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LUMES Masters Thesis

# Connected Consequences: Resource Depletion and North-South Inequities of the Global Material Intensity of the Internet and Mobile Telephony

*Author:*
Hitesh Soneji
Lund University Masters in Environmental Studies and Sustainability Science
hitesh@sonejifamily.org

*Supervisor:*
Dr. Mats Svensson
Lund University Centre for Sustainability Science
LUND, Sweden
mats.svensson@lucsus.lu.se

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**Abstract**

The digital century is well underway, and with it come claims that ICT will enable the promise of sustainability. While ICT does indeed offer potential to improve aspects of life for all peoples, it carries with it serious concerns over toxic exposure, increasing energy consumption, rare minerals depletion, a digital divide, and asymmetrical distribution of benefits.

Using system analysis, an exploration of the sustainability perspective on ICT is presented. Building upon these findings, the study then focuses on the implications of the resource intensity in two specific sectors: mobile telephony and the Internet. Twenty-five rare and toxic minerals are modeled at a global scale. Sustainability damages are valued in Euros utilizing the Environmental Priority Strategies in product design, a life cycle impact assessment tool founded upon the core tenets of sustainability.

The model results show that in 2008, the global resource depletion cost of ICT was 1.9 trillion Euros, while emissions in the informal recycling sector caused 1.5 billion Euros worth of damage. Distributing these costs across the impacted populations provides a per-capita cost of 300 Euros globally and 50 Euros in the informal recycling sector, an extra burden that those engaged in informal recycling have borne. Scenarios show that increased recycling has limited ability to improve sustainability. Meanwhile consumer behavior has a greater potential for improvement via reducing device turnover. In all scenarios, strong sustainability remains elusive for complex technologies, like ICT, that are so fundamentally based upon rare minerals.

# Contents

# List of Tables



# List of Figures

## List of Acronyms

| | |
|---|---|
| BAN | Basel Action Network |
| BAU | Business As Usual |
| CBA | Cost Benefit Analysis |
| CPU | Central Processing Unit (Internal part of a computer) |
| CRT | Cathode Ray Tube |
| EPA | Environmental Protection Agency |
| EPS | Environmental Priority Strategies in product design |
| EOL | End of Life |
| ICT | Information and Communication Technologies |
| ISP | Internet Service Provider |
| ITU | International Telecommunications Union |
| GDP | Gross Domestic Product |
| GeSI | Global eSustainability Initiative |
| GHG | Green House Gases |
| LCA | Life Cycle Assessment |
| LCIA | Life Cycle Impact Assessment |
| MDG | Millennium Development Goals |
| MEFA | Material and Energy Flow Analysis |
| MSWI | Municipal Solid Waste Incineration |
| PC | Personal Computer |
| PGM | Platinum Group Metal |
| PWB | Printed Wiring Board (also known as Printed Circuit Boards) |
| PWBA | Printed Wiring Board Assembly |
| RoHS | Restriction on Hazardous Substances |
| SES | Social Ecological System |
| SVTC | Silicon Valley Toxics Coalition |
| UN | United Nations |
| USGS | United States Geological Survey |
| WEEE | Waste Electric and Electronic Equipment |
| WTP | Willingness To Pay |

## Acknowledgements

Well, first off I must thank the little guy in my life, Kirin, for so many absolutely wonderful smiles and cute yaps while I was a bit stressed out. And, of course, Melissa, my wife, for so much love, caring, and support. Mats Svensson (my supervisor) for his never ending patience and time. My thesis group for their valuable feedback, and several other *peeps* that were excellent sounding boards for ideas and gripes. You all know who you are.

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# 1 Introduction: ICT Meets Sustainability

Information and communication technologies (ICT) have experienced rapid growth and adoption across the world. Mobile phones exemplify the phenomena, having proliferated exponentially in recent years. In 2008, the 4 billionth mobile subscriber came on-line (ITU 2009). This impressive figure not only suggests that ICT has much to offer, but it also highlights the magnitude and breadth of ICT related activity.

Magnitude is precisely what this study is about. With digital technologies intensifying globally, its energy and material demands raise serious questions of limits and sustainability. The market research firm Gartner (2007) estimated that ICT accounts for 2% of global C02 emissions. This may in fact be a low estimate as accounting for energy intense ICT manufacture has been challenging (Williams 2004). In a stroke of clairvoyance, Gartner (2007) actually wrote that "the growth in power requirements and levels of waste that [ICT] produces renders the current state unsustainable." But sustainability suggests even more concerns, such as growing digital inequities within society and rare minerals depletion.

Could the promise of ubiquitous computing and the strive to put a laptop in the hands of every child actually jeopardize two core values of sustainability: intergenerational equity and intra-generational justice (UNCED 1992)? This is the core question which defines this study. Employing a model and synthesizing mineral content data with user trends, I have constructed an estimate for the rare and hazardous minerals intensity of ICT. This mineral flow is then used to develop a sustainability cost to society caused by resource depletion and hazardous emissions in the informal recycling sectors.

The following objectives have guided my work.

1. A system analysis of the sustainability of ICT
2. Compute an economic value for the sustainability cost of ICT's mineral resource demands and hazardous emissions, using the Environmental Priority Strategies in product design (EPS)[1] life cycle impact assessment tool.
3. Connect the individual to the network. Construct a ratio between the sustainability cost of the personal computer and mobile phone to the network infrastructure required to support the individual communication activities.
4. Present an estimate for the magnitude of transboundary (North to South) waste flows associated with ICT end-of-life treatment and the localized sustainability impact of the informal recycling activities.

Ever since the Club of Rome's *Limits to Growth* publication (Meadows 1972), the question of physical limits has always been contested with the hope of technology. Could it be that in ICT we see the hope of technology exacerbating the question of physical limits. Certain technologies have, without question, enabled more efficient use of resources. But in ICT we see a technology so fundamentally different, so invasive in the social ecological system, that its relationship to sustainability is not well understood.

[1] The EPS tool and more details about how it was applied in this study are reviewed in Section 4.3

## 2 Background: Univac to iPhone - From Obscurity to Ubiquity in Fifty Years.

The first electric computing machines began being used for real applications in the 1950's. The 120 kilowatt Univac computer assisted the United States government in its 1950 census. But, the real birth of ubiquitous computing came later, in 1981, when IBM introduced the first personal computer (PC). With the *personal* computer came the vision that every desktop should have a computer. Only two decades later, it seemed that every lap should have a laptop. In less than 25 years, information and communications technologies (ICT) have proliferated into almost every aspect of society. (Kuehr & Williams 2003, Johnson 2006)

Figure 1: The Univac computer in a US Navy electronics supply office. Photo Credit: US Federal Government.

One driver of the adoption of ICT is its rapidly advancing technology and compaction. This progression is commonly referred to as Moore's law, the prediction that the density of transistors will double every 18 months[2]. Greater transistor density enables ICT devices to be made smaller and sold cheaper, even as functionality increases. While Moore's law has held true over the past 40 years, many observers suggest that it has been more a self-fulfilling prophecy than a natural trend of innovation. With Moore's law as a guiding principle, industry has invested heavily to keep up with the advancing target, garnering intense profits in the process. This high rate of return on investment in ICT continues to drive the innovation required to maintain Moore's law. (Grier 2006, Mollick 2006, Edwards 2008)

The progression of technology consistent with Moore's law has thus enabled reduced cost, miniaturization, and increased functionality of ICT. Technological innovation and the opportunities of virtual information exchange are core characteristics of ICT that have driven its rapid and widespread adoption.

Information and Communication Technologies are proliferating fast, perhaps faster than any other major technological advance in human history. Currently, about 1 billion personal computers and over 4 billion mobile phone subscribers are interconnected worldwide. The number of in-use personal computers is growing linearly while mobile phone use is growing exponentially, enabled primarily by huge growth in Asian markets. Driven by rampant growth and short device lifespans, ICT devices are being manufactured at a breakneck pace. Gartner estimates worldwide ICT spending in 2008 to be equal to 3.4 trillion U.S. dollars (Gartner 2008). This is a huge economic sector with proportionally large mineral and waste streams, both sustainability concerns. Furthermore, ICT fundamentally alters so many human activities, that its impact on the social economic system is extremely complicated and challenging to assess.

[2]Gordon Moore, one of the founders of Intel, often contests that the assertion is not his own, or that it was more an assessment of the transistor innovation at the time, and not a prediction of the future march.

# 3 Problem Formulation

## 3.1 The Lens of Sustainability Applied to ICT

Information and Communications Technologies derive their value from the ability to enable the virtual exchange of ideas, knowledge, and information. Neither physical proximity nor physical exchange is required. Nevertheless, the exchange of thoughts occurs almost instantly, and with relative ease. Figure 2 is a box-flow diagram that presents a high level perspective on Information and Communications Technologies (ICT) as they interact with the social ecological system. The diagram also offers insight into how various disciplines have approached their study of ICT.

Virtual exchange forms the gravitational center of the high level perspective drawn in Figure 2. Virtual exchange enables numerous social and economic benefits via the use of ICT devices (left). These devices require inputs of energy and materials, and become toxic waste at end-of-life. The physical pressures induced by ICT devices exert negative externalities on social and environmental systems (right). Meanwhile, the deeper ICT penetrates into society, the greater the socio-economic risks become (bottom). Each of these ICT induced factors is explored further in the next section.

Across the top of Figure 2, I have delineated the realms of several perspectives on ICT. For example, industry and ICT advocates are focused on development of technology itself and the immediate benefits that arise from its use. Green ICT, driven by industry and market research firms, has focused on energy

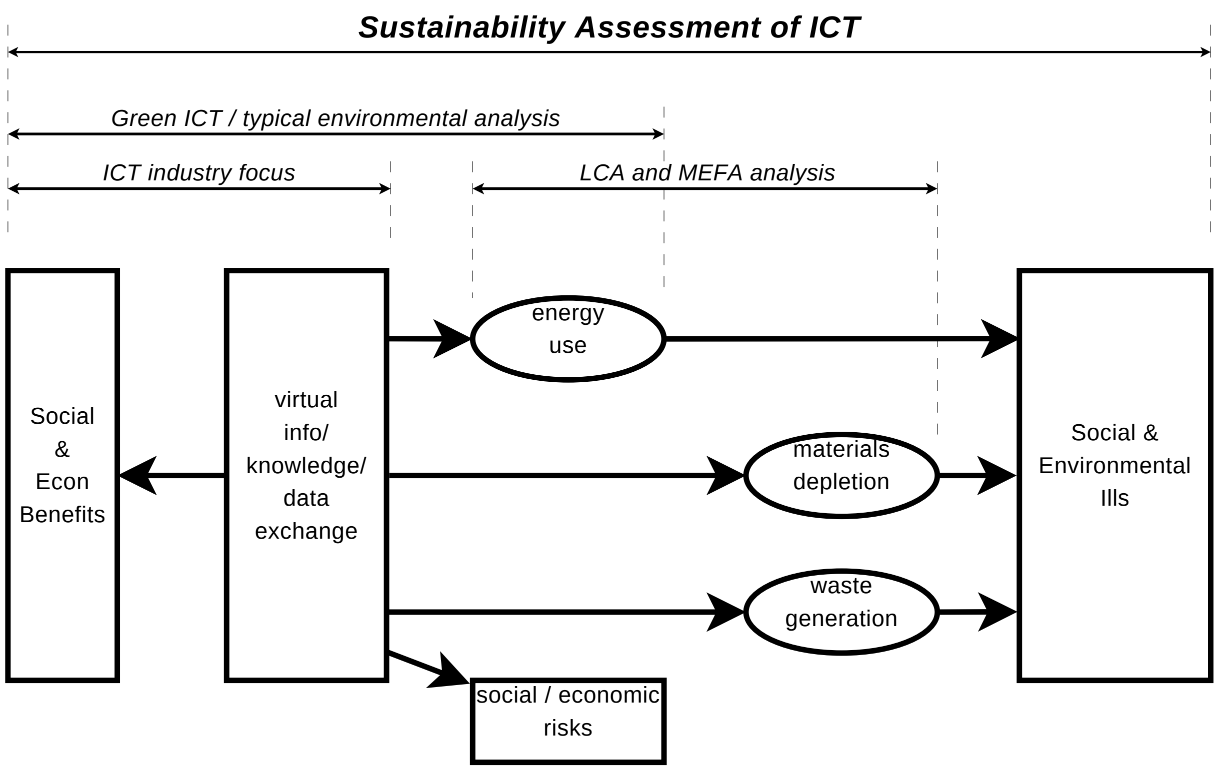


Figure 2: Box flow diagram conceptualizing the sustainability perspective on ICT. Several common perspectives on ICT are delineated, from the focus found in the technology industry to concern over energy use in Green ICT. The less explored sustainability perspective encompasses the broadest scope.

and GHG concerns. Many academic studies have performed Life Cycle Analysis (LCA) or traditional Material and Energy Flow Analysis (MEFA). Meanwhile, the sustainability perspective demands connecting the entire diagram for the whole of society, while paying particular attention to the intra-society inequities.

## 3.2 Opportunities and Threats

In further developing the sustainability perspective, I have explored ICT's opportunities and threats, benefits and disadvantages. Figure 3 presents these. The formulation of social threats and opportunities are supported by the Wuppertal Institute's assessment of ICT vis-a-vis the Millennium Development Goals (Kuhndt *et al.* 2006). Meanwhile Hilty *et al.* (2006b) explores relevance of ICT to environmental sustainability. Matsumoto *et al.* (2005) analyzes ICT's contribution to climate change. Fuchs (2008) questions many of the common perceptions of ICT's role in creating a sustainable society. The figure has been populated with insights garnered from these papers as well as my own formulations and understandings of technology and drivers that have encouraged ICT adoption.

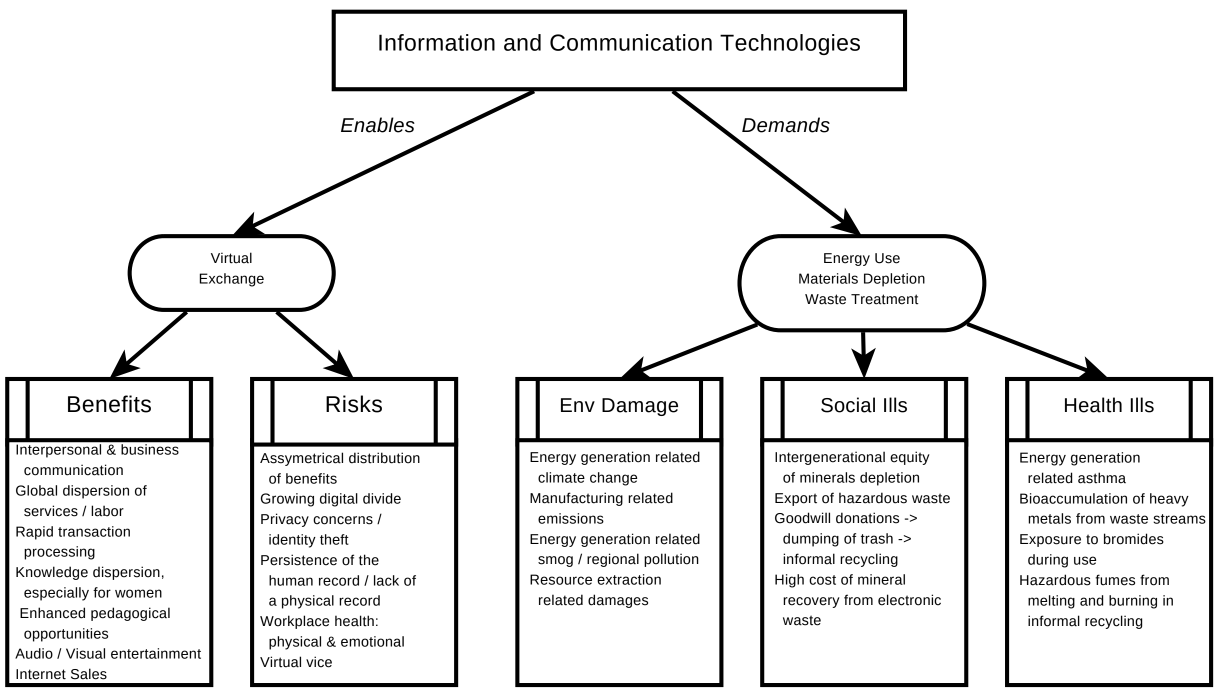


Figure 3: Some of the observed and potential benefits, risks, and damages associated with widespread use of ICT and digital technologies

This listing of opportunities and threats is by no means an exhaustive understanding. Instead, it exemplifies the challenges and opportunities ICT presents in creating a sustainable society. Figure 3 serves to lay the foundation from which to refine the scope and extent of this study. As such, it assisted in the process of working from an effectively unbounded question of ICT's relationship to sustainability to the more focused analysis of resource depletion and hazardous emissions found in this study.

## 3.3 Drawing System Causalities

Causal loop diagrams (CLD) assist in better understanding the causalities within and between systems. Figure 4 provides a CLD which connects the ICT system with the social, business, and ecological systems. The two most influential drivers of the ICT system are guided by business interests (bold arrows). The desire for a return on investment encourages the ICT industry to keep pace with Moore's law (loop 3). It also motivates the entire business sector to use ICT as a tool to grow profits and increase business activities. Reinforcing loops 1 and 2 highlight the opportunities ICT affords the general business sector.

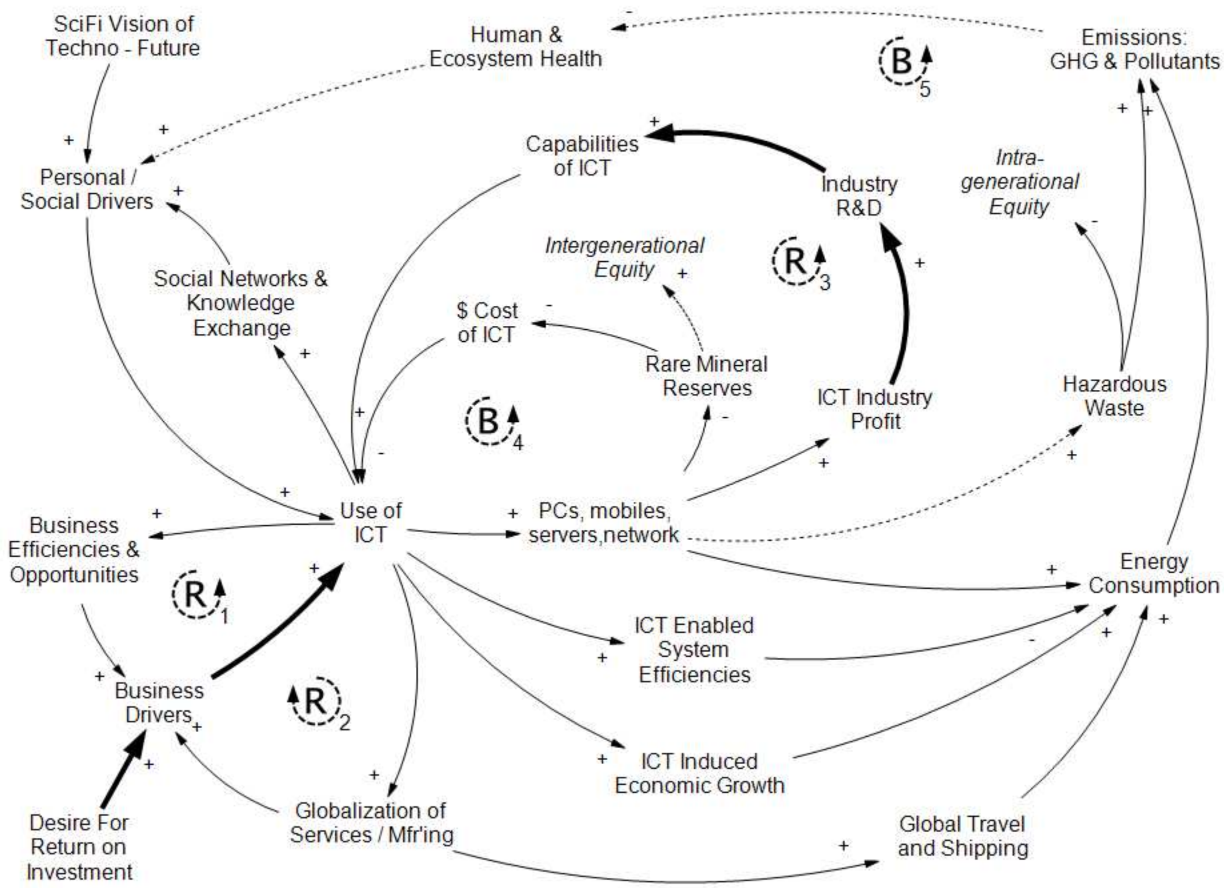


Figure 4: Causal loop diagram of ICT within the social and ecological systems.

Loop 4 balances the system, limiting ICT growth by increasing the cost of rare minerals as reserves become smaller. The dissipation of rare minerals also exacerbates intergenerational inequity. Balancing loop 5 integrates the ecological system, showing the variety of pathways that ICT influences energy consumption and hazardous waste creation. Increased use of ICT results in emissions of green house gasses and pollutants, endangering both human and ecosystem health. Informal recycling activities are represented by a linkage between hazardous wastes and intra-generational equity.

Increased use of ICT also induces macro-level economic growth, which is closely tied to the intensity of energy use and general consumption patterns. The CLD suggests that the hope of dematerialization[3] and green technology is countered by system dynamics affects reinforcing ICT's proliferation, continuing to impact human and ecosystem health. Additionally, the CLD shows that in the present economic systems, intergenerational and even intra-generational interests do not feedback in a clear manner

## 3.4 Refining the Problem: Rare and Hazardous Minerals

The previous sections have shown that ICT's interactions with the social ecological system are intricate, and offer a multitude of areas for study. For example, how well has the social potential of ICT materialized? Greater democratic participation, gender equalization, and providing voice to the disenfranchised were some of the promises. But the modern Internet has become dominated by large media outlets and business interests, obscuring and marginalizing the more commendable goals of sustainability. (Fuchs 2008, Kuhndt *et al.* 2006)

One area of ICT which appears to have not received due attention is the mineral intensity of global ICT consumption. Rare minerals depletion raises concerns of limits and intergenerational equity (Gordon *et al.* 2006, Meadows 1972). Meanwhile, transboundary movement of electronic waste and hazardous minerals recovery in the informal recycling sector suggest disproportionate health and environmental damages intra-generation. These sustainability costs of ICT form a new set of externalities that have yet to be quantified. By definition, these externalities are absent from the accounting tables of our classical economic system. My goal in this study is to begin the process of quantifying the sustainability costs of ICT activities, and connect the costs to a broader discussion of the sustainability of ICT.

[3]Dematerialization is an ambiguous concept which is given more attention in the discussion section. For now, it may be taken to refer to the idea that a society maintains its level of well-being while at the same time reducing the material throughput induced by its activities.

# 4 Analytical Framework

## 4.1 System Analysis and Procedural Rationality

A system dynamics approach is used to grapple with the qualitative relationships and influences between ICT, economics, social, and environmental systems. The complexity of the ICT question make it a prototypical *mess*, a bit of a *wicked* problem (Pidd 2004). This study is based on the approach of procedural rationality suggested by Simon (1954) and as presented by Pidd (2004). Such an approach permits exploration of alternatives within a landscape of incomplete information, human limitations of cognition (with respect to bounded rationality), and a plethora of alternatives whose comparison presents a bit of a *mess* in themselves. Procedural rationality as applied in this context therefore acknowledges the complexity and blurriness of ICT's interactions with the social and ecological systems.

## 4.2 Scope

It has been argued that ICTs have come to behave like general-purpose technologies (Plepys 2002, Kuehr & Williams 2003, Hetemäki & Nilsson 2005) . This implies that its impact is as broad as human harnessing of electricity itself. This parallel with electricity or the internal combustion engine [4] can not be overlooked, as it complicates analysis of ICT. Economic sectors have become blurred: what used to be a newspaper or music on a vinyl record, are now under the purview of ICT. In the past, these sectors were entirely distinct and compartmented, but ICT has blended and obscured the distinction. Such blurring has complicated the investigation of ICT at a system level, and to a certain extent has forced subjective and qualitative assessments. Researchers have observed the direct, secondary, and macro-level effects of ICT; its structural and transformational impacts are numerous. For examples, see Berkhout & Hertin (2004), Plepys (2002), Fuchs (2008), Hilty *et al.* (2006b), and Matsumoto *et al.* (2005).

In order to maintain a reasonable level of tractability, I have chosen to deal with only direct effects of ICT. While the $n^{th}$ order and structural affects are acknowledged, they are beyond the scope of my study, and not dealt with in-depth. While this has greatly narrowed the scope, I maintain a broad perspective in other regards: I account for the global intensity of ICT activities and the distribution of these activities to regions. In my analysis of ICT's mineral intensity, I maintain a concern for future generations as well as present.

Rare and hazardous minerals use raise two sustainability concerns: depletion and toxicity. As such, I have selected 25 minerals, based primarily on their rarity in the Earth's crust and presence in ICT devices. Mineral toxicity and the availability of data further refined the list. This selection is not exhaustive, and technology is constantly evolving to include more minerals and compounds.

I have limited the mineral assessment of ICT to the Internet and mobile telephony, as these two realms of ICT are the most prevalent and rapidly growing sectors. Within the Internet, the focus is on personal computers and servers, while the network of the Internet itself has been excluded. Within mobile telephony, the focus is on mobile phones and the network electronics.

[4] In other words, ICT is like a utility, or a utilitarian like service

## 4.3 Methods and Materials

### 4.3.1 Overview

Material flow analysis[5] is traditionally done via a top down approach, using national or industry monetary flows as an indicator of the material and energy intensity of an industrial sector or geographic region(Suh 2005). Instead, I elected a bottom-up approach, in which the material flow was extrapolated from the micro-level to the macro-level. In other words, I began at the bottom (devices, components), and worked upwards to the top (global Internet). I believe this method captures more precisely the details of each rare and hazardous mineral involved. Aggregate industry and economic data would have failed to provide such level of detail. Furthermore, ICT devices are a product of an extremely globalized manufacturing operation. I am not confident that regional or industry-specific economic indicators would correlate well with the intensity of mineral flows, nor provide the sort of detail necessary for the subsequent sustainability assessment.

By synthesizing a myriad of disparate secondary sources of data, I constructed a high level picture of the sustainability impacts of global minerals intensity of ICT. In extracting data from secondary sources, I was cautious and conservative in data selection. When presented with a range of possible data, I used the low values that would reflect more favorably upon ICT.

In this section I introduce the tools and methods which I used in creating the material flow model. The software is discussed first, followed by a block level view of the model itself, and the methods for putting an economic price on the sustainability damages. The section concludes with the processes used to develop the mineral content and intensity of ICT as well as the end-of-life disposition.

### 4.3.2 Software tools

Two software tools were used to model the material flows: STELLA[6] (a stock and flow modeling tool) and spreadsheet software[7]. I began by compiling and contrasting data within spreadsheets. The spreadsheets were ideal for exploring trends in market data as well as in synthesizing mineral content from multiple sources. STELLA was chosen for its ability to provide a greater level of transparency into the construction and design of the model. It was ideal for modeling the 'in-use' phase of devices with *conveyors*, a built-in feature. Additionally, STELLA enabled the efficient running of scenarios. STELLA also offered the ability to construct a more dynamic system, something the model is well suited to extend into for future studies.

The model and spreadsheets were dynamically linked and the spreadsheets integrated internal dynamic linkages between worksheets, thus allowing for ease of running scenarios as well as changing assumptions regarding data, as better information became available.

### 4.3.3 Constructing the ICT, minerals, and sustainability model

Figure 5 visualizes the model and its connection to the sustainability perspective presented earlier. The model consists of five stages of information or material flow, predominately working linearly from the left to the right of the figure. Each element of the sustainability perspective is represented in the model, with the exception of energy and risks, which are outside the scope of the model. With the sustainability

[5] MEFA is a term commonly used for Material and Energy Flow Analysis

[6] STELLA is is a tool developed by isee systems. Version 9.0.3 was used. `http://www.iseesystems.com/`

[7] OpenOffice 3.1 was used. Files were always stored in Microsoft Excel format (.xls) to facilitate interaction with STELLA.

costs calculated in economic terms, it is then possible to weigh those costs against the use phase benefits that are already registered by the economy. As the CLD highlighted in Figure 4, increasing sustainability costs will eventually lead to economic and social drivers that will counter the benefits offered by ICT.

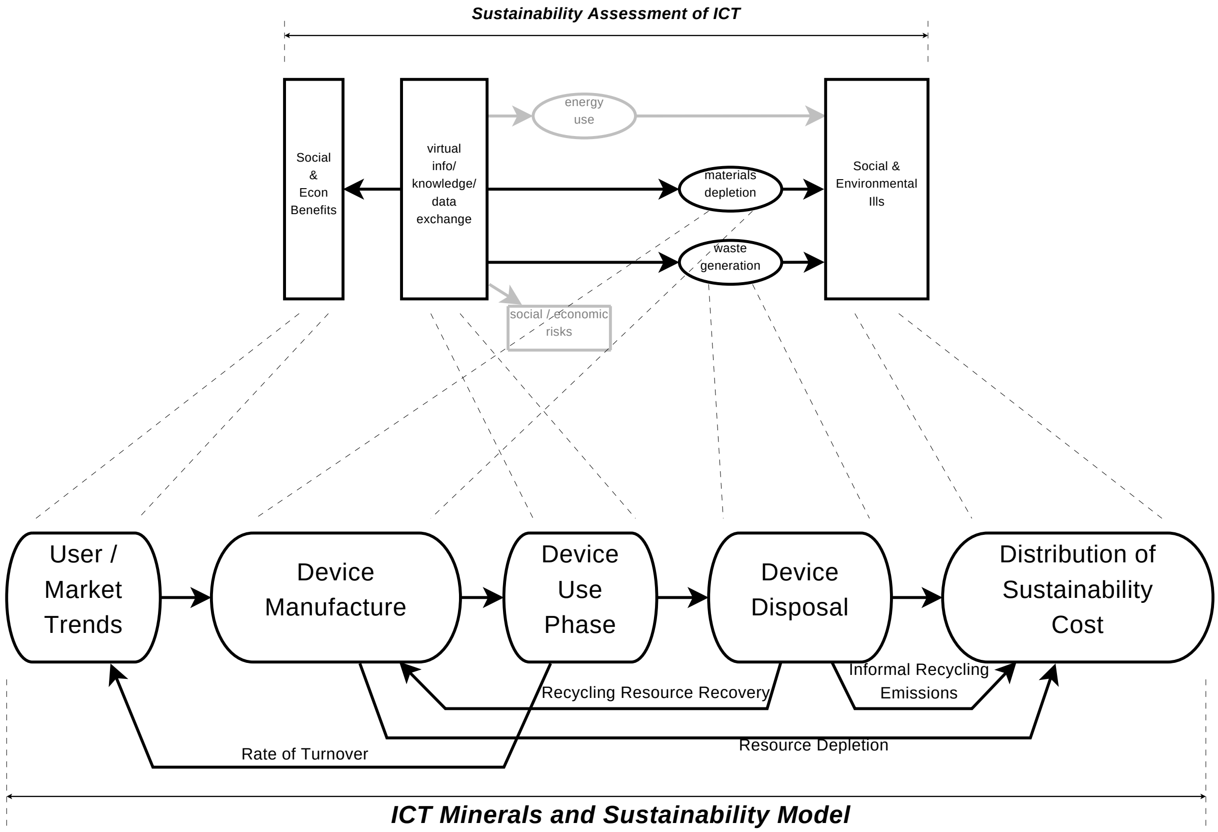


Figure 5: Visualizing the model and its relation to the sustainability perspective on ICT

Trends of ICT users is the primary driver of the model. The trend trajectories can easily be manipulated in the model in order to approximate various proliferation scenarios. This proliferation drives the manufacture of ICT devices, resulting in material depletion. The devices then enter the in-use phase in which they are considered to be meeting the demands of ICT users. The duration of the in-use phase can be manipulated based on the understanding of consumer behavior with regards to device turn-over and disposal. The in-use phase also includes a possible user storage phase where the device does not meet the ICT demand of any user, but it does delay the end-of-life.

Once ICT devices reach end-of-life, they are modeled to encounter one of three fates: 1) municipal landfill or incineration, 2) formal recycling, or 3) informal recycling. Formal recycling entails the treatment of electronics waste using safe and non-hazardous methods for the purposes of maximum mineral recovery. Informal recycling refers to the unregulated, unsafe, and hazardous mineral recovery efforts ongoing in India, China, and Africa. Each of these fates contributes to the sustainability cost in various manners. The end-of-life part of the model offers the greatest degree of uncertainty in the results as little is understood regarding the treatment of end-of-life devices or transboundary movement of electronic waste.

The final stage of the model translates resource depletion and hazardous emissions into sustainability costs. These costs are calculated based upon the Environmental Priority Strategies (EPS) in product design method, a Life Cycle Impact Assessment (LCIA) tool.

**Boundaries** The spatial bounds of assessing the intensity of ICT is global, mostly modeled aggregate at worldwide level. To approximate transboundary flows, geographic regions have been delineated. The regions have been selected roughly by continent, although the US, India, and China have been modeled independently, as their ICT activities are of unique interest in terms of volume of waste exported and rates of ICT proliferation.

I have limited the temporal scale of model simulation to 2020 in order to avoid the uncertainty associated with extrapolating trends over long time frames. Modeling from 1995 to 2020 provides both insight into the historical and near-term intensities of ICT activities. On the other hand, a much longer temporal scale guides the economic assessment of impact. Sustainability costs are determined based on an intergenerational sustainability perspective with a long term outlook on the order of thousands of years.

The methods I employed in each stage of model development are reviewed below. I present the methods employed to value sustainability cost first, as it will help to contextualize the remaining aspects of the model. Specific numerical details and assumptions are presented more thoroughly in the Analysis section and Appendix B.3

### 4.3.4 Valuing damage: Sustainability cost

A significant challenge in evaluating the costs and benefits of complex social ecological systems is quantifying the cost of externalities, and doing so with attention to the principles of sustainability. When transposed into economic currency, I refer to this quantification as the *sustainability cost*. Such transposition is open to significant uncertainty and criticism, but there are available no ideal methods for quantitative comparison.

I assess the *sustainability cost* using the Environmental Priority Strategies in product design (EPS) tool, a life cycle impact assessment tool. (Steen 1999a;b) The decision to use the EPS tool in assessing the sustainability impact was deliberate. While other ready-made LCIA tools exist[8], EPS is transparent in its use of economic currencies and a Willingness-To-Pay(WTP) principle in developing their index, the Environmental Load Unit. Furthermore, EPS is publicly accessible at no charge and offers sufficient transparency that I have been able to work backwards from sustainability damage to economic assessments.

The deliberate selection of EPS for this study is further reinforced by its reliance on the RIO declaration (UNCED 1992) as a guiding principle. For example, EPS uses no discounting for future generations. It assumes that future generations have as much right to a good environment as present generations. It also uses the same WTP values for every geography and person: recognizing that damage to life and ecosystems should carry the same value globally. Furthermore, WTP amounts are based on the value of a statistical life in OECD countries, applied globally, and not reduced by local earning potentials. Therefore intergenerational concerns and intra-generational equity are well represented within EPS. (Steen 1999a;b) For additional background on EPS and its applicability in assessing sustainability, please see Appendix A.

[8] For example ecoinvent (Frischknecht & Jungbluth 2007), Eco-indicator99 (Goedkoop & Spriensma 2001), and IMPACT2002+ (Jolliet *et al.* 2003) are other ready made LCIA tools.

It is not evident from my explorations if others have used EPS (or any LCIA method) in a fashion to provide a monetary valuation of the damage effect. LCIA have traditionally been marketed as methods for weighing between design options. In practice, the LCIA methods have been used ex-post to compare products and/or design choices. While these LCIA methods are designed for (and presumably best suited to) ex-ante design choice comparisons (Baumann & Tillman 2004), I have taken the unusual step of transforming EPS's *relative* valuations to concrete physical currencies. In this way, the cost of ICT material flows in terms of sustainability are quantified in economic terms. EPS presents sustainability costs in 1998 Euros. In order to convert a 1998 Euro to a 2008 Euro, I use the European Central Bank's Harmonized Index of Consumer Prices[9].

#### 4.3.5 Manufacturing and user trends

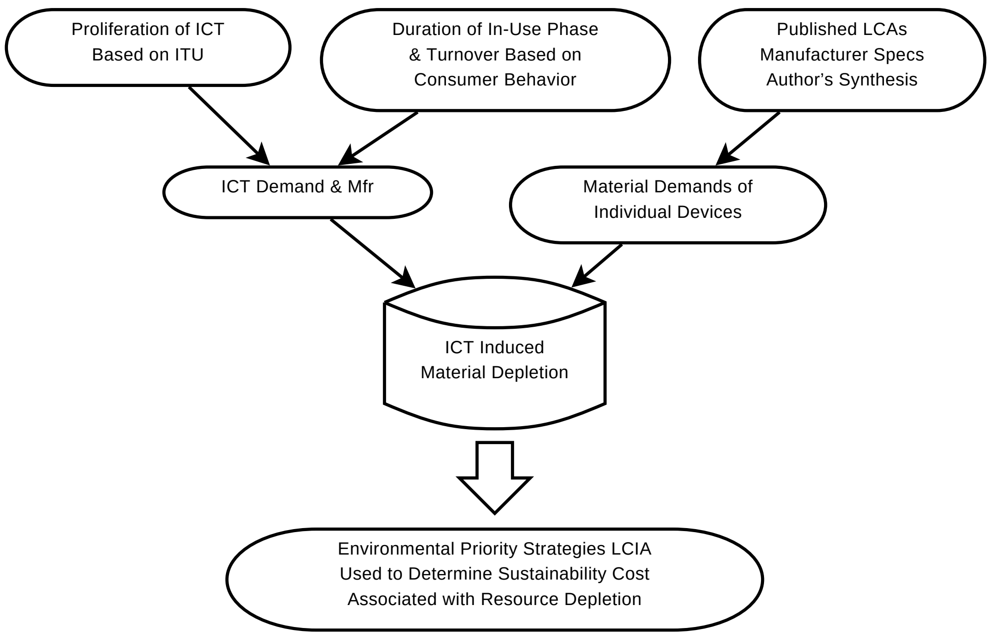


Figure 6: Visualization of the research method used to assess the sustainability impact of the material demands of ICT equipment.

**Proliferation and consumer behavior** Proliferation of ICT devices is the main driver in the model. I have constructed trends of the proliferation of in-use personal computers, mobile phones, and servers. In-use data was more readily available than sales figures from market research firms[10]. While sales figures may have provided a more accurate driver of resource depletion, market research data comes at very high cost and is proprietary. This nature of their databases makes their direct use inappropriate for academic work.

[9] `http://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=122.ICP.M.U2.N.000000.4.INX`

[10] Market research firms heavily engaged in the field of ICT include Gartner, Inc.: `http://www.gartner.com/` and IDC: `http://www.idc.com/`.

In-use figures for personal computers and mobile phones were sourced from the International Telecommunications Union (ITU 2008b; 2009). Personal computer proliferation was extrapolated as a linear trend. Meanwhile, mobile phone proliferation was also extrapolated linearly, but limited to 5 billion subscribers based on principles of saturation and limited likelihood of intense rural penetration and/or rural coverage in developing nations. Global server trends were extracted from a paper by Koomey (2007), which made public a subset of IDC data. These were also extrapolated linearly from the data.

If the research and model can be divided into two major portions: 1) resource depletion and 2) hazardous emissions and mineral recovery, then Figure 6 shows the research method applied in developing the first part: the sustainability cost of resource depletion. (Figure 7 describes the second half, and is discussed below.) Proliferation trends are represented by the top-left most bubble. These are combined with an estimation of consumer behavior and the length of the in-use phase (Kuehr & Williams 2003, Williams *et al.* 2008, US EPA 2008a), providing an estimate for the quantity of devices manufactured in a given year.

**Manufacturing** The right-hand portion of Figure 6 shows the process for developing the mineral intensity for each device manufactured. Each device is modeled as an average representation of devices within a given product category. In other words, the method here assumes every PC is an 'average' PC, every mobile phone, an 'average' phone, and so on. This sort of aggregation is absolutely necessary to make progress and is acceptable under the procedural rationality described above.

Life cycle assessments and studies of printed wiring boards (Scharnhorst *et al.* 2005, Wen *et al.* 2005) provided the mineral content for personal computers (Williams *et al.* 2008, Kuehr & Williams 2003, Socolof *et al.* 2005, Ukai 2007), mobile phones (Scharnhorst *et al.* 2005; 2006), and mobile network electronics (Scharnhorst *et al.* 2005; 2006). Server mineral content was extrapolated from personal computers. I analyzed server manufacturer specifications and developed an estimate for the mineral content of each category of server as a multiple of the mineral content of a personal computer. The details for this procedure are laid out in the Analysis section.

**Resource depletion cost** The model combines the mineral content of each device with its rate of manufacture to provide an overall figure for the rate of mineral depletion associated with each type of ICT device. Each of the 25 minerals has a unique resource depletion cost based on the EPS method (listed in Appendix B.1). Combining each mineral cost with its depletion rate using a weighted summation method, the model computes a total sustainability cost for resource depletion.

### 4.3.6 End-of-life and disposal

End-of-life disposition of ICT devices is a gray area. The actual magnitude and geography of transboundary waste flows is an area acknowledged to be deficient of significant data (Puckett *et al.* 2005). Limited data is available for the country specific intensities of waste generation, but much less is known about the intensity of formal and informal recycling, mineral recovery rates, or transboundary movement of the electronic waste.

Figure 7 outlines the methods used for the second half of the model: hazardous emissions and mineral recovery. In the absence of good information, procedural rationality suggests moving beyond the barrier of imperfect information and formulating an understanding based on best available insight. Therefore in order to move forward in the analysis of ICT sustainability, I have been compelled to create "ball-park"

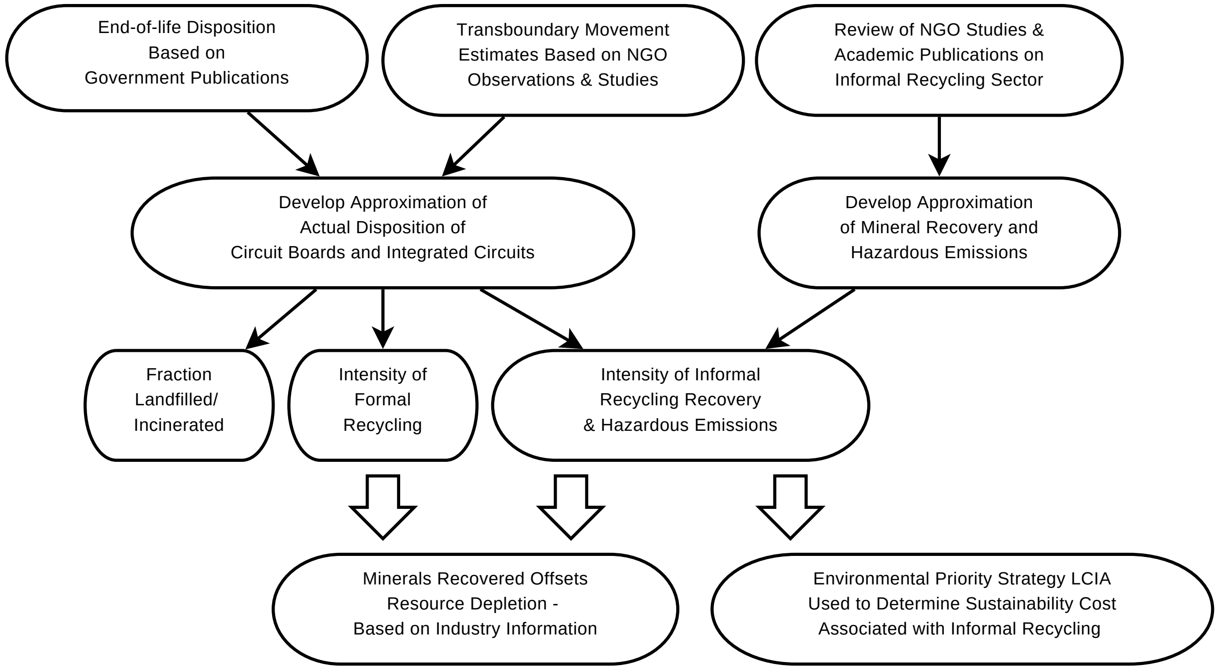


Figure 7: Visualization of the research method used to assess the sustainability of various end-of-life possibilities for ICT equipment.

estimates for the actual disposition of printed wiring boards and integrated circuits associated with the ICT devices under study.

End-of-life disposition is supported by information in Kahhat *et al.* (2008), Williams *et al.* (2008), Savage (2006), Osibanjo (2008), and US EPA (2008b). Estimates for regional exports and the direction of transboundary movement is built upon investigations by Basel Action Network, Silicon Valley Toxics Coalition, and Greenpeace (Puckett *et al.* 2005, Puckett & Smith 2002, Brigden *et al.* 2005, SVTC 2009). The same studies, as well as Porte (2005), Williams *et al.* (2008), and Terazono *et al.* (2006), provide insight into the informal recycling sector activities: minerals recovered, methods used, and emissions associated with informal recycling.

Industry information was used to formulate an approximation of minerals recovered in the formal recycling of printed wiring boards and integrated circuits. ECS Refining Texas, LLC (2009) and Boliden Mineral AB (Theo & Henriksson 2009) are examples of formal processors of electronic waste. Corporate websites and industry publications (Scandinavian Copper Development Association 2004) were used to understand which minerals were being recovered and to what extent. Scharnhorst (2005) also provided details into the industrial processes used by Boliden. The formulation and final conclusions of estimating end-of-life disposition of the minerals can be found in the Analysis section.

Based on the end-of-life formulations arrived at by studying the available literature, the mineral content of each ICT device is divided amongst the three end-of-life fates. Formal recycling and informal recycling both can recoup some of the resource depletion costs. Meanwhile, informal recycling incurs additional costs associated with the emissions of the 25 minerals under study. These costs are localized to the regions in which the informal recycling activities take place. Here again the EPS method is employed to arrive at the sustainability cost of emissions.

# 5 Analysis

The analysis section details the numerical construction of the model, and as such is the most technical portion of the paper. Academic principles require that these details be made transparent.

## 5.1 Global User and Market Trends

The following user trends have been constructed at the global level (unless indicated otherwise):

- Internet Users. (ITU 2009)
- In-use PCs. (ITU 2009)
- In-use Servers by Server Category. (Koomey 2007)
- Regional and Worldwide Mobile Phone Subscribers. (ITU 2008b)

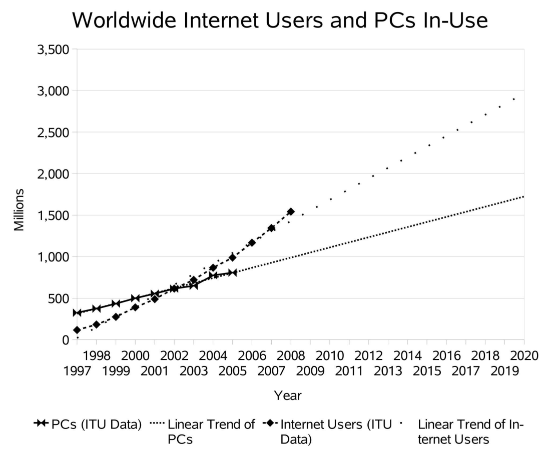


Figure 8: Internet users currently exceed the number of PCs in use.

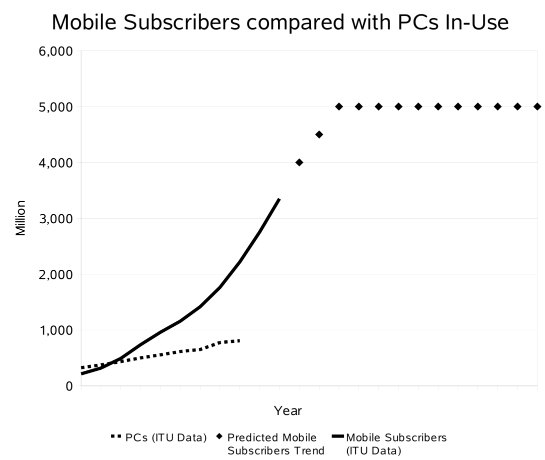


Figure 9: Mobile subscribers have grown exponentially while PC growth has been virtually linear.

Figure 8 shows the trend in the number of Internet users at the global level as well as personal computers in-use. Data was sourced from the International Telecommunications Union (ITU 2009). Linear trends were then constructed to the year 2020. Comparing the data with the trend line, the growth of in-use personal computers appears to be nearly linear. Meanwhile the rate of Internet users[11] appears to have a non-linear growth curve. Furthermore it is evident that number of Internet users far exceeds the number of in-use personal computers. This is most likely due to the broad use of Internet cafes (locutorios, etc) and library access points throughout the world. Another interesting observation can be seen in the data prior to 2001, where the number of personal computers in fact exceeds the number of Internet users. This is most likely due to the lack of connectivity as well as an indication of the infancy of the Internet.

Mobile telephony on the other hand has grown much more rapidly, displaying exponential growth. The exponential growth is currently supported by rapid proliferation in Asian markets. According to the ITU, 2008 marked the year of the 4 billionth mobile subscriber. Two-thirds of humanity has the

[11] Internet users is loosely defined as those who have access and the know-how to use the Internet. It does not imply connectivity or ownership of any ICT. For more information on the concept see ITU's Technical Notes (ITU 2008a).

ability to connect with almost anyone else while on the go. This is an impressive figure no matter one's perspective. Figure 9 compares the growth in PCs and mobiles. For all trends but mobile phones, a linear extrapolation has been assumed. Instead, mobile phones are conservatively modeled to saturate at 5 billion subscribers.

Server data was compiled from Koomey (2007), in which the author was granted the right to publish IDC data publicly. The data presented is thorough, including growth in each server category as well as the top sellers within each category[12]. Server trends are show in Figures 10 and 11. It is interesting to note that high-end sales have remained steady over the years, while low-end volume server sales have grown tremendously. This is most likely due to the growth in Internet websites and low throughput e-commerce. Volume servers are ideal for these applications. The high-end servers are better suited for transaction processing and scientific computing. Credit card and cash machine approvals are examples of high volume transaction processing.

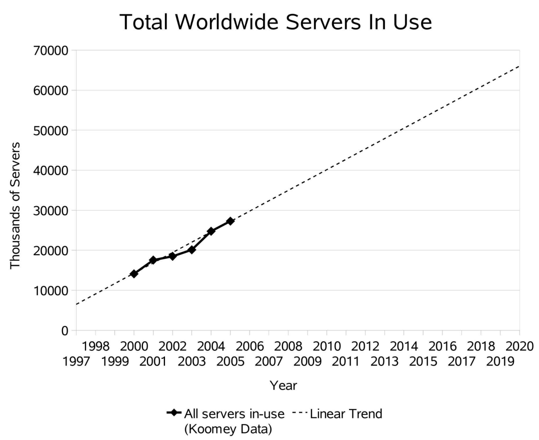


Figure 10: The trend of servers in-use appears to show linear growth at the global scale. This trend is primarily supported by volume server sales. Such growth is consistent and necessary with the vision of the ubiquitous or connected society.

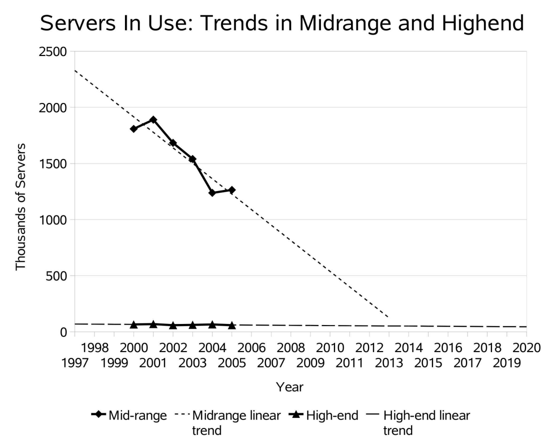


Figure 11: The trend in the high-end is relatively flat, meanwhile mid-range usage is in a decline. This may be due to the lower price/performance ratio offered by volume servers, which as the name implies, has significantly larger sales.

## 5.2 Rare and Hazardous Minerals in Manufacturing

ICT devices are unlike traditional consumer goods in almost every respect. They enable apparently amazing feats of computation and communication. In order to do so, scientists and engineers have devised extremely small and complex devices that are thoroughly organized at the molecular level. Their unique abilities are enabled solely through the use of special minerals, mostly rare and often toxic. With transboundary movement of hazardous e-waste awareness growing, low levels of active mineral recovery, and growth in an informal recycling sector, the minerals intensity of ICT is a sustainability concern. The rapid proliferation of ICT and predictions of ubiquitous ICT, or a connected society, raise growing inter-generational and intra-generational equity concerns from ICT related activities.

Few studies have attempted to grapple with the mineral intensity of ICT at the macro level. Some have focused on energy (GeSI 2008, Gartner 2007), but it is suspected that they underestimate the

[12]Servers are categorized as volume (effectively low-end), mid-range, and high-end servers

manufacturing energy demand of complex integrated circuits (Krishnan *et al.* 2008, Williams *et al.* 2002). The original intent was to include an energy analysis as part of this study, but time and resource constraints have prevented this. Adding energy to this study, using the same bottom-up approach would be a valuable exercise in order to compare and contrast with the results from other (mostly industry) studies of the global energy use of ICT.

### 5.2.1 Mineral selection and mineral reserves

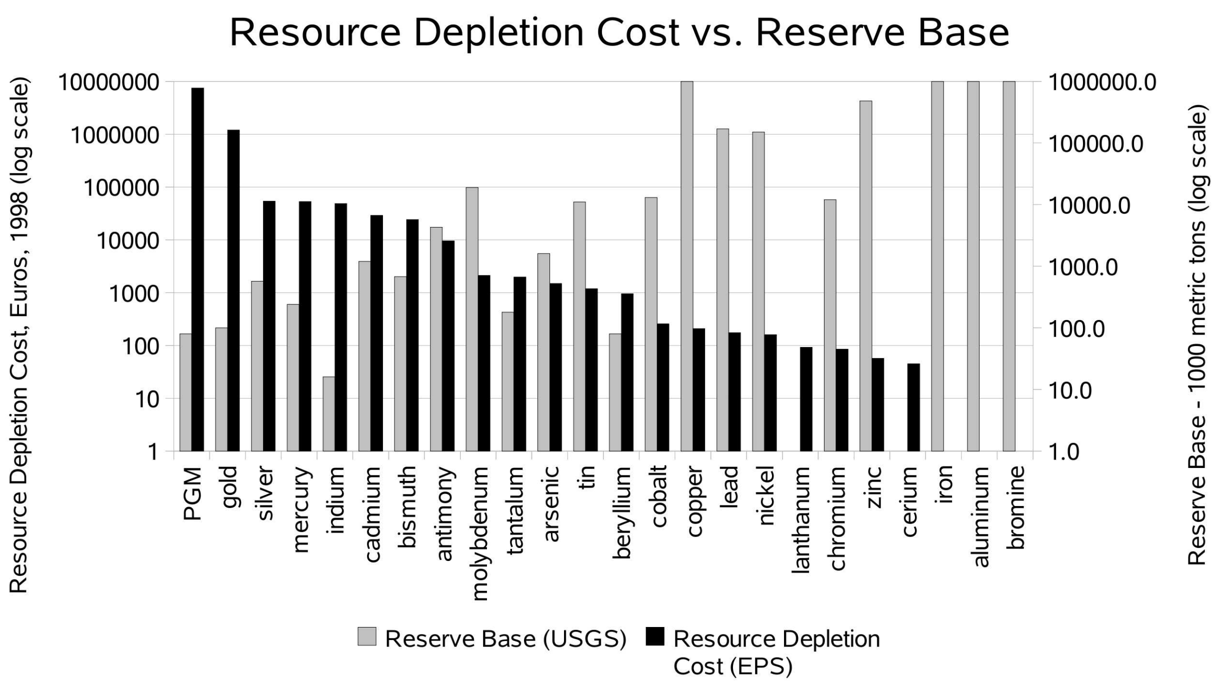


Figure 12: Resource depletion cost in Euros / kg vs. mineral reserves in thousand metric tons. Note that PGM represents the platinum group metals.

Twenty-five minerals were chosen for analysis. They were selected primarily on their rarity in the Earth's crust and presence in ICT devices. Mineral toxicity and the availability of reliable data further refined the list. A sampling of the rare minerals selected are provided in Table 1. An in-depth look at the primary producers reveals that China significantly dominates mineral production for most of the minerals considered. South Africa and Russia are also major producers of some specific rare minerals. Appendix B.1 offers a complete list of the 25 minerals modeled in this study. Meanwhile, Figure 12 shows the relationship between the resource depletion cost as determined by EPS (Steen 1999a;b) and the mineral reserves as determined by the USGS (2009). Note that the graph has independent Y-axes, and is a log scale. The graph shows that the relationship is roughly inverse across all 25 minerals: the smaller the reserves of a given mineral, the higher its resource depletion cost. The relationship is not perfectly inverse as the EPS resource depletion cost is based on the fraction of a mineral in the Earth's crust, not on a prediction of economically extractable reserves.

| Mineral | Annual Mine Production (2008) | Reserve Base[a] | Primary Producers (in order of production) |
|---|---|---|---|
| gold | 2.33 | 100 | China, S.Africa, US, Australia, Peru, Russia |
| indium[b] | 0.57 | 16 | China and others, but significantly less than China. |
| mercury | 0.95 | 240 | China, Kyrgyzstan |
| palladium | 0.206 | | Russia, S. Africa |
| platinum | 0.200 | 80[c] | S.Africa, Russia |
| tantalum | 0.815 | 180 | Australia, Brazil, Ethiopia |

[a]Please see USGS (2009) for a full explanation of how reserve base is calculated.
[b]Indium values are from USGS 2008. In 2009, the USGS withdrew estimates of indium's reserve base.
[c]Platinum reserve base represents the entire platinum group metals, including palladium.

Table 1: A sampling of the rarest minerals analyzed in the model. All units 1000 Metric Tons. A complete list can be found in Appendix B.1. USGS (2009)

#### 5.2.2 Understanding material demands of the building blocks.

Below is a brief overview of many of the most important hardware building blocks to ICT devices, whether in mobile phones, servers, or laptops. These details are here for the reader interested in a cursory background of the minerals and technology of ICT. This section is not essential to the continuity or coherence of the paper.

**Integrated Circuits** Computer chips are integrated circuits. Integrated circuits encompasses a broad category of devices, including CPUs, memory, bios, analog to digital converters, etc. Integrated circuits are possible due to semiconducting devices. Semiconductors are built upon a monolithic foundation of silicon which has been doped[13]. Common dopants include arsenic, boron, phosphorous and occasionally gallium, depending upon the semi-conducting characteristics desired. Dopants are used in extremely small quantities. Layers of insulators and metals are then added upon the foundation to create a network of transistors and circuits that perform the specified function. According to Intel Corp (Johnson 2007), over 60 elements can be found in modern integrated computer chips. This count obfuscates the myriad of compounds required during the intricate chip manufacturing process (Krishnan *et al.* 2008).

The platinum group of metals, although used in very small amounts, are key to integrated circuit functionality. Their rarity in the Earth's crust highlight their potential to be a limiting factor (Alonso *et al.* 2008), although their fraction in an individual integrated circuit is so low that mineral recovery from post consumer devices appears far from economically viable (ECS Refining Texas, LLC 2009, Theo & Henriksson 2009).

**Printed Wiring Boards** Printed Wiring Boards (PWBs) form a key building block of ICTs. If electronic devices can be conceptualized as cities, then the PWBs are the very ground, streets, water mains, and sewers upon which all other physical structures are built. PWBs are sandwiched layers of conductors and insulators. PWBs are typically rich in copper, lead, and other metals. Both because of the high

[13]Doping is a process of adding precise and minute amounts of impurities into an otherwise pure silicon crystal. The impurities are referred to as dopants

temperature nature of assembling electronics and by residential safety laws in most jurisdictions, the PWBs are required to be flame retardant.

The greatest risk to human health during use from PWBs most likely stems from these, typically brominated, flame retardants. The informal recycling sector experiences a far more intense fate of exposure to the combusted byproducts of the flame retardants. Flame retardants are also used in insulators in wiring, cables, and other plastic components of electronics.

**Liquid Crystal Displays** Recent years have experienced significant growth in the number and breadth of applications of flat screen displays (Socolof *et al.* 2005). The majority of these are Liquid Crystal Displays (LCDs). LCDs have been considered a technological advance from the traditional 'monitors' based on Cathode-Ray Tube (CRT) designs. While LCDs consume less energy and space than CRTs during the use phase, it has been argued that their increased energy and resource demands during manufacture may offset the in-use gains (Socolof *et al.* 2005).

Indium (in the form of Indium-Tin-Oxide) is a key ingredient in the manufacture of LCDs in the form of transparent conductors. Indium is suspected to be a limiting factor in LCD proliferation in the next years (Wäger & Classen 2006), although there are conflicting views on this perspective from the mining industry (Phipps *et al.* 2007). It is perhaps a strategy of the mining industry to reassure their clients as well as to head off researchers as they seek other materials, such as graphene (Blake *et al.* 2008), as substitutes. LCDs often use mercury (Hg) in a fluorescent backlight. Mercury is a well documented toxicity risk that is increasingly prevalent in the air and fauna. Platinum group metals are also used in the glass substrate of the displays (USGS 2009).

### 5.2.3 Modeled material demands

A plethora of ICT devices are available in the marketplace, each with its own permutation of features, price point, and target audience. It would be a large endeavor to model such variety. As such, I have chosen to model all devices as sort of an *average* or *typical* device. Additionally, data availability has further restricted the completeness of the accounting. Therefore, it is assumed that the results, the sustainability costs, garnered from this study may be interpreted as a minimum assessment.

Personal computers have the most in-depth data available, including the enclosures, power supplies, and printed wiring board assemblies[14]. The model in this study does not distinguish between laptops and desktops, but the differences are addressed. Additionally, the study assumes that all displays are of the flat screen variety. Table 2 summarizes the mineral accounting for components of the Internet.

For mobile telephony, I have narrowed the detail of accounting further. Only the mineral contributions from Printed Wiring Board Assemblies (PWBA) are included. Therefore, bulk materials associated with cases, enclosures, antenna towers, and base stations are not accounted for. This narrow scope is based not only on availability of data, but is consistent with the focus on rare and hazardous minerals, which are relatively more present in PWBAs. Table 3 summarizes the mineral accounting for mobile telephony.

In all cases, batteries have been excluded from the analysis. Given additional time and resources, there are many opportunities to expand the breadth and scope of the accounting in this model to provide an even more complete picture. The sections below present a more detailed account of how each type of device is modeled.

[14] printed wiring board assembly refers to the populated printed wiring board, including all integrated circuits and other circuit elements that are mounted to it

**Personal Computers** Personal computer mineral content is determined primarily from Williams *et al.* (2008). Williams provides a sum for a desktop PC and display, specifically a cathode-ray-tube(CRT). Two market trends require further processing of the Williams values: 1) laptops are a significant portion of the personal computer market, and 2) flat-screens, or liquid crystal displays (LCDs), are now the most prevalent display technology[15].

In order for the model to reflect current trends in displays, the primary contributors to the CRT mineral values(Kuehr & Williams 2003) were deducted from Williams to arrive at only the mineral content of the PC main unit. LCD mineral content is then determined separately and added to the main unit content within the model. (See more details below.)

The PC main unit data is cross-checked for relevance to the growing trend in laptops. The only minerals which stand out as deserving attention are steel (iron)[16], aluminum, and copper. Steel and aluminum are most prevalent in the casing and internal structural components of desktops. Williams provides a minimum and maximum estimate for both steel and aluminum in desktops. Aluminum ranges from 440 to 720 grams / PC. I estimate that using the low value of 440g is within the range of laptop internal structural hardware, especially when considering that some even use aluminum in the casing. Steel on the other hand ranges from 4470 grams to 6050 grams, completely unreasonable values for a laptop. Due to weight concerns, manufacturers are certain to minimize steel content as much as possible. I have modified the steel content for a PC to be one-half of the Williams value, representing 50% penetration of laptops into the personal computer market. While it may seem that several assumptions have been drawn, both aluminum and steel are of less concern in this study as both their rarity and toxicity are low (Steen 1999a;b). The resource depletion cost from EPS associated with steel is 0.96 euro/kg and aluminum 0.44 euro/kg, the two lowest EPS values of the 25 minerals modeled. It is safe to assume then that the large uncertainty in these two minerals has little impact on the results.

Meanwhile, copper ranges from 670 grams to 1940 grams in Williams' data. The large variance most likely arises in significantly varied power supply ratings and designs. I therefore assume that the low value of 670 grams is suitable for a laptop when also including the laptop's external power supply.

In the model, each PC main unit contains the low value of all 25 minerals, except iron, for which 1/2 of the low value is used. Section B.2 presents the values used in the stock and flow model.

**Personal computer displays** Displays come in two major types: cathode-ray tubes (CRTs, traditional TVs), and liquid crystal displays (LCDs). A slightly old, but thorough life cycle comparison of CRTs and LCDs has been conducted by US EPA (Socolof *et al.* 2001)[17]. Their study includes many of the minerals modeled here. These figures are of relevance, especially since many are unique and rare minerals, like indium, which are key enablers of flat display technology. While much has changed in the marketplace with regards to flat panel displays, namely price reduction along with display size increase, my assessment is such that the rare element data in the US EPA study is still valid. The LCD market trends have been enabled mostly by increased manufacturing capacity, streamlined production methods (especially of the glass substrate), as well as integration of all the circuit elements into fewer chips and PWBs, not by rare materials substitution. (Ukai 2007)

[15]Various types of LCD technologies are used both in laptop displays and flat-screen desktop displays, as well as many flat screen televisions.

[16]Steel is typically formulated with over 90% iron. They are treated synonymously for the purposes of numerical analysis

[17]Socolof *et al.* (2005) continues investigating CRTs and LCD panels outside of the US EPA using what appears to be the same dataset.

| Internet Device | Accounting Method | Notes |
|---|---|---|
| PC main unit | Williams *et al.* (2008) | provides users access to the Internet (clients) |
| displays | Socolof *et al.* (2001) | all displays are assumed to be flat screens |
| servers | as multiples of PC | Complexity of servers was estimated as a multiple of PC complexity. Servers provide web services, data, back-office processing, etc |
| routers/ switches | not included | directs data throughout the Internet |
| cables | not included | all the physical network cabling: fiber and copper |

Table 2: Mineral flow accounting boundaries of the Internet.

**Servers** Only one study was uncovered which presented a life cycle analysis of a server (Hannemann *et al.* 2008). Their study focused on life-cycle exergy, not mineral content. A different study, by Koomey (2007), focused on the energy demands of in-use servers and their facilities. This study was invaluable for providing access to statistics on server sales and figures on servers in-use. Furthermore, Koomey's study distinguished between different server categories, which is of particular importance when considering mineral content. A low-end volume server might weigh approximately 25 kg, while a high-end server closer to 2000kg. Clarity into this disparity is key in order to achieve proper minerals accounting for servers.

Koomey (2007) not only provided server trend data (presented further in Section 5.1), but also server categories and model names of the servers with highest sales within each type. Servers fall in one of three categories depending on their compute power: volume, mid-range, and high-end. Three models were provided for each category.

Using technical specifications for each server model, I computed an estimate for the material demand of each server, effectively as a multiple of the material demand of a single PC. Factors considered in the estimation included the number of processors, cores[18], primary circuit boards, and input/output circuit boards.

I assume that each server core will have supporting hardware approximately equivalent to that in a PC, and that each input/output board leads to either a storage array of hard discs or a network connection. Using these assumptions, I then compute the multiple simply as:

$$\text{Server PC equivalents} = 1 \text{ PC} * \ \# \text{ of Cores} + 0.25 \text{ PC} * \# \text{ of I/O Boards}$$

The results of investigating the various server models and determining their PC equivalents is then used for establishing the minerals intensity of server demands, as well as the PC to Server relationship in practice. Server PC equivalents can be can be found in Appendix B.3.

**Mobile phones and network hardware** All mobile phone data comes from a study of GSM networks in Europe by Scharnhorst *et al.* (2005; 2006). The study provides excellent insight into the printed wiring board assembly content of the most significant aspects of mobile phone networks: phones, base

[18]As integrated circuits continue to become more complex, it has become more difficult to differentiate between a single processor as one CPU core or multiple CPU cores, for example Intel's Xeon chip is available as a dual-core or quad-core. Further complicating matters, servers often use multiple chip modules (MCM) to achieve multiple core type performance. An MCM is a compact PWB with multiple processors arranged to work together.

stations, and switching stations. The study also establishes a relationship between number of users and magnitude of service provision necessary to provide an acceptable level of service, based on European norms. These ratios are not necessarily a good reflection of the global condition. For example, rural areas of India and Africa may have less density of mobile phones, but similar frequency of radio antennas due to the range limits imposed by radio communication and the design of cellular networks. On the contrary, density of users in large Asian cities could push the density of antennas higher than the European norm by reducing mobile phone 'cell' size in order to handle a higher density of voice and data traffic. The variances could go in either direction depending on the specific context, and a more precise assessment of the variation is beyond the scope of this study, therefore I use the European analysis as a good approximation of the global average.

| Mobile Telephony Device | Accounting Method | g/unit | Notes |
|---|---|---|---|
| Phones | PWBA only[a] | 30 | provides users access to telephony |
| Base stations | PWBA only | 159,000 | radio and switching hardware at each mobile antenna |
| Switching stations | PWBA only | 75,000 | regional data and voice switching stations |
| Bulk materials | not included | unknown | enclosures, towers, antennas, etc. |
| Cables | not included | unknown | physical connectivity of the network, including fiber-optic and copper |

[a] All mobile telephone related PWBA data from (Scharnhorst *et al.* 2005; 2006)

Table 3: Mineral flow accounting boundaries of mobile telephony.

The PWBA mass is extracted from Scharnhorst *et al.* (2005; 2006) for each component of the mobile phone network. The PWBA mass is then combined with the aggregate mineral content of PWBA as described in Appendix B.4. Scharnhorst *et al.* (2005; 2006) also provides insight into the average use time of each component. Table 3 summarizes the PWBA content while Appendix B.5 presents turnover rates used as a baseline in the model.

**Unmodeled: process minerals and most bulk materials.** Several studies have investigated the impacts of integrated circuit manufacturing, both in terms of energy demands, materials, and chemicals used explicitly during the manufacturing phase. Krishnan *et al.* (2008) estimate over 38 process chemicals input, in 206 steps, utilizing 52 unique processes in order to manufacture an integrated circuit. All of these minerals are not accounted for. Only the minerals which are part of the finished product are studied. See Williams (2004) and Plepys (2004) for additional information on circuit manufacturing impacts.

As portable ICT devices become more prevalent and often preferred over desktop alternatives, rechargeable batteries become a crucial area of study. Batteries have been excluded here in order to maintain a tractable scope, but would make an excellent area of future study. Finally, except for the PC, bulk materials associated with ICT devices are not included. Examples of bulk materials include the plastic casing of a mobile phone, the steel in a mobile network antenna, and the structural elements of server racks. As these bulk materials are less rare and/or less hazardous, their exclusion is not of significant concern in terms of the sustainability cost.

## 5.3 In-Use Phase

The opportunities and benefits of ICT occur mostly during their in-use phase. These could include sustainability improvements, such as telecommuting, or videoconferencing (Arnfalk 2002). Or they could entail increased travel and shipping demand, as in the case of globalization of business operations. The opportunities are numerous, as discussed earlier, and are also in need of study from a sustainability perspective. The primary characteristic of the in-use phase of concern here is the rapid rate of turn over in devices. Personal computers are estimated to have an in-use life of about 3 years (Williams 2004) and mobile phones about 1.5 years (Scharnhorst *et al.* 2005).

## 5.4 Waste Streams and Recycling

A sustainability assessment with a focus on materials flow would be incomplete without addressing waste streams. In particular, recovery of rare minerals and exposure to hazardous materials in the informal recycling sector are of prime concern, as the analysis will show. Due to rapid advances in technology and the relatively low consumer cost of ICT, the electronic waste streams have been growing worldwide. Waste Electric and Electronic Equipment (WEEE)[19] waste has been estimated to grow at approximately 3-5% annually in Europe (Savage 2006). In the US the figure is between 4 and 7%[20].

Studies by several non-profits and government agencies indicate that e-waste recycling has come to represent different concepts to different people. For some, simple incineration of e-waste may be considered a form of recycling because energy is recovered (although most of the rare minerals and toxic compounds are not). Meanwhile, others consider recovery of plastic and metal enclosures sufficient recycling as these often contribute significantly to the mass of the e-waste streams. Additionally, when speaking of recycling both formal and informal recycling streams must be treated uniquely as the impacts differ immensely. (Savage 2006)

This study's focus on rare and toxic minerals requires attention to the EOL disposition of printed wiring boards and integrated circuits. Data with respect to this aspect of e-waste has been very poorly forthcoming. The Silicon Valley Toxics Coalition revealed that they do not have insight into printed wiring board recycling or mineral recovery (SVTC 2009). Their efforts stop at *pledges* from E-waste *collectors* who are only handlers of e-waste, not directly engaged in resource recovery. Even EMPA, the Swiss Federal Laboratory with significant expertise in the field, provides no clear information on active, legal efforts to recycle e-waste. "Refining of resources in e-waste is possible and the technical solutions exist ..." (EMPA 2008). EMPA does provide further detail regarding methods for proper PWB recovery, but few details are available with regards to active efforts.

Although investigation has revealed that several companies appear to be engaged directly in the recycling and mineral recovery of PWBs in a relatively benign manner, I estimate the fraction of end-of-life devices reaching such a formal recycling facility to be very small (see Table 4). I discuss formal recycling further in Section 5.4.3. The clearest evidence of large scale mineral recovery from e-waste occurs in the informal recycling sectors in China, India, and Africa. Such activities have been investigated in detail by Greenpeace (Brigden *et al.* 2005), Basel Action Network (Puckett *et al.* 2005), and Porte (2005).

In an environment lacking clarity and data, estimates of waste streams, transboundary waste movements, EOL disposition and emissions have been constructed. The estimates are loosely based upon

[19] ICT is but a subset of WEEE, which can include all devices that use electricity, for example a blender or electric drill.
[20] Growth rate computed using data from US EPA (2008b)

observations by US EPA (2008b), EU Joint Research Center (Savage 2006), Silicon Valley Toxics Coalition (SVTC 2009), and Basel Action Network (Puckett *et al.* 2005, Puckett & Smith 2002).

### 5.4.1 End of life pathways

Williams *et al.* (2008) and the US EPA (2008b) have observed that ICT equipment often has two distinct end-of-life (EOL) events. One is the initial EOL where devices are replaced with newer equipment. These replaced devices typically function perfectly and still have value. Most of these devices are put into storage. The second EOL comes several years later when the owner decides to remove from storage old devices and introduce them into the waste stream. At this point, such devices may be so old that their relative usefulness is greatly reduced due to the rapidly changing characteristic of ICT. The storage and secondary-use aspects are modeled based on US EPA estimations (US EPA 2008a).

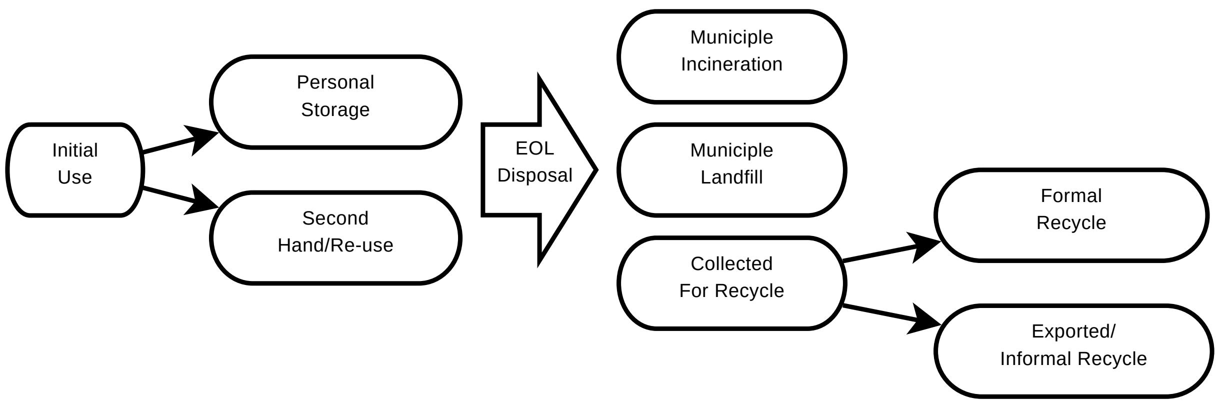


Figure 13: Details of the in-use and end-of-life pathways for ICT consumer devices.

Historically, ICT waste was treated like most other waste: landfilled in North America or incinerated in Europe. Growing concerns over the hazardous content of ICT devices has prompted regulations in the US and EU to curb improper disposal of ICT. Nonetheless, observations by the US EPA show that the bulk of North American ICT is still landfilled (US EPA 2008a).

As ICT waste is collected for recycling, an interesting dynamic behind the movement of such waste has resulted. First, there is an increased trade of e-waste, as traditional avenues for domestic disposal are not available, and/or dumping in China, India, and Africa is economically advantageous. Second, since transboundary movement of hazardous waste is illegal in many jurisdictions, the movement of e-waste has gone unlabeled or under the guise of electronics labeled for re-use. Often such equipment is so outdated that likelihood of reuse is extremely low. These factors have made e-waste extremely challenging to track, quantify, and control. (Puckett *et al.* 2005)

| Landfill or MSWI[a] | PWB and IC's informally recycled | PWB and IC's formally recycled |
|---|---|---|
| 80% | 18% | 2% |

[a]Municipal Solid Waste Incineration

Table 4: Fractional estimates for EOL disposition of ICT (global aggregate).

The in-use and end-of-life pathways of consumer ICT devices have been investigated by the US EPA, BAN, and SVTC. Figure 13 shows the observed pathways. Each of these pathways is modeled for personal computers and mobile telephones. Servers and mobile network hardware do not experience a similar storage or second-use phase. Thus, servers and mobile network hardware skip this stage in the model. The "in-use models" in India and China likely vary from those observed in the US, but are modeled identically as consumer trends in India and China appear to be rapidly changing towards mimicking those in the West.

End-of-life disposition is modeled using two different methods. For the bulk of the results, end-of-life disposition is modeled worldwide as shown in Table 4. The second method is used only to compute estimates for transboundary movement of mobile telephone waste. For this, more spatially specific estimates for end-of-life disposition have been created and modeled. Table 5 lays out the more detailed estimations. The figures in Table 5 are only used in order to quantify transboundary movement of mobile telephony equipment.

### 5.4.2 Transboundary movement

As already discussed, transboundary movement of ICT waste has been difficult to monitor and is often exported and imported illegally. As such, modeling of transboundary movement of ICT waste has been performed only for mobile telephony, and only in order to generate a theoretical estimate of the sustainability cost being exported from region to region. Based on personal communications with SVTC (2009) and investigations by Greenpeace and Basel Action Network (Puckett *et al.* 2005, Puckett & Smith 2002), I have formulated regional estimates for end-of-life disposition and transboundary movement. All estimates are presented as fractions and used in the model *only* for quantifying a theoretical estimate for the transboundary movement of mobile telephony equipment. These "ball-park" estimates are consistent with the procedural rationality discussed in the analytical framework. Table 5 presents the end-of-life disposition for each source geography.

| Source Region | Landfill % | MSWI[a]% | Collected for recycling | Fraction of collected: formally treated | Fraction of collected: exported/ informally treated |
|---|---|---|---|---|---|
| Europe | 20% | 60% | 20% | 50% | 50% |
| USA[b] | 75% | 5% | 20% | 20% | 80% |
| China | 10% | 10% | 80% | 10% | 90% |
| India | 10% | 10% | 80% | 5% | 95% |
| Africa | 10% | 10% | 80% | 5% | 95% |
| Americas[c] | 75% | 5% | 20% | 20% | 80% |
| Asia/Oceania[d] | 10% | 10% | 80% | 5% | 95% |

[a]Municipal Solid Waste Incineration
[b]Data from US EPA
[c]excludes USA
[d]excludes China and India

Table 5: Fractional estimates for EOL disposition of mobile telephony equipment by region

Even more difficult than ball-parking end-of-life disposition has been estimating the direction and fractions of exported goods from region to region. To simplify matters, I have assumed that informal recycling activities are limited to locations in Africa, China, and India. Mobile equipment being used in India or China are assumed to stay mostly within those countries. Remaining regions' exports are assumed to mostly go to India or China with a smaller fraction exported to Africa. Table 6 presents estimated direction and fractions of exported electronic waste.

| Source Region | To Africa | To China | To India |
|---|---|---|---|
| Europe | 20% | 50% | 30% |
| USA | 20% | 50% | 30% |
| China | 5% | 90% | 5% |
| India | 5% | 5% | 90% |
| Africa | 30% | 20% | 50% |
| Americas[a] | 20% | 50% | 30% |
| Asia/Oceania[b] | 10% | 50% | 40% |

[a]excludes USA
[b]excludes China and India

Table 6: Fractional estimates of mobile telephony waste exported to informal recycling sectors

### 5.4.3 Formal recycling in Europe and North America

There appears to be an increasing trend in companies promoting themselves as being engaged in safe, legal mineral recovery from PWBAs. ECS Refining (USA), BOLIDEN of Sweden, UMICORE of Belgium, and Seimans-VAI (Austria) are involved in the business. Their processes are complex industrial procedures with presumably large operating costs. ECS appears to be mainly engaged in recovery of copper, aluminum, and steel. They may also recover solder, which would include tin and lead (ECS Refining Texas, LLC 2009)[21]. BOLIDEN appears to be a well respected recycler of electronics, claiming to recycle 1/3 of the world's *recycled* electronics[22] (Scandinavian Copper Development Association 2004). They are engaged in recovery of a broader range of metals: copper, gold, silver, lead, selenium, nickel, palladium, and platinum (Scharnhorst 2005).

Several papers have been published investigating the feasibility of fractioning PWBs for recovery of minerals in minute quantities. They present a wide array of approaches utilizing mechanical, chemical, and thermal partitioning techniques (Murugan 2008, Galbraith & Devereux 2002, Wen *et al.* 2005). Based on the cost of disposal as well as observations of transboundary movement of e-waste, it is very likely that these facilities handle only a small fraction of ICT at end-of-life.

### 5.4.4 Informal recycling in China, India, and Africa

Enclosures and glass are typically easy to separate from devices and often are done so before export of e-waste to the informal sectors. For recycling of domestic goods in China, India and other places with a

[21]ECS did not return attempts to contact them for more information regarding their mineral recovery activities

[22]Note: Boliden does not recycle 1/3 of the world's electronic waste, but rather, 1/3 of that which is formally processed in smelters, Boliden recycles

thriving electronics scrap commerce, these enclosures and glass are recycled locally. I assume that their recovery is in the 90% range. These materials include aluminum, steel, and gold (which is relatively easy to partition using mercury).

**Printed wiring board assemblies** The informal recycling sectors are primarily concerned with the recovery of copper and solder from PWBA's (Brigden *et al.* 2005). Solder mixtures vary, but typically consist of tin and lead. The EU RoHS initiative has targeted reduction of lead levels in electronics, and specifically solders. The initiative [2006] has resulted in the replacement of lead with various combinations of silver, copper, and trace amounts of bismuth, indium, zinc, or antimony.

| | Sustainability Concern | EPS pathway to sustainability cost |
|---|---|---|
| All recycling | mineral recovery | negates resource depletion by 98% [a] |
| formal fraction | emissions to air | not modeled |
| informal fraction | emissions to air and water | both modeled using EPS values of emissions to air[b] |

[a] The remaining 2% is the cost of mining and refining, which are not recoverable.

[b] EPS offers few valuations for emissions to water, a limitation which forces using emissions to air as a proxy.

Table 7: End-of-life pathways to sustainability costs using EPS.

In China, solder is recovered primarily via heating. In India, both heating, mechanical, and chemical separation of solder was observed. Copper is a key target in Indian acid washes and in both countries' use of shredders. In China, PWB shredding was also observed, with repeated shredding, washing stages to extract certain, unidentified metals. The wash waters were laden with high particulate content, presumably full of plastics and trace metal amounts. (Brigden *et al.* 2005)

Therefore, I assume 100% emissions of all metal contents which are not explicitly recovered. From observations, these metals are either washed away, part of ground-up dump material in open pits, or made airborne via open burning. For metals intended for recovery: copper, tin, and lead, I assume 75% recovery and 25% emissions. These are very rough figures and are primarily intended to provide enough precision to ball-park the localized sustainability cost in the informal recycling sector.

# 6 Results

I begin by showing several results under the business as usual (BAU) scenario, which forms the baseline for comparison. The business as usual scenario was constructed as laid out in the analysis section. I then compare and contrast the BAU with scenarios of lengthened in-use phase for ICT devices and different ratios of improvements in the fraction of ICT being recycled. The scenarios help to form the basis for a discussion of the sustainability of the ICT sector.

As the results will make clear, the total sustainability cost is heavily dominated by resource depletion. Therefore, in order to fairly assess hazardous emissions from informal recycling, the two costs are presented independently.

## 6.1 Resource Depletion Costs

Resource depletion costs are a subset of the larger sustainability costs as discussed above. I present resource depletion first as it represents a good starting point for exploring the scenarios and other sustainability costs that are represented within the model.

Figure 14 shows the resource depletion costs associated with the four sectors of ICT under study. Several interesting observations can be made from this figure. First, the resource depletion cost associated with mobile telephones exceeds that of personal computers[23] by more than a factor of 2. This is most likely caused by two main reasons: 1) the growth rate in mobile telephony is much higher than for PCs and 2) the content of a few specific rare minerals may be higher in the analog circuitry that enables mobile telephones than in general digital computing[24]. Second, the resource depletion costs of personal

[23]Personal computer results in this plot and all others includes the costs of displays.

[24]The reasoning is supported by higher rare mineral content for mobile electronics cited in Scharnhorst (2005) than in general computing as cited by Wen *et al.* (2005). Most notable is the difference in palladium content.

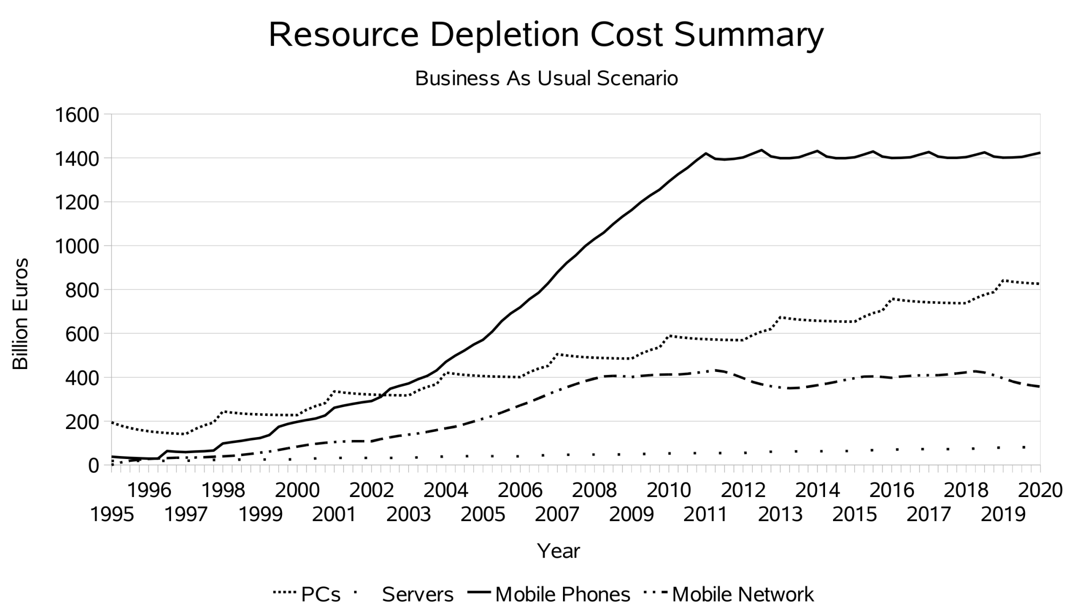


Figure 14: Summary of resource depletion costs associated with the various sectors of ICT under study

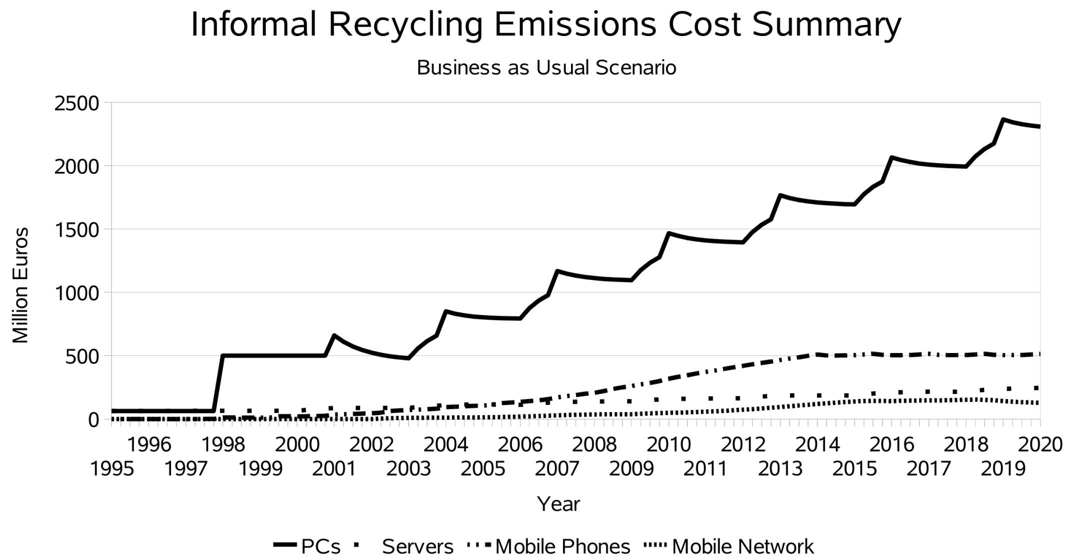


Figure 15: A summary presentation of the emissions cost borne by the informal recycling sectors of China, India, and Africa.

computers versus servers appears to be much closer than one might expect from in-use trends. This can be supported by the understanding that servers are far more complex computers with more intense rare mineral demands. This relationship between personal computers and servers is explored further in section 6.4.

## 6.2 Human and Environmental Damage from Informal Recycling

In this section I would like to present the sustainability cost of emissions in the informal recycling sectors of India, China, and Africa. Unlike the resource depletion costs, these emissions related costs are borne by the local community and environment. From serious health concerns to fouled water and soil, the emissions related to informal recycling are significant. The model has computed the cost of emissions associated only with the 25 minerals under study. It should be noted that there are many other emissions associated with the informal recycling sector, primarily caused by incomplete burning of circuit boards and plastics (Brigden *et al.* 2005). These emissions fell outside of the scope of this model and as such are not included. Therefore, the emissions cost should be considered a low end estimate for the cost of the local sustainability burden that informal recycling communities bear.

Figure 15 shows the BAU cost of emissions in the informal recycling sector for each ICT device. It is interesting to note that the relationship between mobile telephony and personal computing has reversed when accounting for emissions costs. This is perhaps due to the nature of minerals that are recoverable as well as the weak correlation between mineral rarity (EPS resource depletion cost) and toxicity (EPS emissions cost). It should also be noted that the EPS method lacks emissions valuations for several of the rarest minerals in use, thus complicating the creation of a more complete picture of the emissions costs.

The sustainability cost of resource depletion and informal recycling emissions seem to be several orders of magnitude apart. This difference deserves attention. The cost of resource depletion is borne globally, and by future generations perhaps more so than present generations. On the other hand, the damage caused by emissions is predominantly borne by the local communities in which informal recycling takes place. Additionally, these costs are borne by only a handful of generations. If we distribute the costs over the two impacted populations, we find that the large difference shrinks.

| | Model results (million Euros) | Impacted population (billion people) | Per-capita Cost (unit Euros) |
|---|---|---|---|
| Resource depletion cost | 1,990,000 | 6.78 | 300 |
| Informal recycling emissions cost | 1,530 | .03 [a] | 50 |

[a] 1.166 billion for India + 1.333 billion for China + 1 billion for Africa (US Census 2009). Assume 1% of the population is affected.

Table 8: Computation for distributing total ICT sustainability costs to the appropriate impacted populations. Model results for 2008 (BAU) are used. By determining per-capita impact, a comparison of resource depletion and emissions burdens may be more valid.

Table 8 shows an estimation of distributing the sustainability costs across the affected populations. I assume that 1% of the populations of India, China, and Africa are affected, which is probably a high estimate as the informal recycling sectors appear to be consolidated to several locations. A 300 Euro/year cost for resource depletion versus a 50 Euro/year cost to human and environmental health in the informal recycling sectors seems to present a more valid point of comparison. These results could be interpreted to mean that the intergenerational inequity is approximately 6 times as large as the intra-generational inequity, although such a conclusion could be easily contested on criticisms of the EPS valuation scheme.

## 6.3 Quantifying the Export of Harm

Although the transboundary movement of electronic waste is poorly documented and data is lacking, I have attempted to compute a theoretical estimate for the mobile telephones being exported into informal recycling sectors. The results of the model are built upon documented trends in mobile phone usage, turn-over, and end of life disposition. Meanwhile export fractions are best guess estimates. See Section 5.4.2 for details.

Figure 16 presents the results of this exercise in a geographical map. Note the large magnitude of mobile phones in Asia. This end-of-life intensity is indicative of the mobile telephone phenomena which is literally taking off in Asia. Furthermore, it is assumed that there is far greater likelihood that electronics waste meets informal recycling in Asia than it does coming from Europe or North America. This assumption is founded on the existence of a far more organized waste collection program in both Europe and North America.

## 6.4 Drawing Relationships: Connecting the Individual to the Network

Just as any business relies on its back-office to ensure proper operations, personal computing is heavily dependent upon the Internet; the back-office to ICT operations. Similarly, mobile telephony relies on base stations and dedicated switching hardware. Both of these infrastructures are out-of-sight and usually not considered by the individual. The goal in this section is to draw the relationship between

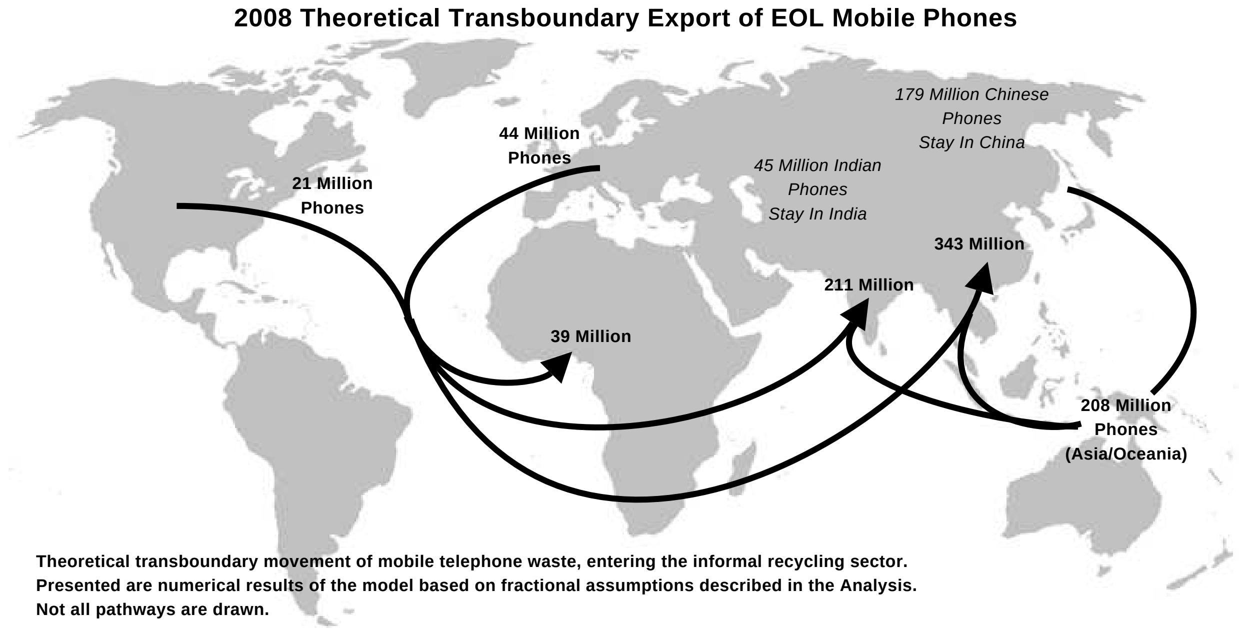


Figure 16: A presentation of the theoretical magnitude of transboundary export of mobile phone waste into the informal recycling sectors. Figures are model results based upon the end-of-life fractions and regional trends presented above.

the micro and the macro level; to show that the use of a PC or a mobile phone has macro-side affects which need to be understood and quantified.

Figures 17 and 18 show the resource depletion ratios of PC:Server and Phone:Network respectively. The resource depletion ratio is smaller than the actual ratio of PC to servers in terms of units in use. The discrepancy can be attributed to the larger complexity of servers, and thus their larger material

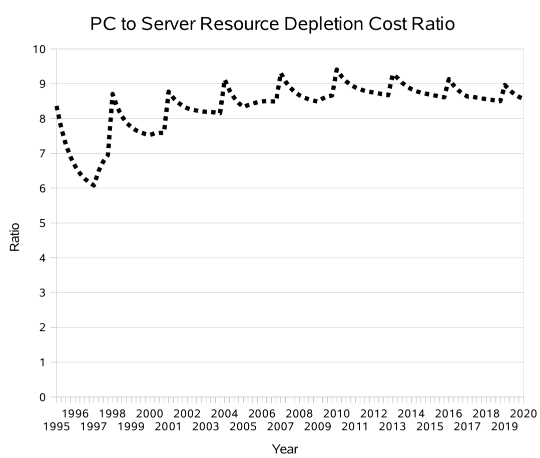


Figure 17: The resource depletion cost of PCs is approximately 8 times as large as that of servers.

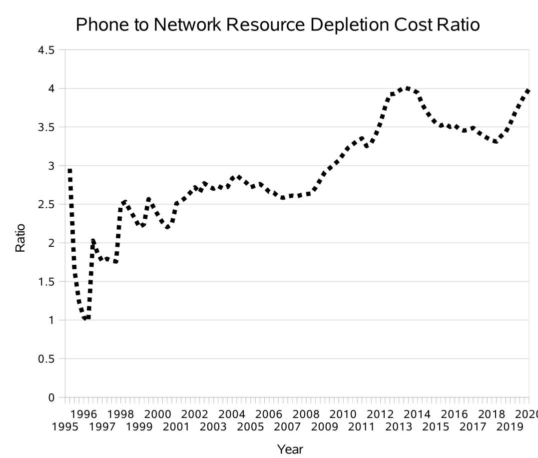


Figure 18: The ratio between mobile phones and network hardware is smaller than PC to server

demand.

The resource depletion ratio between mobile telephones and network hardware is even smaller than for PCs:Servers. This result could be indicative of several factors: it is entirely likely that mobile telephony demands a higher level of network infrastructure, manifested as a high density of antennas and associated hardware that are required to achieve acceptable levels of coverage. There is a proximity component in mobile telephony that is influential in terms of the spatial frequency of base stations. Servers, on the other hand, can be virtually anywhere and still accessible. I should also note that Internet switching hardware was outside the scope of this study. Switching hardware frequency and material intensity could be similar to mobile telephone base stations. It can not be ruled out that inclusion of Internet switching hardware would significantly reduce the PC:Server+Network ratio, bringing the result much closer to the PC:Internet ratio.

## 6.5 Pathways to Mitigating the Sustainability Cost of ICT

The previous sections have attempted to quantify the sustainability cost of ICT by exploring the resource depletion and informal recycling emissions costs. From these results it is evident that ICT has both a high intergenerational and intragenerational cost that has not been accounted for in ICT activities or fees. Policies for internalizing these costs are explored in the discussion section.

Researchers have highlighted that consumer behavior has a large impact on sustainability, especially in ICT where consumers replace devices in relatively short order (Williams 2004, Williams *et al.* 2008, Kahhat *et al.* 2008). PCs typically see a 3 year in-use phase; mobile phones half that (18 months). These same authors suggest that increasing the in-use phase of ICT can help to reduce the sustainability burden. In this section I explore scenarios in which the in-use phase of ICT is lengthened.

I also present scenarios for increased recycling. There are broad goals to achieve greater ICT recycling, especially in Europe (WEEE). The US EPA also has a goal of increasing collection for recycling to 35%.

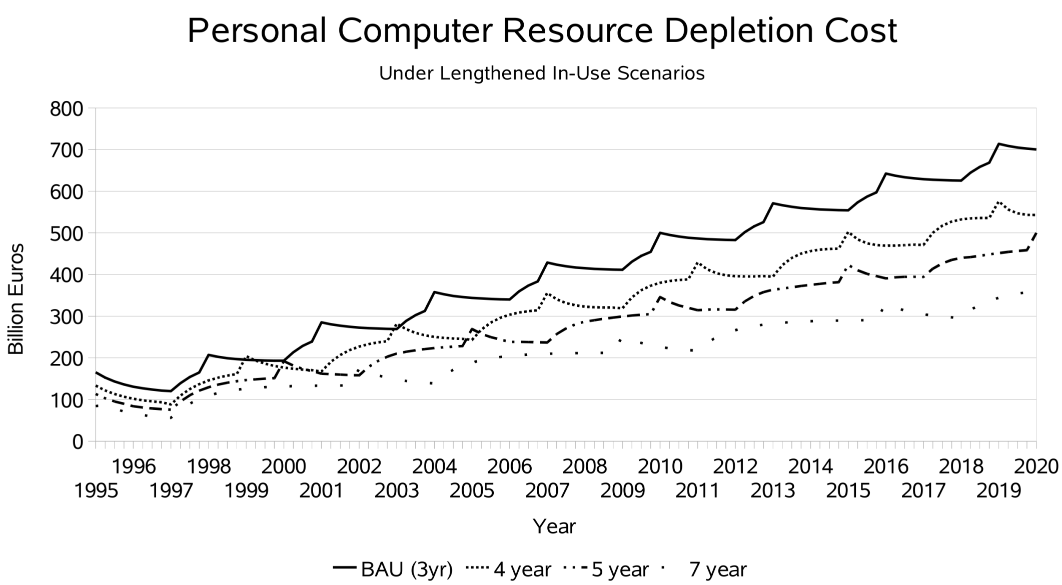


Figure 19: A presentation of the extension of PC in-use phase to different averages.

These policies or goals do not deal directly with the issue of formal vs informal recycling. (Savage 2006) The scenarios included here differentiate between them.

### 6.5.1 Increasing in-use phase

**Personal computers** Figure 19 presents the reduction in resource depletion cost by extending the average in-use phase of personal computers from 3 years to 4, 5, and 7 years. The resource depletion costs decrease significantly with as little as a single year lengthening. It also appears that the incremental improvement decreases slightly as in-use years are added. It is difficult to compare using a given year as the patterns of resource depletion cost are not temporally synchronized between the scenarios.

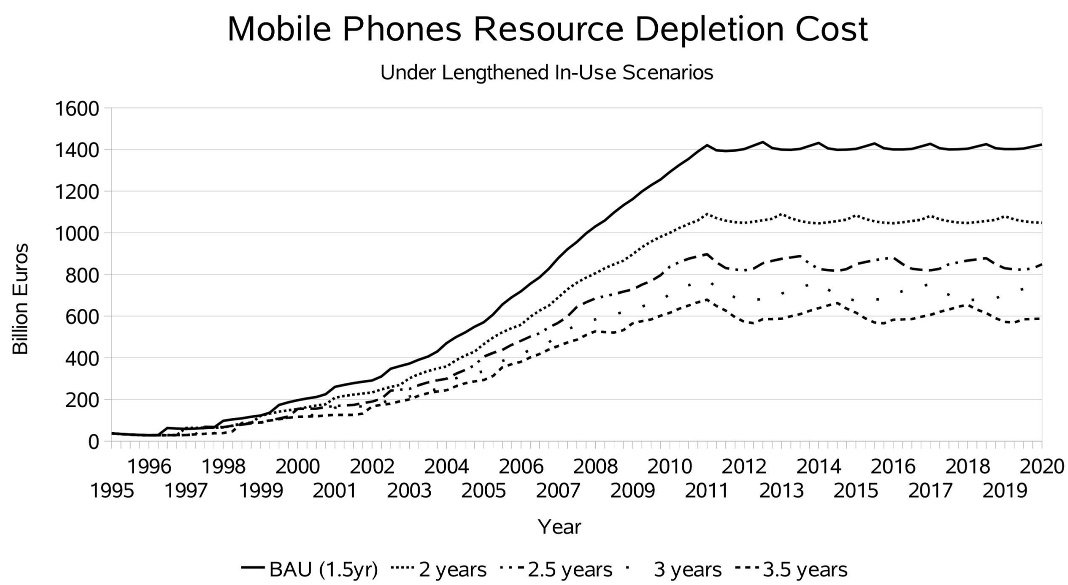


Figure 20: A presentation of the extension of PC in-use phase to different averages. Notice the larger benefits at the initial extension of in-use phase. This is most likely due to the trend being dominated by growth in mobile phones once in-use phase is long enough.

**Mobile telephones** Figure 20 presents the reduction in resource depletion cost by extending the average in-use phase of mobile telephones from 1.5 years to 2, 2.5, 3, and 3.5 years. Table 9 helps clarify the incremental improvement between scenarios for the year 2011. In the table, notice the diminishing rate of return on extending the mobile telephone lifetime. This may be due to the rapid rate of proliferation of mobile telephones negating the savings offered by lengthening of the in-use phase.

| Scenario (In-Use Phase) | Resource Depletion Cost Reduction in 2011 | Incremental Improvement (per year) |
|---|---|---|
| BAU 1.5 years | | |
| 2 years | 23% | 23% |
| 2.5 years | 37% | 14% |
| 3 years | 45% | 8% |
| 3.5 years | 52% | 7% |

Table 9: Reduction of sustainability cost by lengthening mobile phone in-use phase

### 6.5.2 Increasing recycling

Various scenarios for increased recycling are shown in Figure 21. The notation in the legend is Recyc XX-YY where XX is the percentage of end-of-life equipment formally recycled and YY is the percentage informally treated. The business as usual scenario is 2% formally treated and 18% informally treated. The low fractions of formal treatment in the scenarios reflect the reality of PWB recycling today and the difficulties in making it an economically viable activity. What is most striking in this result is that even at 100% collection for recycling, with 10% formally treated and 90% informally treated, the resource depletion cost is only reduced by 6% (in 2010). The best case scenario modeled, where the US EPA target of 35% collection is achieved *and*, more importantly the formal/informal split is 25%/10%, the model shows a 10% reduction in resource depletion cost. This steadfast resource depletion cost highlights the difficulty in mineral recovery in both recycling sectors. It also highlights the extremely rare and conglomerated nature of minerals in ICT, complicating attempts at mineral recovery.

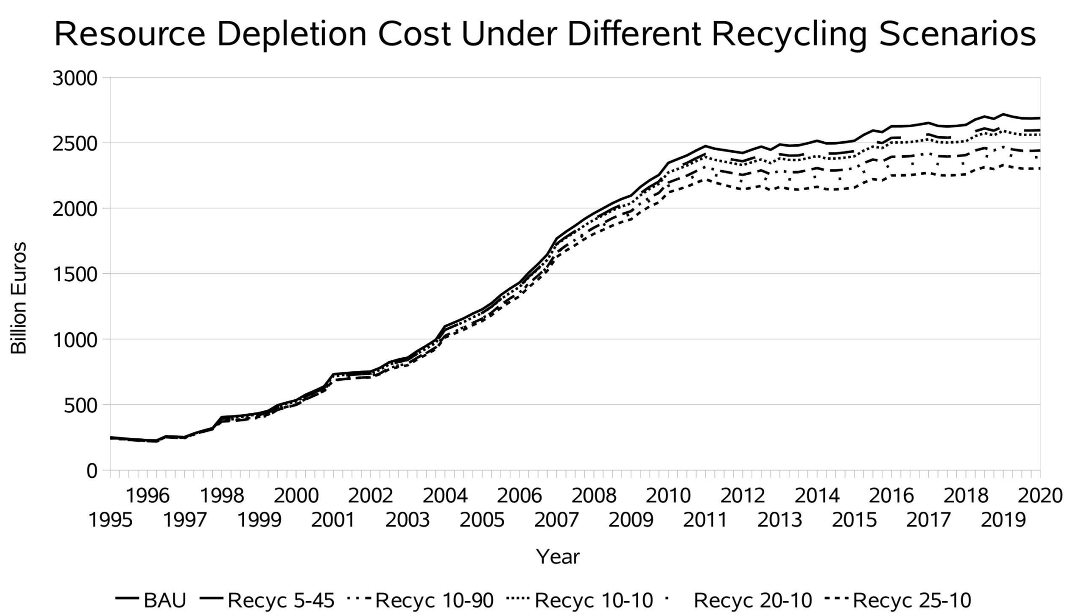


Figure 21: Summary of resource depletion cost under different recycling scenarios

# 7 Discussion

Any study that attempts to economically value externalities is bound to be criticized on numerical grounds. This critique is less relevant to the core value of this study whose main purpose is to convey the magnitude of mineral activity in the ICT sector, the general trends, and how various in-use and EOL scenarios can improve or worsen sustainability. As in the groundbreaking and controversial work by Costanza *et al.* (1997), valuing natural capital and human harm with a sustainability perspective is a challenging and uncertain undertaking.

## 7.1 Ramifications for Sustainability

### 7.1.1 Short-term challenges

The analysis and results have provided insight into a costly mineral flow, accompanied by a damaging toxic waste stream. The intense proliferation trends combined with the rapid device turnover suggest that reducing device flows through the socio-economic system is the quickest pathway to providing a reduction of sustainability cost. This can be accomplished either by reduction or reuse, the first two of the infamous three R's (reduce, reuse, and recycle) of waste management policy. This study further reinforces other researchers' assertions that ICT's direct impact during the use phase is overshadowed by manufacture, materials, and disposal impacts. Thus, lengthening the in-use phase is crucial to reducing the sustainability impact of ICT. Researchers have also suggested that lengthening the in-use phase can be accomplished both via the original user as well as via reuse by second and third hand users, if the appropriate supply chains are set up to support reuse (Williams *et al.* 2008).

The third R, recycle, is both a short and long term challenge. Often, recycling is considered an unquestionable positive. But, the current state of ICT recycling is far from positive, with the informal recycling sector in the South carrying an inequitable burden of toxic damage to health and environment. The analysis suggests that the most pressing challenge in informal recycling is to improve the conditions of those engaged in informal recycling activities. In addition to improving the human conditions, emissions and effluents must be contained.

### 7.1.2 Long-term challenges

The key long term challenge highlighted by this study deals with closing the mineral loops associated with ICT. The rare minerals which are crucial to ICT functionality are slowly dissipating in ICT waste streams. These rare minerals are dispersed in minute quantities in each device. Mineral recovery is challenged by undervaluation, complexity of partitioning conglomerate material like semiconductors, imperfect mineral recovery, and downgrade of mineral quality. All of these factors will need to be continually addressed by policies or innovations if ICT is to move further towards sustainability. It may be that perfect recovery and recycling will never be possible.

### 7.1.3 North - South inequity

The results in this study paint a picture of significantly larger magnitude than that afforded by the classical economic system. The global resource depletion burden is currently around 2 trillion Euros per year, or 300 Euros for every person alive today, whether they use ICT or not. This figure not only highlights the costly resource burden of ICT, but also suggests that half of the human population (predominantly in the conceptual South) is paying a price they can neither afford nor for which they reap any significant benefits.

Furthermore, the informal recycling communities are paying an additional localized sustainability burden of 50 Euros per person. These localized costs are felt more immediately in the form of damage to health and increased mortality. It represents an intragenerational inequity; a cost that should be borne by the users of ICT, but is instead borne solely by informal recycling communities. Here again, the results provide insight into North - South injustice.

### 7.1.4 Grappling with the magnitude

How do the above costs square with the value added in the economy by ICT? Or more simply, how does the sustainability cost compare with worldwide ICT spending.

In 2008, Gartner estimated that worldwide ICT spending was 2.3 trillion Euros (Gartner 2008).[25] This indicates that the resource burden is roughly equivalent to the entire amount of worldwide ICT spending. We could then conclude that if the cost of hardware were to internalize these intergenerational externalities, then the price of ICT devices would need to be at least double their current cost. Achieving such an increase in cost by market mechanisms would be nearly impossible. Instead, Richards (2006) envisions a royalties scheme for minerals extraction that could achieve some degree of internalizing the sustainability cost.

A more appropriate comparison in a cost-benefit analysis might be to weigh the sustainability cost against the value added by ICT. This comparison is complicated by the lack of a reliable recent figure for value added by ICT[26]. This is perhaps a further indication of the degree to which ICT has penetrated human activity. Where does one draw the boundary of economic activities for which ICT has added value? ICT's proliferation has made drawing such bounds extremely challenging.

[25] Gartner published 3.4 trillion U.S. Dollars. Using 1.45 Dollar = 1 Euro, I arrive at 2.3 trillion Euros.

[26] The best figure I found was from 1997, where value added by ICT was estimated at $1.2 trillion U.S. (Kuehr & Williams 2003). But, much has changed within ICT since 1997 as the trends and results in this study both make clear.

## 7.2 Uncertainties and Limitations

### 7.2.1 Quantitative uncertainty

There is a high degree of uncertainty in the results. The EPS valuations offer an uncertainty factor of 2 to 3 based upon standard deviations in a log-normal distribution. The EPS valuations are the most uncertain of all numerical source data, where the uncertainties are not additive. The mineral content data has far less uncertainty than the valuation method. There are two aspects to mineral content, the first referring to mineral reserves. This uncertainty is incorporated into the EPS valuations themselves. The second refers to mineral content in devices. To avoid overestimation, I have always chosen more conservative mineral content values. Considering these factors, the numerical uncertainty of sustainability costs are on the order of a factor of 3 based on standard deviations in a log-normal distribution.

### 7.2.2 Methodological uncertainty

The model is built upon many inferences and assumptions (see the Analysis section) providing a degree of qualitative uncertainty. Quantifying the qualitative uncertainty is much more difficult. Most of this uncertainty is found in end-of-life disposition. As can be seen from the results in 6.5.2, the sustainability costs do not deviate significantly under very different end-of-life scenarios. Therefore, the end-of-life uncertainty provides an insignificant contribution compared with that of the EPS valuations.

Technology is rapidly changing, both manufacturing processes as well as the actual minerals required in the technology. I have assumed that the mineral content of devices today will remain constant into the future. Such an assumption can be argued against from several points. For example, miniaturization should result in less mineral to accomplish the same function. Therefore we could expect mineral content of mobile phones to reduce over time. A counter argument suggests that while mineral content might reduce per function, mobile phones will expand their feature sets, as they have already done in smart phones such as the iPhone, demanding even greater mineral content per device. Such trends are difficult to predict and therefor I have chosen to model an unchanging mineral content.

The choice of valuation method presents its own uncertainty. Selecting another LCIA method would have resulted in different results. One reason for this is that LCIA methods often integrate a discount rate for future generations, while the EPS method does not. Therefore, the use of a different LCIA method would most likely result in a reduced intergenerational cost, bringing resource depletion costs closer to the costs in the informal recycling sectors. I deliberately chose EPS for this study because the use of a discount rate disenfranchises future generations to varying degrees. The EPS method was therefore better suited to represent the principles of sustainability than most other LCIA methods which are more concerned with near-term environmental and health impacts from the product life-cycle.

Any method of valuation has a built-in subjectivity founded in its philosophical underpinning, some more explicit than others. This assertion extends to our present economic system which uses a *collective* subjective valuation. It's main drawback is that all are not equally represented in the collective. And, many are entirely excluded from the collective, including future generations and the economically powerless.

I have used a bottom-up approach in this study. Motivated by a need for details of specific minerals, I could not use a top-down approach, such as economic input-output (EIO) data which are rather dull in their specificity. What I have gained in detail, I have most likely lost in data quality and in completeness of scope. Thus there is uncertainty due to the bottom-up approach. Most likely, this uncertainty is in favor of under-estimating mineral intensities, as significant aspects of ICT could easily fall out of the bounds drawn in a bottom-up method. Many of the studies which I have leveraged for the foundation of my bottom-up construction are based on a hybrid method, one that combines elements of EIO and a bottom-up approach to provide a more complete LCA. Usage of a hybrid approach here may have improved accounting for the whole life-cycle, especially the manufacturing stages which were explicitly excluded from this study.

### 7.2.3 Limitations

This study should not be misinterpreted as a broader life-cycle impact assessment of ICT, but rather a very focused assessment of rare and toxic minerals embedded in ICT devices, their magnitude, and their sustainability cost at the global level. It's applicability in a cost-benefit analysis is limited as this study provides a rather detailed and focused assessment of the societal cost of a very specific aspect of ICT: rare minerals intensity.

The focused scope and narrow bounds have excluded bulk materials such as plastics, the manufacturing stage, and especially batteries. While these results are extremely useful in highlighting the intense use and waste throughput of rare minerals, the scope and bounds suggest two points of caution in their further use: 1) many significant sectors of ICT have been excluded from the accounting and 2) several aspects of the included ICT sectors have not been accounted. The results are then appropriate as a rough low-end estimate as well as a method that can be built upon in order to construct a more complete sustainability assessment of ICT.

# 8 Reducing ICT's Mineral Impacts: Opportunities and Challenges

The analysis and results suggest that there are many behavioral and structural hurdles inherent in ICT that challenge improving sustainability. For example, innovation and low cost of ICT induces faster turnover, leading to greater profits that simply result in more innovation. This reinforcing cycle has played out just as Moore foreshadowed, and the sustainability burden grows with it.

In the sections below, I build upon the results and address many of the common perceptions and hopes of ICT in the context of its mineral intensity. I begin with the manufacturing phase, and address the suggestion that industry has opportunities to adjust the mineral intensity and improve sustainability. I then deal with the in-use and disposal phases. The concerns during the in-use phase are mostly behavioral and structural, while the end-of-life problems relate more to legislation, imperfect markets, and externalities.

## 8.1 Manufacturing

### 8.1.1 Substitution

Any analysis of material flows and associated limits inevitably comes face to face with the realities of substitution. Substitution discussions can follow two threads: that technology will enable the use of substitute materials, or alternatively, that technology or intellectual capital itself can substitute for material capital. (Herring 1999, Solow 1974) The latter is similar to a conceptualization of dematerialization that is dealt with in Section 8.1.2.

Substitution suggests that the material capital that is required to enable ICT is not unique, and that research and advances in technology will result in the substitution of materials whose costs grow too high (as a result of depletion or extraction issues). For example, the auto industry has transitioned back and forth between platinum and palladium dominated mixtures in catalytic converters (Richards 2006).

One potential substitution that may take place in the next 10 years is the substitution of Indium, a key ingredient in LCDs, with the carbon nanotube graphene (Blake *et al.* 2008). Research indicates that nanoparticles (Rickerby 2007) and other novel molecules (Kanjolia 2007) have promising potential and substitution properties, especially in the realm of semiconductors. While there is promise, nanoparticle environmental and health risks are still a matter of much concern and uncertainty (Rickerby 2007). As such, substitution could actually exacerbate sustainability concerns.

A clear understanding of the physical limits imposed by the finite nature of our planet suggests that substitution has its own limits. Each mineral is endowed with a unique set of properties that are finitely substitutable. Richards pragmatically summarizes the discussion:

> although I have great faith in the technological ingenuity of the human species, this process is merely one of dodging the bullet, and delaying the day when we must face up to the fact that an exploding human population is consuming the finite resources of a small planet at an ever-increasing rate. (Richards 2006:p. 328)

See also Newman & Dale (2008) for a more thorough discussion of the limits to substitution.

### 8.1.2 Dematerialization

As this study has been an assessment of the material intensity of ICT in the context of intergenerational equity and intragenerational justice, the concept of dematerialization should be addressed. I perceive a dichotomy between the academic definition and the lay usage of dematerialization. As such, I offer the following two views of dematerialization:

- Increasing resource efficiency of a process is a suitable technical definition for dematerialization (Hilty *et al.* 2006a). It may be expanded to suggest that if the resource flow per unit GDP is reduced, dematerialization is being achieved.
- A more casual view of dematerialization may more accurately be called *miniaturization*. For the lay observer, miniaturization of ICT devices may be associated with dematerialization of consumption.

**Miniaturization** I address the second point first, and then move into a broader discussion valid for both points. While miniaturization may reduce the mass of minerals in the final product, ICT miniaturization is typically enabled through use of even more rare minerals and more energy intense manufacturing processes (Plepys 2002, Williams *et al.* 2002). If we consider the fossil fuel inputs into manufacturing processes as part of the material burden of an ICT device, miniaturization does not correlate well with dematerialization[27]. For ICT devices and electronics in general, miniaturization should not be confused with dematerialization.

Miniaturization of ICT devices has often led to more affordable devices[28]. With increased affordability, there will be increased consumption and a society-wide rebound effect. Hilty *et al.* (2006a) presents a look at mobile phones in Switzerland from 1990 to 2003. While the mass of a mobile phone reduced from 350g to about 100g, over the same time, the total mass of mobile phones sold per year went from 10T to about 450T. Miniaturization also works against hopes of recycling and mineral recovery. As devices get smaller, users are more likely to simply discard ICT devices in household waste flows, or worse yet, discard them as litter.

Within the framework of sustainability, focus on the aggregate mass of resource flow obfuscates a more important concern: the nature of the materials and minerals involved in the resource flows. For example, would it be considered a reasonable trade off to reduce the material intensity of a process 10-fold by using rare and toxic materials? In the case of ICT, the increased use of rare minerals highlights concerns of intergenerational equity associated with resource depletion, a core focus of this study. Toxic materials imported into informal recycling communities, poisoning their air, water, and deteriorating their health raise serious intragenerational concerns.

**Relative dematerialization** The technical definition of dematerialization which is a ratio of economic productivity to resource flow seems to me untrue to the literal construction of the word. Under a neo-classical economic growth paradigm, this sort of dematerialization results in an ever increasing material throughput. As highlighted in the previous paragraph, it also raises the spectre of treating all materials alike, as if 1 kg of platinum was the same as 1kg of wood. If sustainability demands intergenerational equity, this is not possible in a climate of increased material throughput, especially for rare minerals which constitute the flagship ingredients to the 'ubiquitous computing society' envisioned by some.

**Ethereal economy** Having discussed the direct relationship between ICT and materials, I would like to touch upon hopes in a knowledge-based or ethereal economy. Humans are at the end of the day,

[27] For example, Williams *et al.* (2002) calculates 1.7kg of resources to manufacture a single 2g computer chip: an input to output ratio of over 800:1.

[28] Miniaturization may not be the primary cause of price reductions, but there is a strong relationship between the two, and is related to Moore's Law (see Section 2).

nothing if not real material beings with real material needs and desires. While we may send e-mails instead of letters, read on-line in place of on paper, we still eat, travel, shop, consume clothes and furniture, and all with abandon. Each dollar gained within the ethereal economy may grow and multiply via the pathways of intellectual capital. But, I argue that most intellectual capital is eventually traded in for material goods. Therefore, the growth that is so welcome in the ethereal economy results in a corresponding growth in the material economy. The two are inseparable.

William Rees of Ecological Footprint fame has argued that intellectual capital based economies and service based economies, thus ethereal economies, are far from dematerialization precisely for this macro-level, economy wide growth potential and wealth. (For more, see a discussion of the topic in Herring (1999), and particularly the ideas of Rees).

Despite all claims to 'virtualization' proffered by ICT, it must be remembered that the appearance of virtualness ends somewhere. At this juncture, substantive, physical, material and energy demands ensue. What is virtual is a temporal dislocation of the physical presence from the dimension of the user to a far off, hidden, ignored dimension, be it in a server farm (as I have shown in this study), or a far off workforce. It may be paralleled loosely with the disconnect from reality offered by the modern day supermarket. The typical supermarket customer has completely lost the awareness that vegetables must be grown somewhere, by someone or some machines, and utilize many inputs before being transported and preserved on its way to the supermarket. The virtualization offered by ICT is merely the same charade on steroids.

### 8.1.3 Modularity

Environmentalists and advocates of sustainability often suggest that the main problem with ICT is its lack of modularity; in other words, it is difficult, impossible, or useless to upgrade devices. I believe that hope in modularity lacks a clear understanding of the complexity of hardware and the rate of innovation within the ICT industry. Having worked in the digital circuits industry for over 8 years, I do not believe modularity of ICT can come to fruition until the technology itself reaches maturity. Maturity will enable devices to be designed with modularity in mind as a mature ICT industry focuses more on component interoperability at the hardware level, rather than maximizing performance (or utility). When this will occur is a matter of unending debate. Considering the immense momentum and financial capital invested in research facilities and industry (Grier 2006), I do not foresee it occurring in the short-term. Until then, industry and consumers will prioritize innovation over modularity and longevity.

## 8.2 ICT Usage

### 8.2.1 Reducing turnover, increasing in-use phase

The model results have shown that one of the most important factors in minerals depletion and hazardous emissions is the rate of device turnover. This is not only an issue in rich nations. Device turnover appears to be high in all markets. Somehow, the in-use phase of devices must be extended, the same conclusion reached by Williams (2004) and Kahhat *et al.* (2008). Such behavioral shift will be extremely challenging considering the low cost of many ICT devices and the rapid rate of technological innovation, encouraging people to shift to new devices with the latest features.

High turnover contributes to industry profits. Short-term mobile phone contracts that include free or low-cost phones may drive the 18 month mobile phone turnover. Pathways to reduce device turnover will most likely require intervention from outside the free market, but may not be very effective. Waste handling fees charged at the point of purchase in certain markets (e.g. California) have not appeared to slow consumption rates, most likely because the fees are nominal compared to the cost of devices.

Determining an appropriate and effective policy instrument that permits a certain level of proliferation of ICT, but at the same time limits the turnover is a fertile area for study. Balancing proliferation with turnover is important in order to equitably enable the opportunities of ICT while limiting the resource depletion and emissions threats.

### 8.2.2 Rebound effects

In the context of a growing Green IT movement advocating for better energy efficiency of computers, servers, and server facilities, (Gartner 2007) it is crucial to keep in mind the system response to such efforts. Now is an opportune time to expand and apply the long standing discussion around rebound effects specifically as they relate to ICT and technology enabled activities.

I include here a discussion of rebound as relevant not only to energy use in ICT, but also to the question of rare mineral use in the ICT sectors. Microeconomic efficiencies of energy savings and reduction of materials used in each ICT device can induce macroeconomic growth, via reduce cost per utility. If ICT can be treated as a general-purpose utility, like energy (as suggested by Plepys (2002) and Kuehr & Williams (2003)), then I think the rebound effect is extremely relevant. Any attempt to make ICT more efficient (especially in production) or less material intensive will reduce the cost of ICT. Cheaper devices will result in more intense consumption of ICT, both increased proliferation and more rapid turnover. A quick look at the historical trends of ICT cost vs ICT consumption shows this to be true, and is in many ways the socio-economic ramifications of Moore's law[29].

One may conclude from my results that ICT should be made more efficient: rare minerals content should be reduced. Such a reduction would most likely yield cheaper ICT devices and could result in even greater growth in proliferation, nullifying, if not reversing, any savings gained from efficiency. Although resource intensity reduction is needed, it must be coupled with other economic signals to address the rebound effect. I touch upon this further below.

Binswanger (2001) goes further in a discussion of rebound in the context of technological progress and sustainability. Binswanger (2001) turns attention to applying rebound to time-saving innovations; both those that save work-time per task as well as reduce time required to consume an equivalent unit of service. ICT can be considered a clear example of a time-saving innovation[30]. Communications happen quicker and at lower cost to the consumer. Documents are produced faster, without a secretary or type-writer, and in significantly greater abundance. Music, photos, and movies can be *consumed* more easily and faster. E-commerce enables quick "click consumption". Thus, ICT, as a time-saving innovation induces more consumption, perhaps both at the micro and macroeconomic levels. A theoretical and more detailed application of the rebound effect on the ICT society seems appropriate in light of the time-saving and consumption inducing nature of ICT.

### 8.2.3 The office - home redundancy

In developed countries, it seems that many people effectively have more than one computer or mobile phone[31]. One reason for this appears to be dual 'ownership', one at work and one at home. While in

[29] Moore's Law is briefly discussed in Section 2

[30] It could be argued that many an Internet users wastes more time on-line than is saved, but this misses the point. In the context of this discussion, ICT is primarily a time-saving innovation.

[31] This is supported by 110% mobile phone penetration in Europe and casual observation.

most cases a single machine could effectively provide the same level of service at both locations and in both realms.

Addressing this redundancy could reduce some of the material flows discussed above. As there is a growing preference for laptops, the mobility of machines is well suited to serving both home and office roles. There are some serious structural hurdles to such a dual role. Corporations are typically hyper-concerned with their data as well as with any data an employee might download (strict corporate ethics guidelines).

What might a solution to these conflicting interests look like? For example, one could conceive of a single laptop design containing two hard disks, physically separating corporate and personal realms, while the rest of the laptop hardware would not need to be duplicated. The ability to easily switch between work and personal modes could be integrated into this dual purpose laptop. Further investigation should be conducted with regards to creating single machines that meet the expectations of both corporations and individuals, while at the same time reducing some of the sustainability cost.

### 8.2.4 Telecentres: alternatives to one laptop per child

The one laptop per child project may seem admirable at first. But in rural Africa and India, a laptop without Internet connectivity and a stable electricity supply could be considered a waste of resources. Some have claimed that the one laptop per child effectively resulted in a competitive effort by industry to further miniaturize and reduce the cost of a full fledged laptop for not so altruistic goals. Such accusations aside, the one laptop per child project is easily a geographically misplaced Western solution to a Western problem. Western technology has many cultural and language barriers that a $100 laptop can not overcome. The intense proliferation of laptops as envisioned by the project would result in significantly more resource depletion and hazardous emissions costs than the business as usual scenario presented above. (Kraemer *et al.* 2009)

Providing rural and poor people an opportunity to reap some of the benefits and opportunities of ICT demands understanding the social context of their situation (Kraemer *et al.* 2009). The digital divide is not only about distributing laptops, it is also about addressing the differences in the ability to take advantage of ICT (Kuehr & Williams 2003). Better success could be experienced via telecentres and open computing locations (Rao 2008). Telecentres are established in rural areas by government and/or NGOs, with awareness of the needs of the community, Internet connectivity and stable power. The telecentres provide a computing environment open to the community at large. Often, individuals more familiar with ICT are there to assist and guide. Such a setup provides a shift from the capitalist consumption and ownership model while providing a more efficient and successful approach to closing the digital divide. If resources on the scale of $20 million that the one laptop per child project has already attracted (Kraemer *et al.* 2009) were directed to establishing telecentres, the opportunities of ICT could be more broadly distributed with a much reduced sustainability cost.

## 8.3 End-of-life

### 8.3.1 Complexity of recycling

The results have made clear that even with a high level of collection for recycling and a high rate of formal recycling, there will remain a large resource depletion cost. The analysis provides insight into the reasons. Mineral recovery in any recycling process of alloys and otherwise conglomerate material (like electronics) is inefficient and imperfect, often resulting lower grade mineral recovery. (Richards

2006) There is therefore a constant rate of dissipation of valuable resources, similar to the never ending thermodynamic march towards entropy.

Continued high resource depletion costs suggest that the policy focus on electronic waste treatment and mineral recovery may be both insufficient and misguided with regards to sustainability concerns. Williams *et al.* (2008) has gone further to suggest that increased collection for recycling has inadvertently caused more harm than it has helped because of the undue burden placed on informal recycling communities. The results in this study would appear to support such an assertion.

### 8.3.2 False prices and imperfect markets

Much of the topics under consideration in this study come down to market imperfections. The basic charge is that rare minerals do not carry a price commensurate with their actual value to society or future generations (Richards 2006). Instead, minerals are typically priced near the cost of extraction, with a little price elasticity dependent upon short-term supply and demand. As such, there is little market incentive to conserve or recover minerals from electronic waste.

This study has shown that legislation regarding electronic waste has not been effective at actually recovering a significant portion of the mineral content. Legislation in most cases has addressed collection of e-waste and recovery of bulk materials. Lacking economic incentives, the technologies needed to better treat electronic waste are unlikely to be developed. Instead, only informal recycling sectors appear economically viable. The sustainability ramifications of this reality have been made clearer by the results of this study.

Kahhat *et al.* (2008) explores a deposit based market scheme for increased recycling in the US, similar to the deposit system used for beverage containers. Such a scheme addresses collection, not necessarily the cost of mineral recovery. Perhaps the most effective pathway to increasing the rate of formal recycling would be to internalize the full cost of recycling at the point of purchase. This fee can not simply be a recycling collection fee. It must actually cover the entire cost of collection, recycling, and mineral recovery in formal recycling sectors.

### 8.3.3 Unequal burdens

One of the most striking outcomes of this study is how imperfectly our economic system represents the core tenets of sustainability. Our economic system tacitly enables the export of electronic waste into the informal recycling sector. It is the cheapest disposal avenue for the rich. Meanwhile the poor in the informal recycling sectors experience a tremendous sustainability cost from the hazardous emissions. If these externalities were appropriately accounted for, if the consumers and disposers of electronic waste bore the full burden of informal recycling, it is improbable that these hazardous activities would not be amended into safer, more formal recycling efforts. Instead, at present, dumping is far more economically viable than proper treatment. It is a shame that informal recycling has received so much media attention, yet so little has been done to improve the conditions in the informal recycling sector.

It is highly unlikely that informal recycling activities will cease. With increasing mineral prices, informal activities are likely to intensify. Western governments so concerned with electronic waste collection should turn their attention towards assisting the improvement and cleanup of informal recycling activities. While these activities are certainly not registered businesses, enough is known about their whereabouts that outreach should be possible. With NGO cooperation, simple improvements in equipment, procedures, and ventilation could greatly improve the human health conditions for workers and reduce environmental emissions.

# 9 Conclusion

I have investigated Information and Communication Technology's (ICT) rare and hazardous minerals intensities, and computed sustainability costs associated with resource depletion and informal recycling. In 2008, the global resource depletion cost of ICT was 1.9 trillion Euros, while emissions in the informal recycling sector caused 1.5 billion Euros worth of damage. Distributing these costs across the impacted populations, provides a per-capita cost of 300 Euros globally and 50 Euros in the informal recycling communities, an extra burden that those engaged in informal recycling can hardly afford. Scenarios have shown that increased recycling has limited ability to improve sustainability. Meanwhile consumer behavior has a greater potential for improvement via reducing device turnover. In all scenarios, strong sustainability remains elusive for complex technologies, like ICT, that are so fundamentally based upon rare minerals.

The focus must be on reducing device redundancy and turnover. The marginal improvements in opportunities from multiple, redundant devices can not justify the sustainability cost. Despite low production costs for ICT devices, their purchase price should internalize the cost of formal recycling and mineral recovery. Legislation to achieve higher rates of collection for recycling are initial steps in the right direction. But, legislation must be expanded and enforced to address the increasing trade in e-waste that has resulted. Additionally, governments and NGOs should engage with informal recycling sectors to improve conditions for workers and the environments they are damaging. Meanwhile, rural areas and poor communities would be better served by telecentres than by proliferation of devices. Ultimately though, it may be that legislative mechanisms are insufficient and internalizing sustainability damages politically infeasible.

ICT's resource intensity is of too great a magnitude, and its macro scale impacts on growth are too great for ICT induced efficiency and recycling to resolve. While it may be that ICT inherently has little hope of meeting strict definitions of sustainability, the results do show potential pathways to incremental improvements. In evaluating these opportunities, the social and economic conditions can not be ignored. A solution suitable for Europe and North America may be wholly out of place in Africa or rural Asia. In the opportunities for mitigating the unsustainable aspects of ICT, the difficulty lies in individual behavioral choices and established structures hindering more sustainable outcomes.

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# A EPS background

EPS was developed initially at at the behest of Volvo in cooperation with the Swedish Environmental Research Institute. Subsequently, it was developed further by the Centre for Environmental Assessment of Products and Material Systems at Chalmers in Goteborg, Sweden. EPS is a damage focused method, using a willingness-to-pay (WTP) approach to valuing damage to "five safeguard subjects": human health, biological diversity, ecosystem production capacity, abiotic resources, and cultural and recreational resources (Baumann & Tillman 2004). These safeguard subjects were chosen based upon the United Nation's RIO declaration (UNCED 1992, Steen 1999a).

Steen (1999a) presents a thorough discussion regarding the development of the WTP values used. A summary of the salient numbers are included here. For each year of lost life, the WTP figure is 85,000 EUR. Severe morbidity is valued at 100,000 EUR per person, while moderate and mild morbidity are valued at 10,000 EUR per person per year. Nuisances, like noise and reduced visibility are valued at 100 EUR per person per year. (All Euros in this paragraph are 1998 Euros).

It is far more difficult to apply contingent valuation methods on resource depletion. There exists no way to ask future generations how much they are willing-to-pay for certain resources. As such, Steen develops a model for sustainable resource extraction methods, based upon the most sustainable practices known for resource extraction from ordinary rock (as opposed to mineral rich ores). The model paints a painful picture, but one that represents future generations equitably, as they are voiceless in our present economic valuation systems. The resource depletion costs for the 25 minerals of focus in this study are presented in Table 10.

# B Stock and flow model data

## B.1 Mineral list, annual production, reserves, and resource depletion cost

All mineral data is from the USGS (USGS 2009). Indium values are from USGS 2008. In 2009, the USGS withdrew estimates of indium's reserve base. Platinum reserve base represents the entire platinum group metals, including palladium. Annual min production figures for cerium and lanthanum were fabricated for the model. EPS values are 1998 Euros from Steen (1999a;b). Number in the first column indicates the model array index.

| # | Mineral | Annual Mine Production in 2008 (1000 tons) | Reserve Base (1000 tons) | EPS Resource Depletion in (Euros/kg) | Primary Producers (in order of production) |
|---|---|---|---|---|---|
| 1 | aluminum | 39700.000 | | 0.44 | China, Russia, Canada, US |
| 2 | antimony | 165.000 | 4300 | 9580.00 | China by large margin |
| 3 | arsenic | 53.500 | 1605 | 1490.00 | |
| 4 | beryllium | 0.180 | 80 | 958.00 | US, China, Mozambique |
| 5 | bismuth | 5.800 | 680 | 24100.00 | China, Mexico, Peru |
| 6 | bromine | 298.000 | Large | 0.00 | Israel, China, Jordan, Japan |
| 7 | cadmium | 20.800 | 1200 | 29100.00 | China, Korea, Kazakhstan, Canada, Japan, Mexico |
| 8 | cerium | 1000.000 | | 45.20 | No data, rare earth element. |
| 9 | chromium | 21500.000 | 12000 | 84.90 | S. Africa, Kazakhstan |
| 10 | copper | 15700.000 | 1000000 | 208.00 | Chile, US, Peru, China |
| 11 | cobalt | 71.800 | 13000 | 256.00 | Congo, Canada, Zambia, Australia, Russia |
| 12 | gold | 2.330 | 100 | 1190000.00 | China, S.Africa, US, Australia, Peru, Russia |
| 13 | indium | 0.568 | 16 | 48700.00 | China, others but significantly less than China. |
| 14 | steel | 2200000.000 | 160000000 | 0.96 | China, Brazil, Australia, India |
| 15 | lanthanum | 1000.000 | | 92.00 | No data, rare earth element. |
| 16 | lead | 3800.000 | 170000 | 175.00 | China, Australia, US, Peru |
| 17 | mercury | 0.950 | 240 | 53000.00 | China, Kyrgyzstan |
| 18 | molybdenum | 212.000 | 19000 | 2120.00 | US, China, Chile, Peru |
| 19 | nickel | 1610.000 | 150000 | 160.00 | Russia, Canada, Indonesia, US |
| 20 | palladium | 0.206 | | 7430000.00 | Russia, S. Africa |
| 21 | platinum | 0.200 | 80.0 | 7430000.00 | S.Africa, Russia |
| 22 | silver | 20.900 | 570 | 54000.00 | Peru, Mexico, China, Chile |
| 23 | tantalum | 0.815 | 180 | 1980.00 | Australia, Brazil, Ethopia |
| 24 | tin | 333.000 | 11000 | 1190.00 | China, Indonesia, Peru |
| 25 | zinc | 11300.000 | 480000 | 57.10 | China, Australia, Peru |

Table 10: Rare and hazardous minerals analyzed in the model. All values in thousand metric tons.

## B.2 PC mineral content

The minerals flow estimates for personal computers are based on a composite of data presented in Williams *et al.* (2008), Kuehr & Williams (2003), Scharnhorst *et al.* (2005), Scharnhorst *et al.* (2006), and Wen *et al.* (2005). Using this method, the total resource depletion cost per PC is about 1,090 Euros (1998 value). The number in the first column indicates the model array index.

| # | element | grams / PC | EPS resource depletion cost in 1998 Euros/kg | Euros/PC Resource Depletion Cost | EPS Uncertainty |
|---|---|---|---|---|---|
| 1 | aluminum | 440 | 0.44 | 0.19 | 2.0 |
| 2 | antimony | 2.4 | 9580.00 | 22.99 | 3.0 |
| 3 | arsenic | 0.06 | 1490.00 | 0.09 | 2.2 |
| 4 | beryllium | 0.28573 | 958.00 | 0.27 | 3.0 |
| 5 | bismuth | 0.23 | 24100.00 | 5.54 | 2.2 |
| 6 | bromine | 10.8 | 0.00 | 0.00 | 1.0 |
| 7 | cadmium | 3.28 | 29100.00 | 95.45 | 2.2 |
| 8 | cerium | 0.02 | 45.20 | 0.00 | 3.0 |
| 9 | chromium | 0.05 | 84.90 | 0.00 | 3.0 |
| 10 | copper | 670 | 208.00 | 139.36 | 3.0 |
| 11 | cobalt | 0.03320 | 256.00 | 0.01 | 3.0 |
| 12 | gold | 0.08 | 1190000.00 | 95.20 | 3.0 |
| 13 | indium | 0.04 | 48700.00 | 1.95 | 3.0 |
| 14 | steel | 2235 | 0.96 | 2.15 | 2.2 |
| 15 | lanthanum | 0.0120 | 92.00 | 0.00 | 3.0 |
| 16 | lead | 27 | 175.00 | 4.73 | 2.2 |
| 17 | mercury | 0.00360 | 53000.00 | 0.19 | 2.2 |
| 18 | molybdenum | 0.0620 | 2120.00 | 0.13 | 3.0 |
| 19 | nickel | 4.5 | 160.00 | 0.72 | 2.2 |
| 20 | palladium | 0.02000 | 7430000.00 | 148.60 | 3.0 |
| 21 | platinum | 0.06600 | 7430000.00 | 490.38 | 3.0 |
| 22 | silver | 0.4000 | 54000.00 | 21.60 | 2.2 |
| 23 | tantalum | 0.28573 | 1980.00 | 0.57 | 3.0 |
| 24 | tin | 47 | 1190.00 | 55.93 | 2.2 |
| 25 | zinc | 21 | 57.10 | 1.20 | 2.2 |

Table 11: Mineral estimates and resource depletion costs per PC.

## B.3 Construction of server mineral content

Figure 22 shows the server models used to represent each server category. These were the top sellers worldwide in 2005 according to Koomey (2007). Manufacturer technical specifications were used to determine number of processors, mainboards, and I/O boards. A total PC Multiplier was created using the formula:

$$\text{Server PC equivalents} = 1\ \text{PC} * \#\ \text{of Cores} + 0.25\ \text{PC} * \#\ \text{of I/O Boards}$$

In the model, each server is assumed to have the mineral content of as many PC's as the Server PC equivalents indicates. See more details in 5.2.3

| ***Server Category*** | **Max Processors (cores)** | **Max Mainboards or MCMs** | **Estimated or Max I/O Boards** | **Weight Fully Configured (kg)** | | **Cores * 1 PC** | **I/O Boards * 1/4 PC** | **Total PC Multiplier** |
|---|---|---|---|---|---|---|---|---|
| **High-End** | | | | | | | | |
| Sun E25K | 72 | 18 | 72 | 1122 | | 72 | 18 | **90** |
| HP 9000 Superdome | 128 | 16 | 192 | 1196 | | 128 | 48 | **176** |
| IBM P5 595 | 64 | 8 | 432 | 2458 | | 64 | 108 | **172** |
| | | | *Unweighted Average:* | *1592* | *Unweighted Average:* | *88* | *58* | **146** |
| **Mid-Range** | | | | | | | | |
| IBM i5 520 | 2 | 1 | 126 | ?? | | 2 | 31.5 | **33.5** |
| IBM p5 570 | 4 | ?? | 14 | 65 | | 4 | 3.5 | **7.5** |
| Sun V490 | 4 | 2 | 6 | 44 | | 4 | 1.5 | **5.5** |
| | | | *Unweighted Average:* | *54.5* | *Unweighted Average:* | *3.33* | *12.17* | **15.5** |
| **Volume Srvr** | | | | | | | | |
| Dell 2850 | 2 | 1? | 3 | 27 | | 2 | 0.75 | **2.75** |
| HP DL360 | 2 | 1? | 2 | 16.82 | | 2 | 0.5 | **2.5** |
| HP DL380 | 2 | | 4 | 27.27 | | 2 | 1 | **3** |
| | | | *Unweighted Average:* | *23.7* | *Unweighted Average:* | *2* | *0.75* | **2.75** |

Figure 22: Computations for Server Multiplier Values

Volume Server Specs:
`http://www.sun.com/servers/highend/sunfire_e25k/specs.xml`
`http://h18000.www1.hp.com/products/quickspecs/11721_div/11721_div.HTML#Technical%20Specifications`
`http://www-03.ibm.com/systems/p/hardware/highend/595/specs.html`

Mid-Range Server Specs:
`http://www-07.ibm.com/servers/eserver/hk/iseries/hardware/smallmed/520/specifications/`
`http://www-03.ibm.com/systems/power/hardware/systemp/midrange_highend/570/specs.html`
`http://sunsolve.sun.com/handbook_pub/validateUser.do?target=Systems/SunFireV490/spec`

High-End Server Specs:
`http://www.dell.com/downloads/global/products/pedge/en/2850_specs.pdf`
`http://h10010.www1.hp.com/wwpc/us/en/sm/WF06a/15351-15351-3328412-241644-241475-1121486.html`
`http://h10010.www1.hp.com/wwpc/us/en/sm/WF06a/15351-15351-3328412-241644-241475-1121516.html`

## B.4 Printed wiring board assembly content

Populated printed wiring board assembly (PWBA) aggregate data is synthesized from Scharnhorst *et al.* (2005) and Wen *et al.* (2005). There in one significant point of discrepancy between both studies, which is understandable given the aggregate nature of the result and the heterogeneous nature of PWBAs. Palladium stands out as being uniquely more valuable in analog devices used for radio communication, in the case for mobile telephony. Therefore, two PWBA values are used in the model: one for mobile telephony related electronics and the other for general purpose computing. Percentage by weight of the 25 minerals of concern as well as plastic and ceramics are presented below.

The model uses 0.005% as the fraction of palladium in general purpose computing.

| Model # | Mineral | % of PWBA |
|---|---|---|
| 1 | aluminum | 4.8000 |
| 2 | antimony | 0.4500 |
| 3 | arsenic | 0.0476 |
| 4 | beryllium | 0.0714 |
| 5 | bismuth | 0.0714 |
| 6 | bromine | 2.7000 |
| 7 | cadmium | 0.0395 |
| 8 | cerium | 0.0050 |
| 9 | chromium | 0.1310 |
| 10 | copper | 3.5000 |
| 11 | cobalt | 0.0083 |
| 12 | gold | 0.0005 |
| 13 | indium | 0.0714 |
| 14 | steel | 10.6000 |
| 15 | lanthanum | 0.0030 |
| 16 | lead | 3.0000 |
| 17 | mercury | 0.0009 |
| 18 | molybdenum | 0.0155 |
| 19 | nickel | 0.3000 |
| 20 | palladium | 0.1429 |
| 21 | platinum | 0.0035 |
| 22 | silver | 0.1000 |
| 23 | tantalum | 0.0714 |
| 24 | tin | 3.0000 |
| 25 | zinc | 1.4000 |
| | ceramics/glass | 49.0000 |
| | plastics | 17.70000 |

Table 12: Material fractions of printed wiring board assemblies

## B.5 Mobile network treatment and mineral content

The components of mobile telephony are modeled as varying masses of PWBA based on Scharnhorst *et al.* (2006), shown in Table 13. Since mobile subscribers is the main driver of the model, the remaining network components are determined as a ration to the number of mobile phones in operation, as shown in Table 14.

| | Mobiles | Base Transceiver Station | Base Station Controller | Mobile Switching Center |
|---|---|---|---|---|
| AverageUseTime[years] | 1.5 | 7 | 8 | 10 |
| PWBA[g/unit] | 30 | 31,350 | 128,000 | 74,750 |

Table 13: Mobile network PWBA content

| | Ratio |
|---|---|
| Mobiles : Base Transceiver Station | 899 |
| Mobiles : Base Station Controller | 71976 |
| Mobiles : Mobile Switching Center | 143953 |

Table 14: Ratio of mobile phones to network hardware

### B.6 End of life treatment of minerals

Table 15 shows the percentage of each mineral and its direction of flow in the model depending upon its end of life disposition. Notice that many materials lack an EPS emissions cost. This is because those minerals had no data in the EPS valuation scheme. A zero indicates that the mineral was included in the EPS valuation scheme with an emissions cost determined to be negligible. For more on the formulation of these values, please see Section 5.4.

| # | Mineral | Formal Recycling % Recovered | Informal Recycling % Recovered | Informal Recycling % Emissions | EPS Emissions Cost in 1998 Euros/kg |
|---|---|---|---|---|---|
| 1 | aluminum | 95 | 90 | 10 | |
| 2 | antimony | 0 | 0 | 0 | |
| 3 | arsenic | 0 | 0 | 100 | 95.30 |
| 4 | beryllium | 0 | 0 | 0 | |
| 5 | bismuth | 0 | 0 | 0 | |
| 6 | bromine | 0 | 0 | 0 | |
| 7 | cadmium | 0 | 0 | 100 | 10.20 |
| 8 | cerium | 0 | 0 | 0 | |
| 9 | chromium | 0 | 0 | 100 | 20.00 |
| 10 | copper | 95 | 75 | 25 | 0.00 |
| 11 | cobalt | 0 | 0 | 0 | |
| 12 | gold | 95 | 90 | 10 | |
| 13 | indium | 0 | 0 | 0 | |
| 14 | steel | 95 | 90 | 10 | |
| 15 | lanthanum | 0 | 0 | 0 | |
| 16 | lead | 80 | 75 | 25 | 2910.00 |
| 17 | mercury | 0 | 0 | 100 | 61.40 |
| 18 | molybdenum | 0 | 0 | 0 | |
| 19 | nickel | 80 | 0 | 100 | 0.00 |
| 20 | palladium | 70 | 0 | 0 | |
| 21 | platinum | 70 | 0 | 0 | |
| 22 | silver | 80 | 0 | 0 | |
| 23 | tantalum | 0 | 0 | 0 | |
| 24 | tin | 80 | 75 | 0 | |
| 25 | zinc | 0 | 0 | 100 | 0.00 |

Table 15: End of life fractions for material recovery and emissions

## C Stock and flow model snapshots

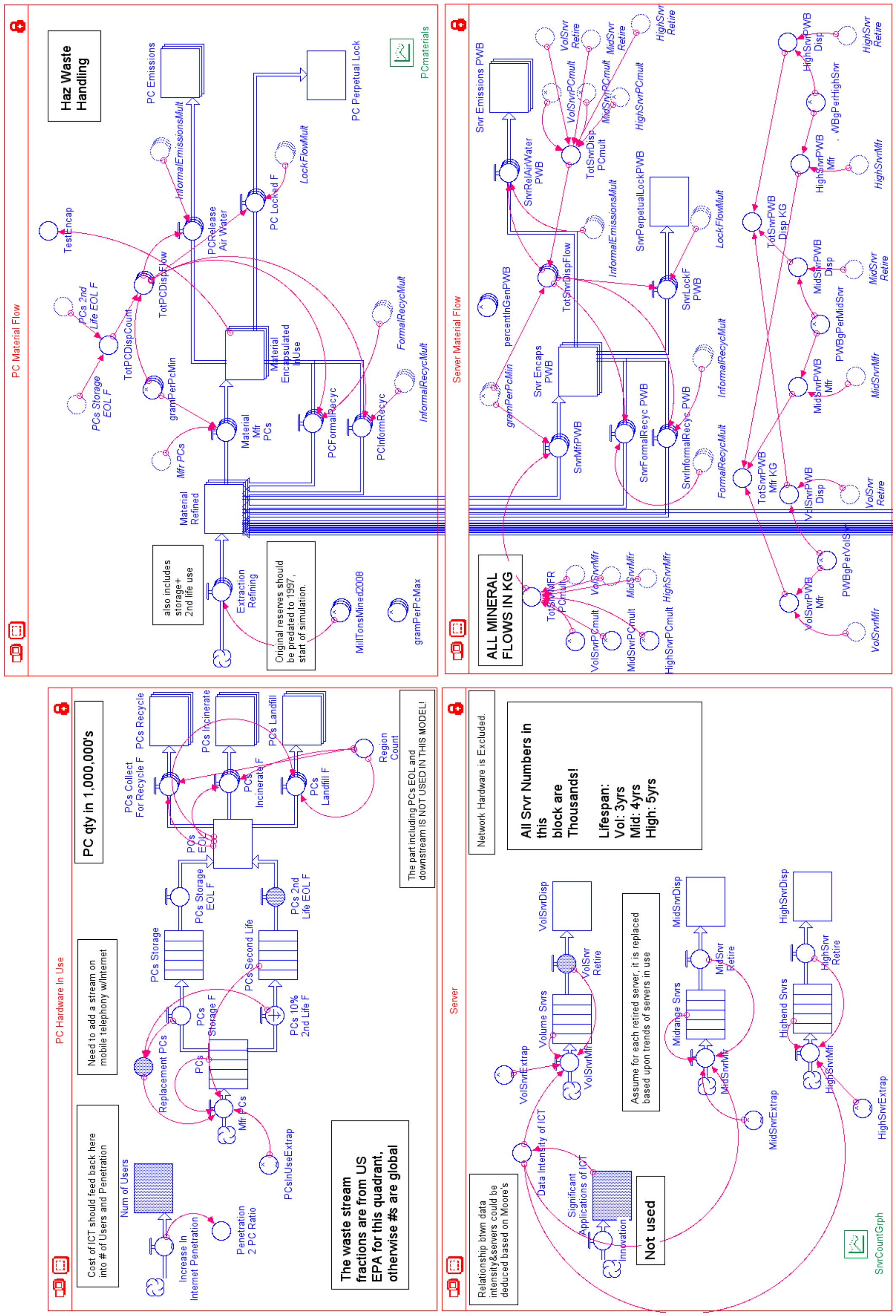


Figure 23: PC and Server Model Snapshot

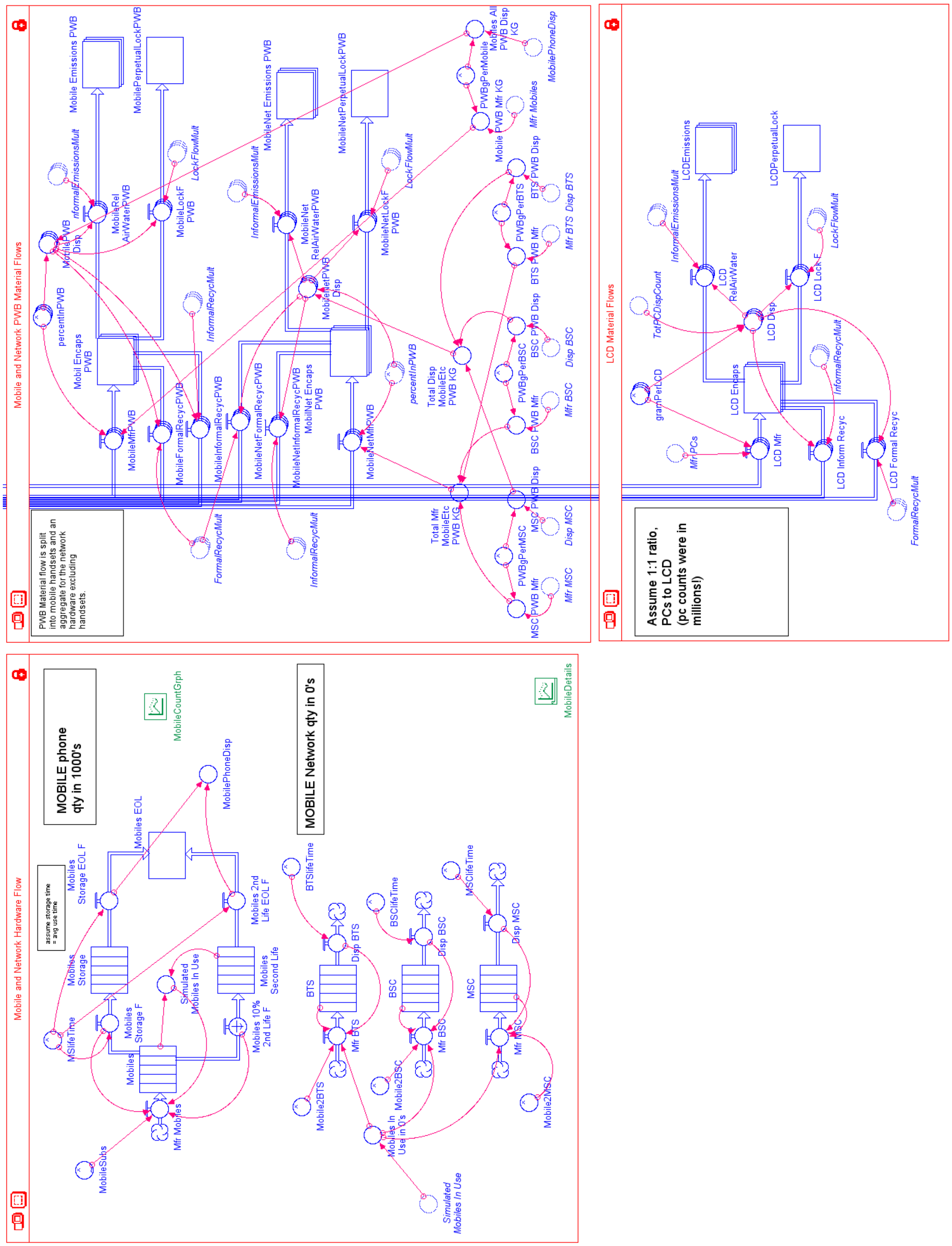


Figure 24: Mobile Telephony and LCD Snapshot

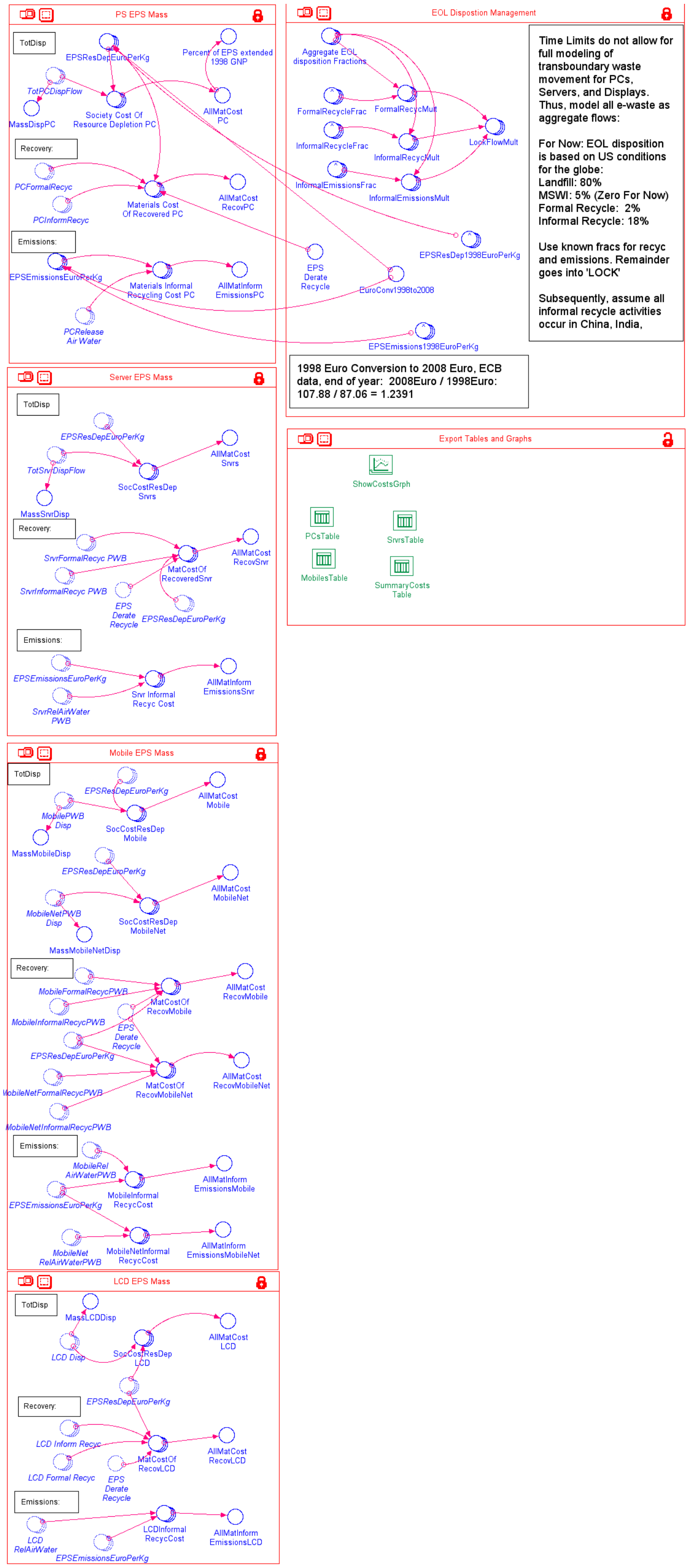


Figure 25: End-of-life disposition and EPS Valuation Model Snapshot