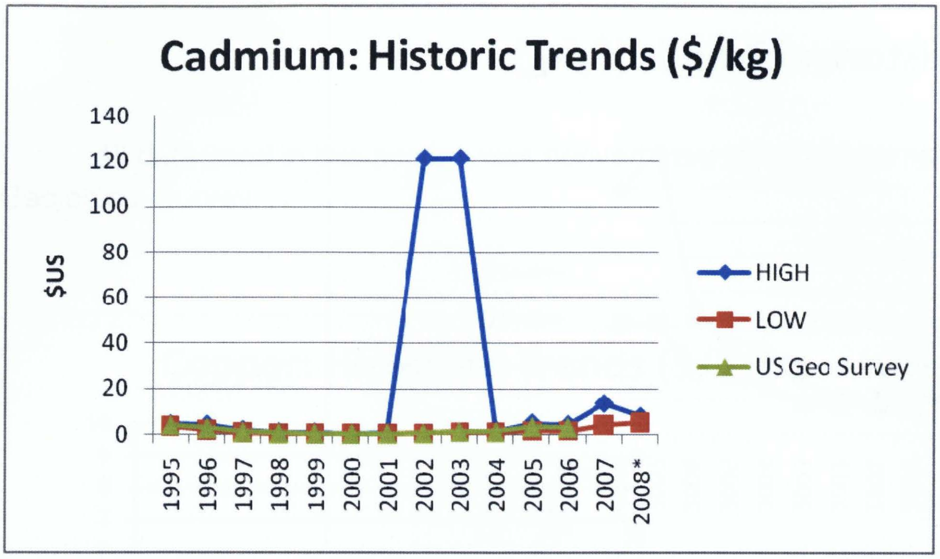




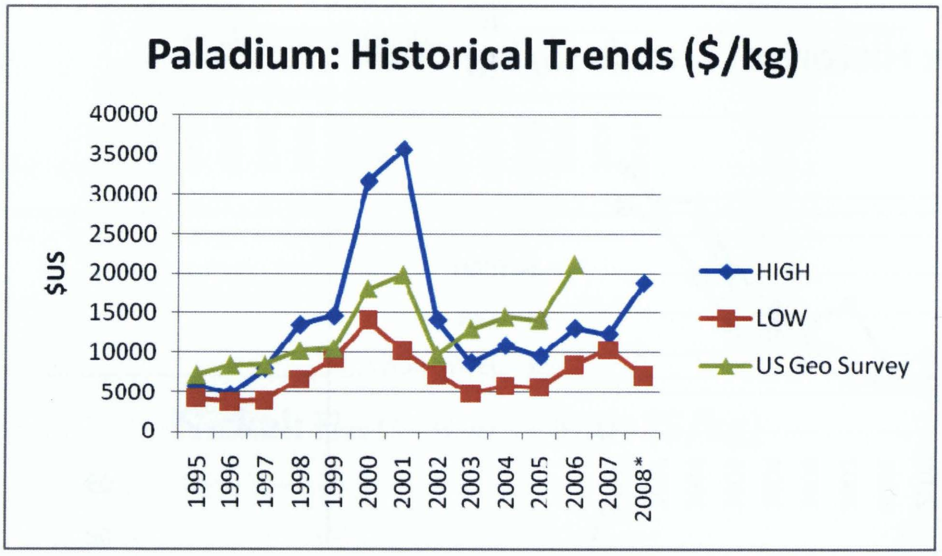
Lead: Historical Trends ($/kg)
$US
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey



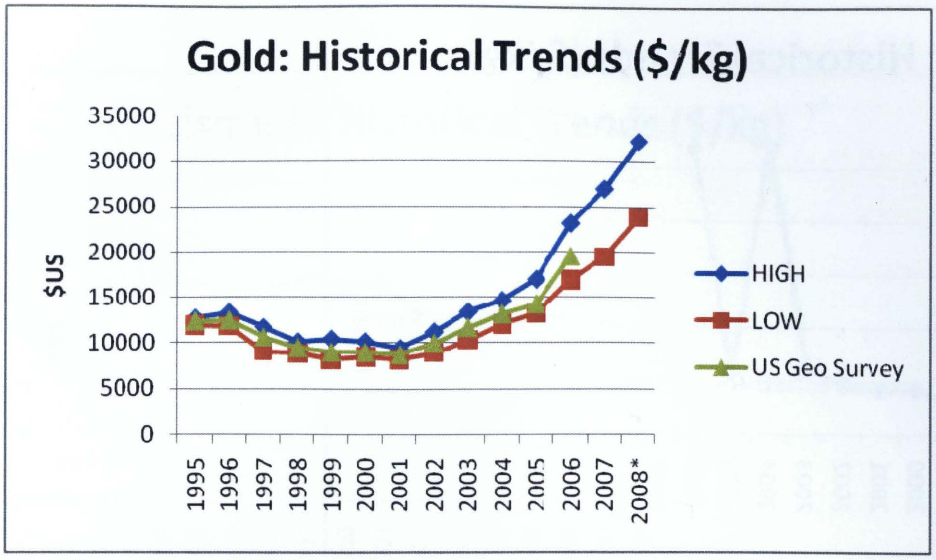
Antimony: Historical Trends ($/kg)
$US
8
7
6
5
4
3
2
1
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey

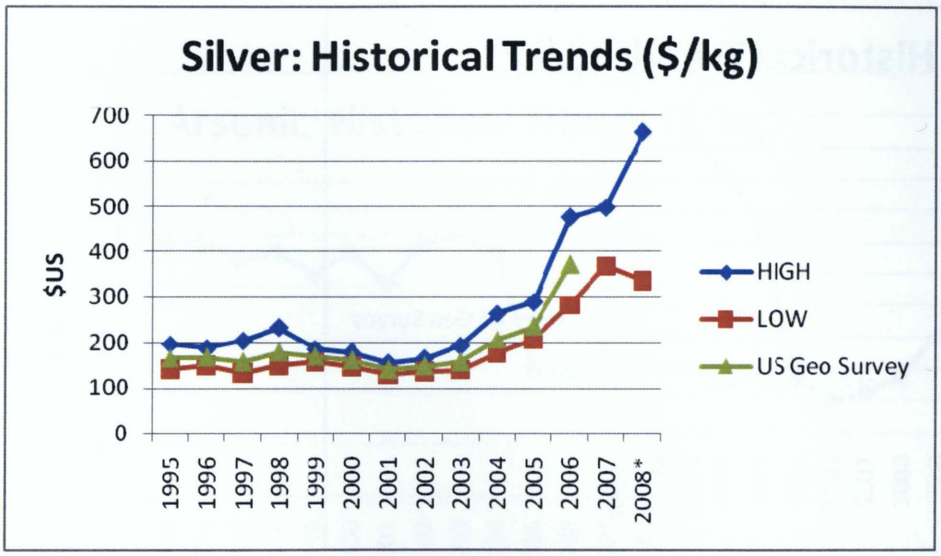


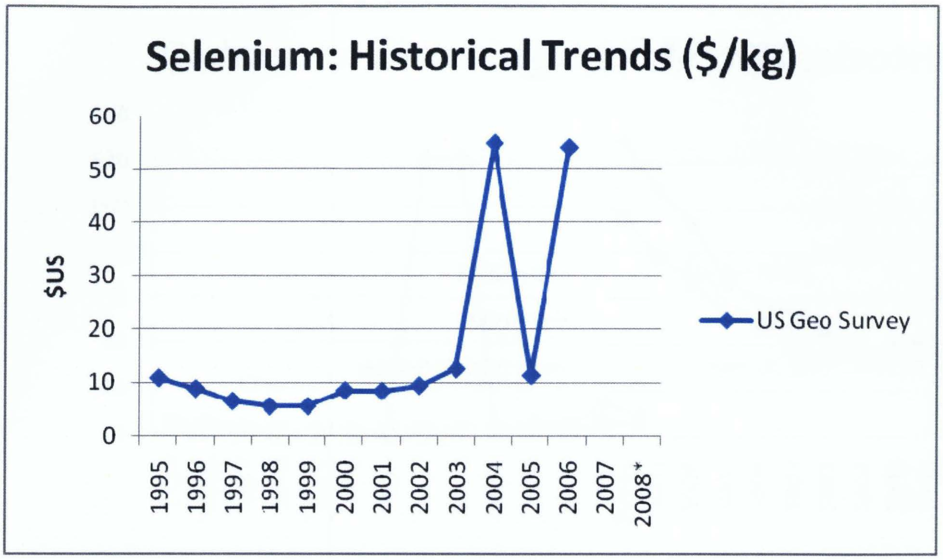
Cadmium: Historic Trends ($/kg)
140
120
100
80
60
40
20
0
$US
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey

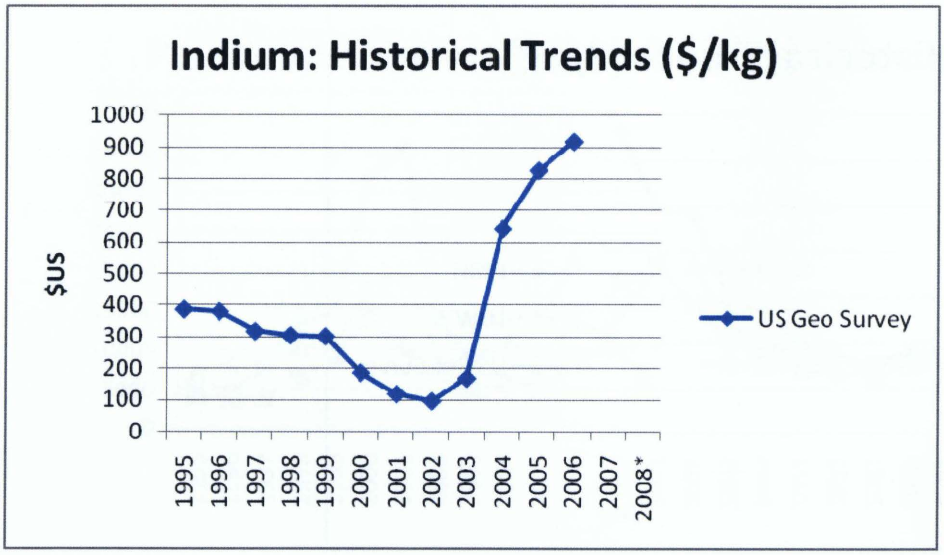


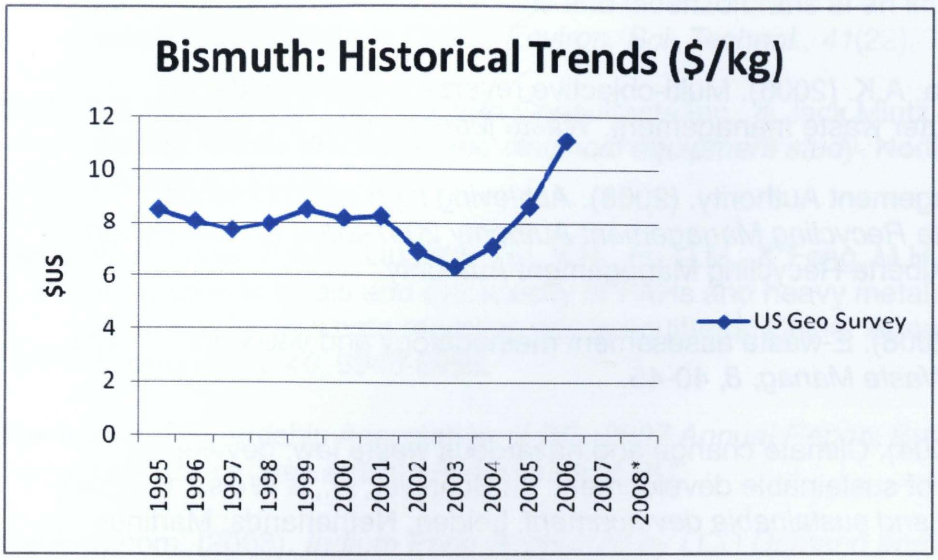
Paladium: Historical Trends ($/kg)
40000
35000
30000
25000
20000
15000
10000
5000
0
$US
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey


Gold: Historical Trends ($/kg)
$US
35000
30000
25000
20000
15000
10000
5000
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey

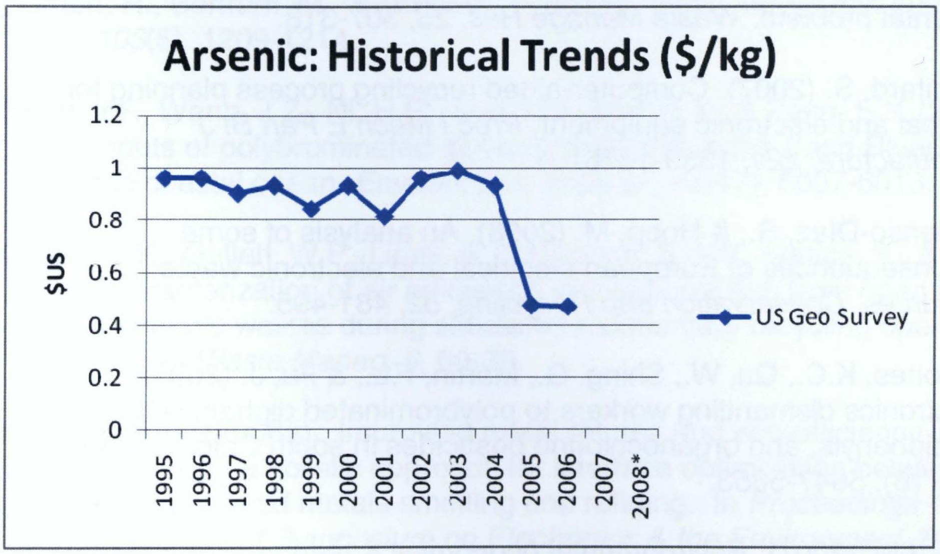

Silver: Historical Trends ($/kg)
$US
700
600
500
400
300
200
100
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
HIGH
LOW
US Geo Survey


Selenium: Historical Trends ($/kg)
60
50
40
30
20
10
0
$US
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
US Geo Survey


Indium: Historical Trends ($/kg)
1000
900
800
700
600
500
400
300
200
100
0
$US
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
US Geo Survey



Bismuth: Historical Trends ($/kg)
$US
12
10
8
6
4
2
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
US Geo Survey



Arsenic: Historical Trends ($/kg)
$US
1.2
1
0.8
0.6
0.4
0.2
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008*
US Geo Survey

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List of Abbreviations

BAT	Best Available Technologies
BAP	Benzo(a)Pyrene
BFR	Brominated Flame Retardants
BMP	Best Methods Practice
EBIT	Earnings Before Interest and Taxes
EOL	End-of-Life
EPA	The United States Environmental Protection Agency
EPSC	Electronic Product Stewardship Canada
EU	European Union
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCD	Liquid Crystal Display (monitor)
MFA	Material Flow Analysis
NPV	Net Present Value
OECD	Organization for European Cooperation and Development

OES	Ontario Electronic Stewardship
PAH	Polycyclical Aromatic Hydrocarbon
PBDD/F	Polybrominated dibenzo-*p*-dioxin or dibenzofuran
PBDE	Polybrominated Diphenyl Ethers
PC	Personal Computer
PCB	Polychlorinated biphenyl
PCDD/F	Polychlorinated dibenzo-*p*-dioxin or dibenzofuran
PWB	Printed Circuit Board
PWF	Present Worth Factor
RDF	Refuse Derived Fuels
SA	Sensitivity Analysis
UPMR	Umicore Precious Metals Refining (Belgium)
VER	Verified Emission Reduction rate
WDO	Waste Diversion Ontario
WHO	World Health Organization
WEEE	Waste Electronic and Electrical Equipment