The Environmental Gains of Remanufacturing: Evidence from the Computer and Mobile Industry

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ABSTRACT AND KEYWORDS

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Abstract

Remanufacturing has long been perceived as an environmentally-friendly initiative. The question of how remanufacturing moderates the relation between environmental impact and economic returns is still unanswered, however. In this paper, we focus our attention on the electronics industry. In particular, we take a close look at remanufacturing within the mobile and personal computers industries. We analyze whether remanufacturing for such products substantially mitigates the energy used in the life-cycle of these products, or whether as in most electrical equipments, it can only marginally contribute to such reduction. Using both process-based and economic input-output data, we show that remanufacturing significantly reduces total energy consumption. Furthermore, we test the ubiquitous hypothesis that the market of remanufactured products is composed by products that have been downgraded and are therefore sold for prices below the average price of the new equipments. Using data from 9,900 real transactions obtained from eBay, we show that this assumption is true for personal computers, but not for mobiles. More importantly, despite the fact that remanufactured products may suffer downgrading, and that consumers therefore command a high discount for them, the economic output per energy unit used is still higher for remanufactured products. We thus conclude that remanufacturing for these two products is not only environmentally friendly, but also eco-efficient.

Keywords: Sustainability, eco-efficiency, remanufacturing, closed-loop supply chains.

1 Introduction

Electronic appliances have become part of our daily lives. Personal computers, mobile phones and digital cameras used to be luxury products some decades ago, whereas today they are found in most of the homes around the world. It is estimated, for instance, that the number of computers in the world has surpassed the billion units mark in 2008 (see Reuters (2008)). The research firm *Informa* estimated there are 3.3 million mobile phone subscriptions worldwide (see Reuters (2007)). A number of other electronics are produced at numbers in the same order of magnitude, e.g. Sony alone has recently shipped its 100 millionth camera (Canon (2008)).

It is not unreasonable to say that these appliances have changed the world we live in. Personal computers have increased productivity in offices and factories. Mobile phones have facilitated communication enormously. Recent research even suggests that mobile phone adoption is an important vector of poverty reduction (Waverman et al. (2005), Jensen (2007)).

A serious downside of the electronics industry, however, is its environmental impact. Electronic equipments contain a myriad of toxic substances. These substances can be extremely damaging for humans and the environment (European Comission (2008), The Commission of the European Communities (2008)), and many of them are released back to the environment at the end-of-life of the product. Electronic products are also responsible for a significant amount of the energy used in households Tukker et al. (2005). Some also require an impressive amount of energy to produce. This consumption is responsible for a number of other threats to the environment, including Global Warming.

One very common way for companies to reduce their negative environmental impact and to recover substantial value from electronic products is remanufacturing (in this paper we use the terms remanufacturing and refurbishing interchangeably). Remanufacturing can be broadly defined as the activity to bring a product to a certain condition level (see Thierry et al. (1995), Thierry (1997)). In many cases, remanufacturing brings a used product to the same functional and cosmetic level as a new one (Guide and van Wassenhove (2002)).

A number of companies in the electric and electronic industries have embraced remanufacturing initiatives to close the loop in their supply chains. Bosch, Canon, HP, IBM, Kodak, Océ and Xerox are commonly found brand names in closed-loop supply chains and sustainable supply chains streams of research (Ayres (1997), Krikke et al. (1999), Fleischmann et al. (2003), Debo et al. (2006)).

Literature in the field of reverse logistics, however, has only partially answered the question of how efficient and effective remanufacturing is in mitigating the environmental impact caused by the electronics business. In the further sections we define what we understand to be effectiveness and eco-efficiency in the context of this article, and we discuss the literature upon we base our definitions. It suffice to say now that we measure effectiveness as a function of the amount of energy used for remanufactured and new products. Eco-efficiency incorporates the output generated by the remanufactured and new products, and it is measured as the ratio between economic output and energy consumed (see Huppes and Ishikawa (2005)).

The key question of this article is whether remanufacturing does effectively and efficiently reduce the environmental impact of electronic products. We focus our efforts on the supply chains of personal computers and mobile phones. The reason to narrow our analysis to these two products lies in the sheer volume in which they are remanufactured and discarded.

In this paper we address the two research questions. The first research question is:

R1. How effective is remanufacturing in mitigating the environmental impact of electronic products?

Despite the fact that remanufacturing is widely accepted as an environmentally-friendly activity, literature suggests that remanufacturing does not necessarily reduce the total energy consumption of products. For electric equipments such as refrigerators, tv sets and refrigerators, , for instance, remanufacturing will at best cover an insignificant part of the energy used during the entire life cycle of these products (for a review of the energy consumption for these products see Quariguasi Frota Neto (2008)). A number of articles have addressed the energy consumption of mobiles and computers, separately. They have used both process-based methods and Economic Input-Output Life Cycle Assessment (LCA) Models. An LCA provides the valuation of the environmental impacts of a given product or service. Quariguasi Frota Neto et al. (2009) present evidence that different products can have very different energy consumption during their lives, and that decision makers should take this differences into account to optimize their supply chains in terms of business and the environment.

Williams (2004), Gotthardt et al. (2005), Williams and Sasaki (2005), Choi et al. (2006) and TIAX LLC (2006) have published results for the energy consumption of computers. Companies like Dell and Apple have also made information available about the energy consumed during the usage phase of their equipments (Apple (2007b), Dell (2007a)). For mobiles, McLaren and Piukkula (2004), Gotthardt et al. (2005), Singhal (2005) and Frey et al. (2006) in turn have estimated the energy consumed during the life cyle of mobiles. Despite the fact that the authors of these articles have done a outstanding job calculating the energy of the many phases of these products, in our opinion a compilation and comparison of the results is still missing. Since these articles reach their results using different methodologies, data and assumptions, it is worth to verify if they have reached roughly the same result.

Our second research question is:

R2. How eco-efficient is remanufacturing for electronic products?

The previously mentioned articles either look at the energy consumption only or the energy consumption and the energy gains of reusing and remanufacturing. The analyses, however, overlook the economic benefits of remanufacturing and manufacturing. On the one hand, remanufactured products may demand less energy during their lives than new ones. On the other hand, *ceteris paribus*, they are likely to sell for less than their new counterparts. From pure logic only it is not possible to tell, therefore, whether remanufacturing is a more eco-efficient solution than manufacturing, and empirical data is needed to answer this question. To our knowledge, we are the first in the literature to empirically analyze this questions.

Our research questions are translated into the following hypotheses:

H1.1. Remanufacturing is **not** an effective way to mitigate the environmental impact caused by personal computers.

H1.2. Remanufacturing is **not** an effective way to mitigate the environmental impact caused by mobile phones.

H2.1. Remanufacturing is **not** an eco-efficient way to mitigate the environmental impact caused by personal computers.

H2.2. Remanufacturing is **not** an eco-efficient way to mitigate the environmental impact caused by mobile phones.

This paper is organized as follows. In Section 2 we investigate how effectively remanufacturing can mitigate the energy consumed of electronic equipment. In Section 3 we compare remanufacturing with other economic activities in terms of its eco-efficiency. Section 4 we summarize our main findings.

2 The effectiveness of remanufacturing in mitigating the environmental footprint of electronics

In this Section we analyze R1. In the subsequent subsections we show how we measure environmental impact, we present the unit of analysis and the main assumptions. Furthermore, we summarize the data we used. Moreover, we test H1.1. and H1.2, and perform a robustness check of our findings.

2.1 Unit of analysis

In this section, we intend to analyze how effectively remanufacturing mitigates the environmental impacts of computers and mobiles. The concept of effectiveness in business is intrinsically associated with performing a task thoroughly and without flaws. Effectiveness is, therefore, not necessarily related to how costly an activity can be. We analyze the effectiveness of a remanufactured product as compared to its original counterpart. More specifically, we compare the amount of energy used per year during the entire life cycle of manufactured and remanufactured products. In Section 3, we extend this analysis to include the economic dimension.

We use the Cumulative Energy Demand (CED) as our measure of environmental impact. Recent studies show a high correlation between CED and the Eco-indicator 99 aggregated result. The Eco-indicator 99 is a widely used impact assessment method for LCA. The aggregated result is a measure, based on the weighted mean of the many environmental impact dimensions that comprise the indicator. The downside of the Eco-indicator 99 is the difficulty to measure if compared to other indicators, such as CED. The reason is that many more data and calculations are necessary to calculate the Eco-indicator 99 than to estimate CED. Given the good correlation between the two indicators, CED is considered to be a good substitute for the Eco-indicator 99 (Helias and Haes (2006)).

Results observed by Helias and Haes (2006) also show a high correlation between some of the disaggregated environmental impact indicators that are part of the Eco-indicator 99, (e.g. resource depletion, marine toxicity, etc) and CED. Walk et al. (2005) find an overall Spearman correlation of $\rho^2 = 0.94$ between the CED and the aggregated Eco-indicator results, as well as individual impact correlations ranging from $\rho^2 = 0.73$ to $\rho^2 = 0.96$.

2.2 Main assumptions

Our main assumptions in this article are:

- The average life span for the remanufactured products is the same as the average life span of the new counterparts.

As in Williams (2004), we assume that the life cycle of the remanufactured product is the same as for the manufactured one. Given the short life cycle of new electronic products of approximately two years, we find it reasonable to assume that the life cycle of the remanufactured product will not be shorter than two years.

- The energy efficiency of the remanufactured products is the same as the energy efficiency of the new products.

We define energy efficiency as the amount of energy used per period for a given electronic product. For electronic products with such short life cycles, we have no reason to believe that the energy for remanufactured products would be different from their new counterparts. Furthermore, as we verify when performing the sensitivity analysis, assuming a higher energy consumption for remanufactured products will not change our main results.

- The energy required to remanufacture these products equals 20% of the energy used to manufacture them.

Little information is available regarding the amount of energy used in remanufacturing computers and mobiles. Williams (2003) provides two estimates for the energy used to remanufacture computers. If no upgrade is performed the energy is insignificant. Upgrading a computer would require 30% of the energy used to manufacture. This information is only pertinent for one particular type of computer (and for one type of upgrading), however, and not for the entire sector of remanufactured computers. The reason is that the information in the percentages of computers that are only repaired and not remanufactured (and have therefore different energy consumption profiles) is not available. Moreover, even the estimation for remanufacturing a given computer does not directly translate into the average energy necessary to remanufacture a computer. White et al. (2002) claim that the process of remanufacturing itself will demand less energy than the energy used to recover the product to the point of remanufacturing (i.e. the energy used to transport the product from the consumer to the remanufacturing facility). To the best of our knowledge, there is no study in which energy for remanufacturing is estimated for an average remanufactured computer. We decided to use 20% as an educated guess of the proportional amount of energy necessary to remanufacture a computer.

It is important to point out that the aforementioned assumptions will be relaxed in subsection 2.6. In that section we will test whether our conclusions hold for different scenarios of energy consumption, life span usage and the required energy for remanufacturing.

2.3 Data

There are a number of ways to collect data for an LCA. Potential sources of data include measurements, interviews, literature search, theoretical calculations, database search, and qualified guessing (Pré Consultancy (2008)). In our analysis, we use literature search and database search as the main sources of data. The reasons for such approach is twofold. The first reason regards feasibility. For the scope of the article, it would be impossible, for instance, to measure the energy used in the production of the electrical and electronic components. A thorough LCA of one of these equipments, and in particular an electronic one, would be material enough to fill a complete article or Ph.D. thesis (see e.g. Scharnhorst (2005) for mobile telecommunication). The second is the level of detail of the LCA. As we are interested in energy consumption only, and more specifically in getting an overview of the energy consumption in each phase of the life cycle of the product, data from literature and databases suffices.

We look at different sources to triangulate the results. The results are both based on process-based LCA methods and Economic Input-Output Models, improving then the validity and generalizations. Process-based LCA methods requires the inventory of all activities necessary to the production of a given product, and their respective emissions. Economic Input-Output Models are much simpler to implement and are based on Economic Input-Output Matrices. For definitions of process-based LCA methods and Economic Input-Output Models see Carnegie Mellon University Green Design Institute. (2008).

For transportation, we estimate the CED in two ways. First, if available, we extract the data directly from the literature. In some cases, the life cycle information found in the literature already includes transportation. If the data for the environmental footprint of transportation are not available, we estimate them. Our estimations are based on estimations for the distance traveled by the equipment, and on the ratios between distance traveled and energy consumption found in BUWAL (http://www.admin.ch/buwal (2007)).

Regarding energy consumption of usage and manufacturing we use the data found in the literature. The usage of databases here is not appropriate due to the high energy consumed by the manufacturing of some very specific components of electronic equipments. General databases, such as the BUWAL-250, provide the energy used to manufacture raw materials, but not electronic parts. Using only the primary materials available in these databases (i.e. plastic, steel) would thus distort the results, since most of the energy in the production phase goes into microprocessors (Scharnhorst (2005), Williams and Sasaki (2005)).

The data itself used in this section has been obtained from LCAs contained in scientific papers, websites and white reports of OEMs, and information in the database BUWAL-250. A detailed description of the data can be found in the appendix. The LCAs used as the source of the data for this section had to meet the following criteria:

- The LCA has been published in a book edited by a trustworthy institution (e.g., the United Nations' University), in a report from a major OEM (e.g., Dell, Apple), in a paper or presentation in a respectable journal or conference in the field of Industrial Ecology (e.g. *Journal of Industrial Ecology*), in a report by a major consultancy company in the field of LCA, or in a master dissertation or a Ph.D. thesis from respected institutions.
- The LCA should contain the total or proportional energy demand used in the life cycle of the product or the amount of fossil fuel used.

In the next section we analyze the energy consumption in the forward chain.

2.4 Analysis of the energy consumption for the forward chain

In this section we describe the data regarding the energy usage during the life cycle of the products we analyze. More specifically, we analyze the energy consumed during the manufacturing, transportation and usage phases.

Include Figure 1

Computers

Comprehensive results on the environmental impact of computers are scarce (Williams and Sasaki (2005), Thollier and Jansen (2007)). The reason for such scarcity is that the information on the environmental footprint of chip manufacturing is also very limited. This manufacturing phase is fundamental for the amount of energy consumption, since it counts for a considerable amount of energy consumed during the production phase (Gotthardt et al. (2005), Williams and Sasaki (2005), Thollier and Jansen (2007)). Information about the environmental footprint of chip manufacturing has been recently provided in Williams et al. (2002).

We base our analysis on the results obtained by Williams et al. (2002), Williams (2004), Williams (2005), Gotthardt et al. (2005), Choi et al. (2006), TIAX LLC (2006) and the web pages of computer manufacturers (i.e. Apple (2007a) and Dell (2007b)).

According to Williams (2005), a total of 240kg of fossil fuel is used to produce a computer. As a comparison, Williams (2005) provides the following data: an automobile requires 2,000kg of fossil fuel to be produced, so the fossil fuel demand of a personal computer life cycle per year is approximately 60% of a car's fuel demand for production (per year). Another interesting comparison is the one with refrigerators. Considering that one changes one's computer every two years, and one's fridge every ten years, these two appliances consume approximately the same amount of energy during per year during their life time (Williams and Sasaki (2005), Williams et al. (2008)).

Contrary to most of the other electric appliances, the highest environmental burden of computers is due to the production phase. The result concerning the proportional amount of energy consumed in manufacturing is consistent with those found in Williams (2004) Gotthardt et al. (2005), and Choi et al. (2006) (see Figure 1).

According to Williams (2005), the usage phase is responsible for only 25% of the computer's CED. The result is similar to those found in Williams (2004), Gotthardt et al. (2005), and Choi et al. (2006) (see Figure 1). The absolute amounts of energy used found in the different studies are very similar. The results for energy consumption found in Williams (2004), Gotthardt et al. (2005), Williams and Sasaki (2005), TIAX LLC (2006), Apple (2007b), Dell (2007b) vary from 1,500MJ to 1,872MJ, or less than 25% between the lowest and the highest estimation.

Include Table 1

Note that the environmental impact of the transportation phase is negligible if compared to the complete life cycle's environmental impact. It is worth to mention, however, that transportation's impact may vary from irrelevant to small, depending on the assumptions made. For desktop computers, Williams and Sasaki (2005) suggest that transportation is not negligible: in a worst-case scenario of $5,000$km traveled by a 24kg computer, by truck, the energy consumed by transportation is estimated to be 680MJ, around 10 percent of the energy necessary to produce the computer, and approximately a 8% of the energy consumed in the entire life cycle of the product. As pointed out by Williams and Sasaki (2005), the difference between the worst and the best case scenario for transportation's environmental impact might be tenfold.

The aforementioned results align with those found by Gotthardt et al. (2005): in a desktop, the production phase is responsible for 60% of all the energy consumed, while usage consumes 39% and transportation around 1%. Choi et al. (2006) present similar results: 85% of the energy is consumed in the manufacturing phase, while 15% is used in the usage phase. Transportation is reclaimed to be irrelevant.

It is important to note that although the production phase yields most of the CED, reclaiming such burdens via traditional bulk recycling is impossible. The reason for such apparent paradox lies in the semiconductors embedded in computers: the majority of the energy and raw material (and therefore waste) is used to produce the semiconductors, and very little can be claimed back via bulk recycling. For details on data, assumptions and calculations, see annexes.

Mobile phones

Similar to the analysis for computers, we use different sources to enable triangulation of the results. We base our analysis on the results obtained by Schaefer et al. (2003), McLaren and Piukkula (2004), Gotthardt et al. (2005), Singhal (2005), and Frey et al. (2006). These are technical reports by independent firms, technical reports from OEMs, and scientific papers. Results are presented in Figure 2 and Table 2.

The results for mobile phones resemble those for computers, although on average usage is a more important factor for mobile phones than it is for computers. Gotthardt et al. (2005) indicate that most of the energy is used in the production phase. These findings are consistent with those in McLaren and Piukkula (2004), Singhal (2005) and Frey et al. (2006). They are also consistent with the results found by Nokia, using a more aggregated environmental measure (LCA Center (2007)). The results in Gotthardt et al. (2005) also show that the energy recovery of the bulk recycling phase is irrelevant. Furthermore, the production phase is responsible for approximately 60% of the overall environmental impact, excluding transportation. In that case, however, transportation does not significantly contribute to the overall environmental impact. In absolute values, the estimations for CED in McLaren and Piukkula (2004), Singhal (2005), Frey et al. (2006) are very similar to each other.

The reason why manufacturing dominates the energy consumption in mobiles seems to lie, as in computers, in their embedded electronic components, such as printed circuit boards for mobiles (Scharnhorst (2005)). Singhal (2005) shows that the production of the Wiring Board (PWB), Integrated Circuits (ICs), and Liquid Crystal Display (LCD) dominates the consumption during the life cycle of a mobile. For electronic equipment, therefore, little energy can be claimed via bulk recycling, but a substantial amount can be reclaimed via reuse or remanufacturing of used electronic equipments.

Include Figure 2

The estimated proportional amount of energy used during the usage phase varies from 29% to 41%.

The results regarding usage vary considerably, mainly due to the assumptions regarding the life span of the equipment and the number of hours used per year. Despite the significant differences between the estimations, however, the estimation of the amount of energy consumed in the usage phase is, for all cases, less than the estimated amount of energy consumed in manufacturing.

Include Table 2

The amount of energy used in transportation varies from insignificant to more than a tenth of the total energy consumed in the life cycle. Despite the variance within the estimations, for all of them transportation consumes significantly less energy than the other two phases.

2.5 Manufacturing vs remanufacturing: analysis of effectiveness

As previously presented in this section, manufacturing dominates the energy consumed during the entire life cycle of computers and mobiles. Reducing the energy demanded via remanufacturing, therefore, can drastically diminish the amount of energy consumed during the life cycle of these products. Figure 3 illustrates the difference in energy consumption between new and remanufactured computers and mobiles.

Include Figure 3

It is easy to see that, for personal computers, remanufacturing can substantially mitigate the necessary energy for the entire life cycle of the product.

For mobiles, remanufactured products also demand much less energy during their life cycles. Figure 4 illustrates the CED for manufactured and remanufactured mobile phones.

Include Figure 4

2.6 Robustness check

In this sub-section we analyze the robustness of the assumptions defined in Section 2.2. More specifically, we show whether our results still hold with much more strict scenarios. The scenarios that we analyze are the following:

- The average life span for the remanufactured products is 75% of the average life span of the new counterparts. The other assumptions remain the same.
- The average life span for the remanufactured products is 50% of the average life span of the new counterparts. The other assumptions remain the same.

For these two scenarios, we multiply the the energy in the production phase by, respectively, 4/3 and 2. It means, for the first scenario, that 4 remanufactured computers are needed to substitute three new ones.

- Remanufactured products consume 25% more energy than new ones. The other assumptions remain the same.
- Remanufactured products consume 50% more energy than new ones. The other assumptions remain the same.
- The energy required to remanufacture these products equals 50% of the energy used to manufacture them.

For all scenarios analyzed, remanufactured products consume less energy than manufactured ones. Figure 5 illustrates the results for the aforementioned scenarios for personal computers. Figure 6 illustrate the results for the next scenarios for mobile phones. Hypothesis H1.1. and H1.2. are, therefore, rejected.

Include Figure 5

Include Figure 6

3 The eco-efficiency of remanufacturing

3.1 Eco-efficiency

In this section we intend to answer the research question *R2* and hypotheses H2.1. and H2.2. The first step is to define clearly what we understand to be eco-efficiency.

The term eco-efficiency has first been proposed in 1992, during the Rio Earth Summit in 1992, by the World Business Council for Sustainable Development (WBCSD). In a few words, eco-efficiency implies "doing more with less" or "creating more value with less impact".

> "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity."(Schmidheiny (1992))

A second definition is proposed by the European Environmental Agency (EEA). It defines eco-efficiency based on the concept of sustainable development coined by the Brundtland Commission (Brundtland (1997)):

> “A concept and strategy enabling sufficient delinking of the “use of nature” from economic activity needed to meet human needs (welfare) to allow it to remain within carrying capacities; and to permit equitable access and use of the environment by current and future generations.” (EEA (2007)).

This definition of eco-efficiency is as difficult to operationalize as the definition for Sustainable Development proposed by the Brundtland Commission. The main reason for that difficulty lies in the fact that the constructs that define it are, themselves, not properly delineated.

Huppes and Ishikawa (2005) propose a different definition for eco-efficiency based on the concept of Pareto optimality. According to this definition, a process is called eco-efficient if there is no room for decreasing its environmental impact without increasing its costs or vice-versa. In other words, something (e.g. a supply chain, or a country) is eco-efficient if it belongs to the Pareto efficient production frontier regarding costs and environmental footprint. On a macroeconomic level, an activity is eco-efficient if it is Pareto efficient regarding economic output and environmental impacts. This definition of eco-efficiency, as a measure of how efficiently we use natural resources, is advocated in Kuosmanen and Kortelainen (2005), Hellweg et al. (2005), Scholz and Wiek (2005) and Kobayashi et al. (2005). Furthermore, it is used in companies such as Bosch (Otto et al. (2006)) to evaluate different alternatives of products and processes. Figure 7 illustrates the frontier.

Include Figure 7

We define eco-efficiency in the same way as a measure of efficiency, as in the aforementioned work of Kuosmanen and Kortelainen (2005), Hellweg et al. (2005), Scholz and Wiek (2005) and Kobayashi et al. (2005). We examine, therefore, the total environmental impact divided by the economic activity generated by the same activity.

3.2 Comparing eco-efficiency: manufacturing vs remanufacturing

In order to analyze the eco-efficiency of manufactured and remanufactured items, further information regarding the economic activity generated by each of these activities is necessary. In a broad sense, we intend to determine the direct economic output generated by manufacturing and remanufacturing activities per unit of energy spent. Furthermore, we test whether the eco-efficiency of the two groups is significantly different.

3.2.1 Eco-efficiency of personal computers

In order to estimate the energy consumption in manufacturing and remanufacturing, we use the data from Williams (2005). As the figures for the energy consumed by computers described in Section 2 in their entire life cycle are similar, we use one of the estimates (Williams and Sasaki (2005)) for energy used during the life-cycle of a computer. 5,040MJ are consumed during the manufacturing phase. Concerning remanufacturing, the total energy consumed equals 1,008MJ (i.e. 20% of the energy used for new computers).

Regarding the price, we assume that the average price of a PC is $550 (according to the marketing search company NPD, an average PC in the United States would sell for $550 in 2008. See *http://www.consumersearch.com/apple-laptops/mac-vs-pc* for more details).

In order to estimate the average price for computers, we collected $1,194$ observations of desktop computers sold on eBay United States between 24/12/08 and 24/02/09. We extracted our data from the sub-category: "Desktop PCs" in the category "Computing". We have used the keyword search: "desktop". We have selected the condition: "refurbished". In the American eBay products are classified, according to their conditions, in three groups: "new", "used" and "remanufactured". We find that the average price for refurbished computers is $172 and varies from $32.25 to $750. Figure 8 represents the price distribution in the sample.

Despite the fact that manufacturing is responsible for the majority of the energy consumed during the life cycle of a computer, and that remanufacturing only consumes a fraction of the original energy, remanufactured computers may command more energy per economic output generated than manufactured ones. The reason is simple: remanufactured products are sold with high discounts, even when they have exactly the same functionality of new ones. Furthermore, in many cases, remanufactured PCs do not have the same functionality of new ones, and have even lower value. As this problem can not, therefore, be solved by simple logic, we need to empirically investigate whether remanufactured products are more eco-efficient than manufactured ones. We do so by testing the difference in eco-efficiency between the groups of manufactured and remanufactured products.

For new computers, using the aforementioned data (5,040 MJ as the energy used per computer manufactured and $550 dollars as its average price), a total of approximately 9.16 MJ is necessary to create an output of dollar in the economy.

Include Figure 8

For a remanufactured computer, 5.83MJ of energy is used to generate a dollar. Furthermore, only approximately 13% of the remanufactured computers use more energy than the amount of energy used in manufactured ones to generate an output of a dollar. The other 87% remanufactured computers are, therefore, more eco-efficient in terms of energy consumption.

An ANOVA test shows that the difference in eco-efficiency between the two samples (new and remanufactured computers) is statistically significant ($p \leq 0.05$). We consider the two samples to be normally distributed, with averages 9.16 and 5.83. The standard deviation of the Winsorised sample of remanufactured products (we eliminated the 5% and 95% tails) equals 1.71. Based on the average energy necessary to create one dollar of outcome, hypothesis H2.1. is rejected

3.2.2 Eco-efficiency of mobile phones

In order to estimate the energy consumption in manufacturing and remanufacturing of mobile phones, we use the data from Singhal (2005). Furthermore, we assume that remanufacturing only takes 20% of the energy consumed during the manufacturing phase. We also consider the same life span for manufactured and remanufactured products.

We estimate the average sale price of mobiles to be \$108.83. This is the average value of the 123,249 mobiles sold between 21/12/08 and 17/03/09 in eBay United States (Category: Cell Phones *in* Cell Phones & Smart Phones. Keyword search: “mobile”+ “phone”. Condition: “new, never open”) It is worth mentioning that our estimate for the prices of new mobiles is consistent with the estimate of independent research firms. The IT firm NPD estimated, for instance, that in 2007 the estimated prices of mobiles were \$84.

In order to estimate the average price for remanufactured mobiles, we collected $7,710$ observations of mobiles sold in eBay between 05/12/08 and 05/03/09 (Category: Cell Phones *in* Cell Phones & Smart Phones. Keyword search: “mobile”+“phone”. Condition:“refurbished”). The average selling price was \$100.82. This value is only about 10% lower than the average price of the manufactured product. The average price for remanufactured mobiles is much higher (proportionally to the value of a new equipment) than the average value of remanufactured computers. Furthermore, we did not find a significant difference between the prices of manufactured and remanufactured equipments.

For remanufactured mobile phones, 0.13MJ is necessary to produce a dollar outcome. This value is much higher than the value for computers, both manufactured and remanufactured. For new mobile phones, 1.48MJ is necessary to produce a dollar outcome. Remanufacturing thus seems more attractive for mobiles than it is for computers. For mobile phones, approximately 98% of the remanufactured products are more eco-efficient than the average new mobile phone.Furthermore, an ANOVA test shows that the difference between the two samples (new and remanufactured computers) is statistically significant ($p \leq 0.01$). Figure 9 illustrates the difference in discounts for remanufactured items for mobile phones and computers.

Hypothesis H2.2. is thus rejected.

3.3 Implications

The fact that remanufacturing is more eco-efficient than manufacturing for computers and mobile phones, supports a number of legislations for the waste of electronic equipment that regard re-using and remanufacturing as an environmentally friendly activity. The European WEEE directive, for instance, refers in its eighth paragraph that:"(...)Where appropriate, priority should be given to the reuse of WEEE and its components, subassemblies and consumables".

It is worth emphasizing, however, that the idea that remanufacturing, in itself, improves the sustainability of electrical and electronic products is not generalizable to other products currently covered by the WEEE. For electrical appliances, such as refrigerators, research indicates that increasing the life span can cause a shift in environmental impact (e.g. less waste, but more energy consumed) rather that mitigating the overall environmental impact of the products (for a review of these studies see Quariguasi Frota Neto (2008)).

Regarding electronic products, in particular PCs and mobiles, increasing their life span seems like a rare example where the positive environmental effects are undisputed (in this paper we discuss energy consumption only, but other environmental impacts are also reduced when life span is increased, e.g. electronic waste). Given the fact that most energy in the life cycle of these products has been consumed before the first user starts them, extending their life cycle can substantially reduce their energy demand. Remanufacturing, should therefore be encouraged from an ecological point of view. LCAs derived from both process-based LCA methods and economic input-output models point to this same direction.

In our opinion recovery solutions aim not only to preserve the environment, but also to create economic output. In a number of situations, remanufacturing will render products that on the one hand cause less impact on the environment, but on the other hand are much less desirable. It is paramount, therefore, to determine whether such decrease in value of remanufactured products will make them less eco-efficient than their new counterparts.

Under the "eco-efficiency lenses", despite the fact that the value of remanufactured computers and mobiles are, in average, lower if compared to new ones, we have shown that the economic output per unit of energy used is still higher for these products.

4 Conclusions and further research

In this paper we investigate how effectively and efficiently remanufacturing in the electronic industry influences the environmental footprint of the sector.

We investigate the assumptions using environmental data from a number of sources, scientific papers, websites and white reports of OEMs, and from information in the database BUWAL-250. Moreover, we select papers using different methodologies of energy assessment (i.e. process-based LCA methods and economic input-output models). Economic data are extracted from research by consultancy firms and economic input-output databases.

We find that remanufacturing is an effective way to reduce energy consumption in the life cycle of computers and mobiles. We propose different assumptions for (i) energy consumption of the remanufactured products (ii) energy used to remanufacture these products and (iii) life span of the remanufactured products. We conclude that our findings are robust under a number of not very restrictive assumptions.

In a second step, we compare the eco-efficiency of remanufacturing vis-a-vis manufacturing. We show that remanufacturing can also play an important role in mitigating economic output generation and energy consumption. The fact that consumers command a high discount for remanufactured products, however, makes the differences between the eco-efficiency of manufacturing and remanufacturing smaller than the differences in their energy consumption. This discount makes remanufactured mobiles and computers less eco-efficient, but still significantly more eco-efficient than their manufactured counterparts.

It is worth mentioning that in this article, we address energy consumption only, as measured by CED. CED is often regarded as a good indicator for environmental impact, as presented in Section 2.3. Follow up research is necessary to determine the effectiveness and eco-efficiency of remanufacturing, when accounting for other environmental indicators, such as toxic substance releases.

A number of other avenues of research are still to be explored regarding how remanufacturing interacts with the so called 3P: people, planet and proft. On the people's dimension, for instance, determining the total employment created by this activity can be an interesting avenue of research.

Figures and Tables

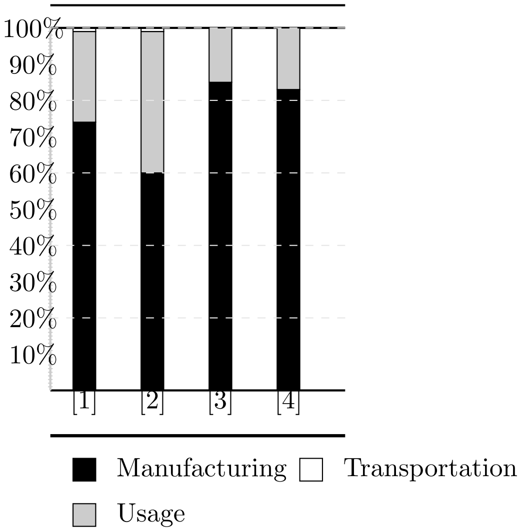

Figure 1: Cumulative Energy Demand (%) for the different phases of the life cycle of a personal computer. Data for production and usage were obtained from [1] Williams and Sasaki (2005), [2] Gotthardt et al. (2005), [3] Choi et al. (2006), [4] Williams et al. (2002) and [5] Atlantic Consulting and IPU (1998). Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

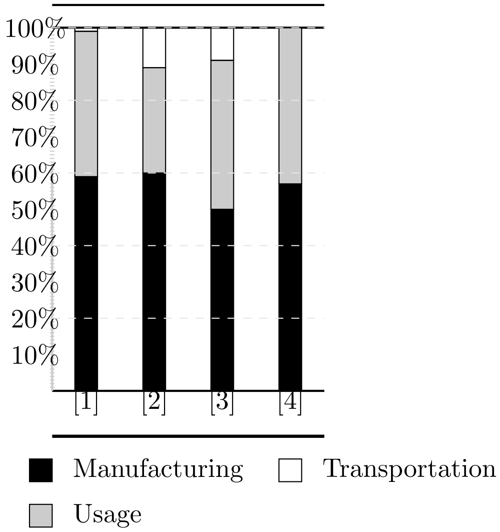

Figure 2: Cumulative Energy Demand (%) for the different phases of the life cycle of a mobile phone. Data for production and usage were obtained from [1] Gotthardt et al. (2005), [2] Singhal (2005), [3] Frey et al. (2006), [4] McLaren and Piukkula (2004) . Data regarding transportation has been estimated using BUWAL-250. See appendix for details.

Table 1: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer. The analysis includes the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand expressed in MJ. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund (2007)). ^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment. $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^{\diamond}$
Manufacturing				
Williams (2005) and BUWAL-250	240^{l}	$5,040^{l}$	$74^{c(l,e)}\%$	$4.67^{c(l)}$
Gotthardt et al. (2005) and BUWAL-250	N.A.	N.A.	$60^{c(l,e)}\%$	$2.50^{c(l)}$
Choi et al. (2006) and BUWAL-250	N.A.	N.A.	$85^{l}\%$	N.A.
Williams (2004)	290^{l}	$7,320^{l}$	$83^{l}\%$	$6.77^{c(l)}$
Usage				
Williams (2005) and BUWAL-250	80^{l}	$1,680^{l}$	$25^{l}\%$	$1.02^{c(l)}$
Gotthardt et al. (2005) and BUWAL-250	N.A.	N.A.	$39^{c(l,e)}\%$	$1.61^{c(l)}$
Dell (2007b)	$93^{c(l)}$	$1,960^{l}$	N.A.	$1.81^{c(l)}$
Choi et al. (2006) and BUWAL-250	N.A.	N.A.	$15^{l}\%$	N.A.
Apple (2007c)	$89^{c(l)}$	$1,872^{l}$	N.A.	1.80^{l}.
Dell (2007c)	N.A.	N.A.	N.A.	6^{l}
TIAX LLC (2006)	78^{l}	$1,656^{l}$	N.A.	$1.53^{c(l)}$
Williams (2004)	N.A.	$1,500^{l}$	$17\%^{l}$	$1.39^{c(l)}$
Transportation				
Williams (2005) and BUWAL-250	$1.4^{c(e,l)}$	28^{e}	1%	≤ 0.10
Gotthardt et al. (2005) and BUWAL-250	$1.4^{c(e,l)}$	28^{e}	1%	≤ 0.10

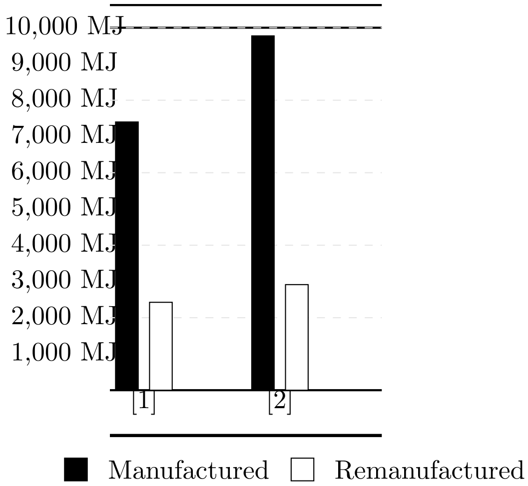

Figure 3: Cumulative Energy Demand (%) for the manufacturing and remanufacturing of computers expressed in MJ. Data for production and usage were obtained from [1] Williams and Sasaki (2005), [2] Williams et al. (2002) . Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

Table 2: Cumulative Energy Demand for the different phases of the life cycle of a mobile phone. FFD† is the fossil fuel demand in kg of fossil fuel.CED‡ is the cumulative energy demand expressed in MJ. $\diamond$ prices are expressed in US dollars. Source:www.carbonfound.org (CarbonFund (2007)).^{l} refers to data extracted directly from the literature. ^{e} refers to values that have been estimated in our study, e.g., transportation moment. $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD†	CED‡	CED (%)	carbon offset costs$^\diamond$
Manufacturing				
Gotthardt et al. (2005) and BUWAL-250	N.A.	880^l	$59^{c(l)}$%	0.81
Singhal (2005)	$2.4^{c(l)}$	150^l	60^l%	0.12
Frey et al. (2006)	$8^{c(l)}$	$(132-165)^l$	$50^{c(l)}$%	0.15
McLaren and Piukkula (2004)	$7.6^{c(l)}$	160^l	$57^{c(l)}$%	0.15
Usage				
Gotthardt et al. (2005) and BUWAL-250	N.A.	587^l	$40^{c(l)}$%	0.55
Singhal (2005)	$1.2^{c(l)}$	77^l	29^l%	< 0.10
Frey et al. (2006)	$6^{c(l)}$	116^l	$41^{c(l)}$%	0.15
Schaefer et al. (2003)	N.A.	$94^{c(l)}$	N.A.	< 0.10
McLaren and Piukkula (2004)	$4.28^{c(l)}$	90^l	$32^{c(l)}$%	< 10
Transportation				
Williams (2005) and BUWAL-250	insignificant	insignificant	≤ 1%	< 0.10
Singhal (2005)	$0.5^{c(l)}$	28^l	11^l%	< 0.10
Frey et al. (2006)	$1^{c(l)}$	31^l	$9^{c(l)}$%	< 0.10
McLaren and Piukkula (2004)	$1.43^{c(l)}$	30^l	$11^{c(l)}$%	< 10

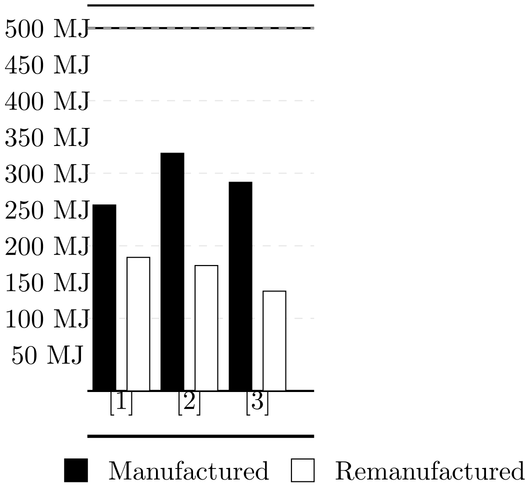

Figure 4: Cumulative Energy Demand (%) for the manufacturing and remanufacturing of mobiles expressed in MJ. Data for production and usage were obtained from [1] Singhal (2005), [2] Frey et al. (2006), [3] McLaren and Piukkula (2004). Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

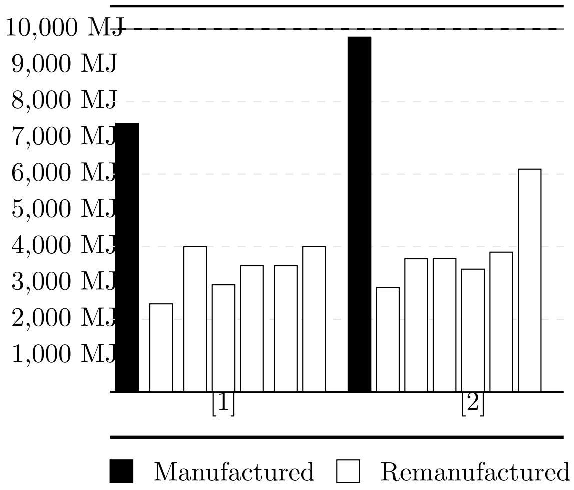

Figure 5: Cumulative Energy Demand (%) for the manufacturing and remanufacturing of computers expressed in MJ. Data for production and usage were obtained from [1] Williams and Sasaki (2005), [2] Williams et al. (2002) with different scenarios. The scenarios presented in Section 2.6 are shown in white, sequentially. Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

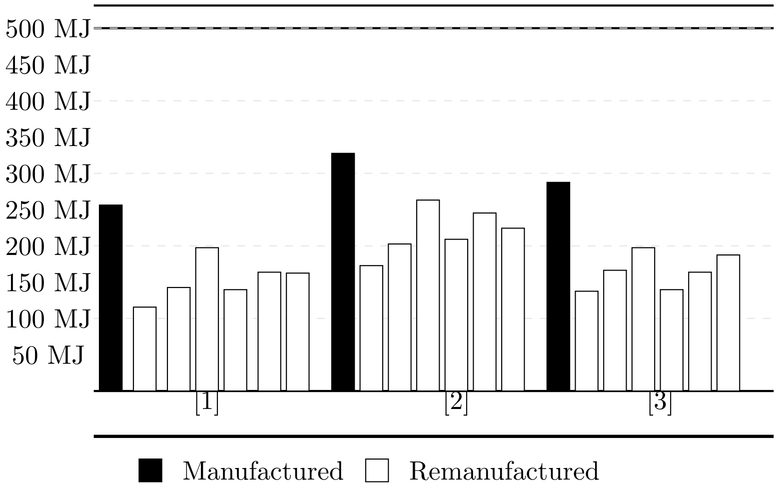

Figure 6: Cumulative Energy Demand (%) for the manufacturing and remanufacturing of mobiles expressed in MJ. Data for production and usage were obtained from[1] Singhal (2005), [2] Frey et al. (2006), [3] McLaren and Piukkula (2004). The scenarios presented in Section 2.6 are shown in white, sequentially. Data regarding transportation have been estimated using BUWAL-250. See appendix for details.

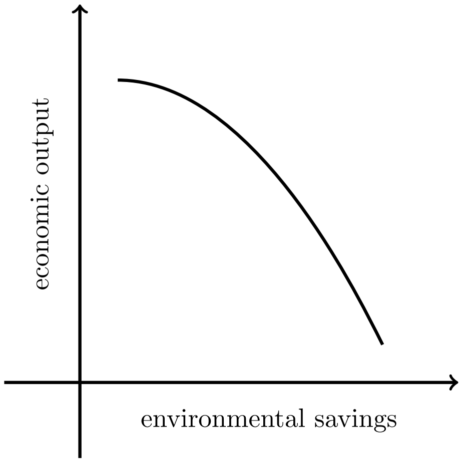

Figure 7: Eco-efficient frontier. Adapted from Huppes and Ishikawa (2005)

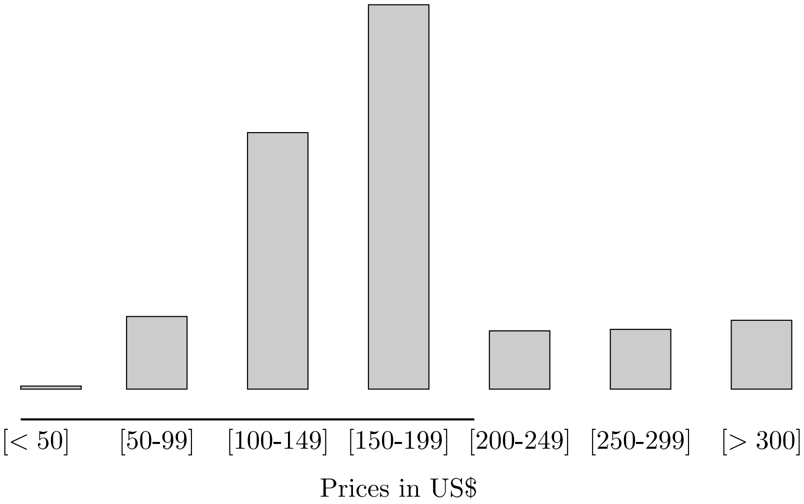

Figure 8: Remanufactured computer prices and frequencies

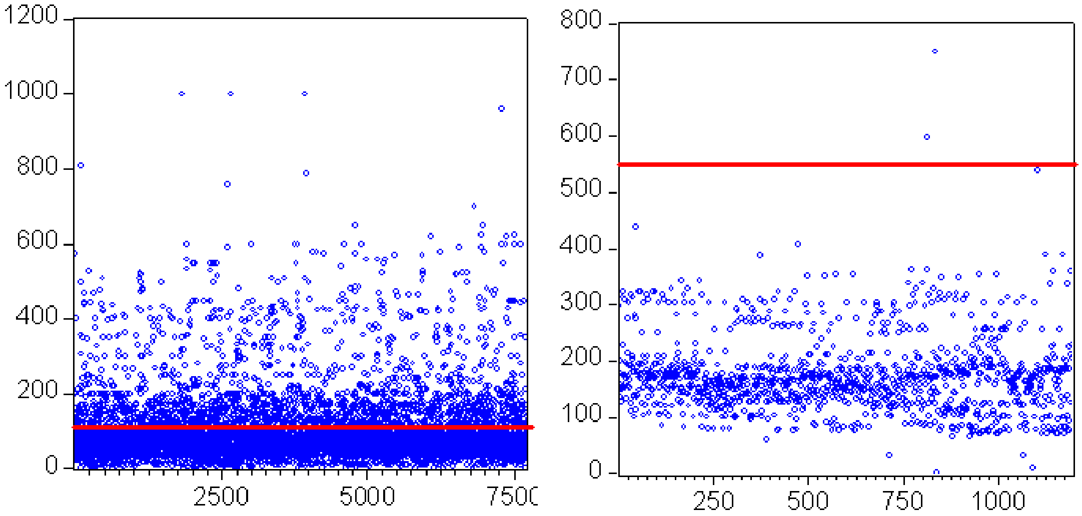

Figure 9: Prices for remanufactured mobiles and computers. The horizontal red line represents the average price of , respectively, new mobiles and computers

5 Acknowledgement

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Appendix

The appendix summarizes the data used for the assessment of energy consumption.

Table 3: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer. The analysis include the computer's monitor. FFD[†] is the fossil fuel demand in kg of fossil fuel. CED[‡] is the cumulative energy demand. ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD[†]	CED[‡]	CED (%)	carbon offset costs[◇]	monitor	main assumptions	calculations
Manufacturing							
Williams (2005) and BUWAL-250	240^{l}	$5,040^{l}$	$74^{c(l,e)}\%$	$4.67^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature).
Gotthardt et al. (2005) and BUWAL-250	N.A.	N.A.	$60^{c(l,e)}\%$	N.A.	CRT	N.A.	N.A.
Choi et al. (2006) and BUWAL-250	N.A.	N.A.	$85^{l}\%$	N.A.			
Atlantic Consulting and IPU (1998)	172^{l}	$3,630^{l}$	$26\%^{l}$	$3.36^{c(l)}$	CRT	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD.	$FFD = 3,630/21 = 172$
Williams (2004)	290^{l}	$7,320^{l}$	$83\%^{l}$	$6.77^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
Williams (2006)	290^{l}	$6,400^{l}$	$81\%^{l}$	$5.99^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
Usage							
Williams (2005) and BUWAL-250	80^{l}	$1,680^{l}$	$25\%^{l}$	$1.02^{c(l)}$	CRT	none	In Williams (2005) it is claimed that the energy consumed in the usage phase is $\frac{1}{3}$ of the energy used in the production phase. The energy consumed in the usage phase is, therefore: $\frac{1}{3} \cdot 5,040$. Considering the same FFD/CED ratio we calculate the CED and CED(%)
Gotthardt et al. (2005) and BUWAL-250	$83^{c(l)}$	$1,740^{l}$	$39^{c(l,e)}\%$	$1.61^{c(l)}$	N.A.	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD. We also assume that the computer has been used for two years	$FFD = 1740/21 = 129$
Dell (2007b)	$93^{c(l)}$	$1,960^{l}$	N.A.	$1.81^{c(l)}$	LCD	We consider the following specifications: Intel Core 2 Duo,17 " screen, flat panel, in usage for 7 hour a day, maximum performance 1h a day.We assume that the computer has been used for 2 years.	$FFD = 1960/21 = 93$
Choi et al. (2006) and BUWAL-250	N.A.	N.A.	$15^{l}\%$	N.A.	excluded	we approximate CED from GWP	N.A.
Apple (2007c)	$89^{c(l)}$	$1,872^{l}$	N.A.	1.80^{l}	LCD	We assume a 20-inch iMac, working 8h usage per day, 7 days a week, with Energy saver enabled. We also assume the same FFD/CED found in Williams (2005) to calculate FFD.	FFD=1872/21=89
Dell (2007c)	N.A.	N.A.	N.A.	6^{l}	LCA	none	no calculations (values extracted directly from the literature).
Atlantic Consulting and IPU (1998)	$485^{c(l)}$	$10,200^{l}$	$74\%^{l}$	$9.43^{c(l)}$			
TIAX LLC (2006)	78^{l}	$1,656^{l}$	N.A.	$1.53^{c(l)}$	laptop	based on the estimation for a laptop in 2005	no calculations (values extracted directly from the literature)
Williams et al. (2002)	N.A.	$1,500^{l}$	$17\%^{l}$	$1.39^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)
Williams (2006)	59^{l}	$1,270^{l}$	$19\%^{l}$	$1.17^{c(l)}$	CRT	none	no calculations (values extracted directly from the literature)

Table 4: Cumulative Energy Demand for the different phases of the life cycle of a personal desktop computer (cont.). The analysis include the computer's monitor. FFD† is the fossil fuel demand in kg of fossil fuel. CED‡ is the cumulative energy demand. ^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

Transportation							
Williams (2005) and BUWAL-250	$1.4^{c(e,l)}$	28^e	1%	≤ 0.10	(-)	We assume that a computer travels $1,000km$ in a 16t truck and weights $10kg$	According to BUWAL-250, a 16t truck has the has the efficiency of 2.88MJ/t*km. The energy spent is, therefore $\frac{1{,}000 \cdot 10 \cdot 2.88}{1000} = 2.88$. Considering the ratio 21MJ/kg of fossil fuel (Williams (2005)) we have $\frac{28}{21} = 1.4kg$ of fossil fuel.
Gotthardt et al. (2005) and BUWAL-250	$1.4^{c(e,l)}$	28^e	1%	≤ 0.10	(-)	We assume that a computer travels $1,000km$ in a 16t truck and weights $10kg$	According to BUWAL-250, a 16t truck has the has the efficiency of $2.88MJ/t*km$. The energy spent is, therefore $\frac{1{,}000 \cdot 10 \cdot 2.88}{1000} = 2.88$. Considering the ratio 21MJ/kg of fossil fuel (Williams (2005)) we have $\frac{28}{21} = 1.4kg$ of fossil fuel.

Table 5: Cumulative Energy Demand for the different phases of the life cycle of a mobile phone. The analysis include the computer's monitor.FFD[†] is the fossil fuel demand in kg of fossil fuel.CED[‡] is the cumulative energy demand. ⋄ prices are expressed in U$ dollars. Source:www.carbonfound.org (CarbonFund (2007)).^{l} refers to data extracted directly from the literature. ^{e} refers to value that have been estimated in our study, i.e. transportation moment $^{c()}$ refers to values that have been calculated. The parameters are the aforementioned l and e.

source of data	FFD[†]	CED[‡]	CED (%)	carbon offset costs[⋄]	main assumptions	calculations
Manufacturing						
Gotthardt et al. (2005) and BUWAL-250	*N.A.*	N.A.	$59^{c(l)}$%	0.81	direct from literature.	
Singhal (2005)	$2.4^{c(l)}$	150^l	60^l%	0.12	data comes directly from literature, for "light" usage. The data differs little from the "high" usage data.	$FFD = 60\% \cdot 4 = 2.4$
Frey et al. (2006)	$8^{c(l)}$	$(132 - 165)^l$	$50^{c(l)}$%	0.15	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD	$FFD = 165/21 = 8$
McLaren and Piukkula (2004)	$7.6^{c(l)}$	160^l	$57^{c(l)}$%	0.15	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD.	$FFD = 160/21 = 7.6$
Usage						
Gotthardt et al. (2005) and BUWAL-250	N.A.	N.A.	$41^{c(l)}$%	0.55	direct from literature	
Singhal (2005)	$1.2^{c(l)}$	77^l	29^l%	< 0.10	data comes directly from literature, for "light" usage. For "high" usage, the energy consumed in the usage phase is equal to 101MJ. It is assumed in Singhal (2005) that the mobile is used for two years	$FFD = 60\% \cdot 4 = 2.4$
Frey et al. (2006)	$6^{c(l)}$	116^l	$41^{c(l)}$%	0.15	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD. No information is available concerning the number of years the mobile is used	$FFD = 116/21 = 6$
Schaefer et al. (2003)	N.A.	$94^{c(l)}$	N.A.	< 0.10	data for annual consumption comes directly from Schaefer et al. (2003). The energy consumption includes the energy dissipated by the mobile charger when charging a full mobile battery. We assume that the mobile is used for 2 years	(N.A.)
McLaren and Piukkula (2004)	$4.28^{c(l)}$	90^l	$32^{c(l)}$%	< 10	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD. It is assumed in McLaren and Piukkula (2004) that the mobile is used for two years	$FFD = 90/21 = 4.28$
Transportation						
Williams (2005) and BUWAL-250	insignificant	insignificant	$\leq 1\%$	< 0.10	We assume that a mobile travels $1,000km$ in a 16t truck and weights $0.13kg$ (Nokia (2007))	According to BUWAL-250, a 16t truck has the has the efficiency of 2.88MJ/t*km. The energy spent is, therefore $2.88 \cdot 1000 \cdot \frac{0.13}{1000} = 0.4$
Singhal (2005)	$0.5^{c(l)}$	28^l	11^l%	< 0.10	data comes directly from literature	
Frey et al. (2006)	$1^{c(l)}$	31^l	9^l%	< 0.10	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD.	$FFD = 31/21 = 1$
McLaren and Piukkula (2004)	$1.43^{c(l)}$	30^l	11%	< 10	we assume the same ratio FFD/CED found in Williams (2005) to calculate FFD.	$FFD = 30/21 = 1.43$

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