Personal Computer Remanufacturing and Energy Savings

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1 Introduction.

Personal computer devices have become ubiquitous today. Starting with being a product driven by market demand, the computer has become one of the major market drivers, forcing other products and technologies to conform to its existence. As a result computer hardware production volume has grown exponentially [5] over the past decade, with more than 64 million personal computers (desktop and laptop computers) installed in the United States in 2007 alone [8]. Expeditiously growing versatility and improving functionality of personal computer devices causes consumers to change their computers much prior to mechanical or electrical failure, leading to several tons of usable devices being abandoned every year. This has increased concerns about hazards associated with electronic waste all around the country, as the US EPA [8] analyze electronic waste in the US to promote eco-friendly end of life options for computers. Their surveys and findings have declared land filling to be much more common than both recycling and incineration of personal computer devices. However, the most common end of life option undertaken for desktop computers, laptops, and computer monitors is either reuse or storage. The fact is that many of these devices are abandoned due to mere obsolescence and in actuality are good enough for continued use or can at least be resold to suffice less intensive computing requirements. This would instantly save on the energy and environmental impacts associated with both manufacturing and production of raw materials for the new device otherwise purchased. If followed for every computer, these savings would cumulatively be gigantic and very impressive. This implies that computer devices should be used and continued to be reused (if they suffice application requirements), until they undergo a permanent failure where in recovery is impossible or as intensive as manufacturing a new personal computer device.

This study is to analyze the energy savings potential of remanufacturing of personal computers (PC). 'Personal Computers' includes desktop control units, laptops (notebooks), and computer monitors (CRTs and LCDs). Remanufacturing by definition entails complete disassembly of a returned computer, followed by critical inspection for any defects, and finally refurbishing, or revival of usable components to a "like new" condition. The components discarded, are replaced by either new or similarly remanufactured components. Finally, all the revived components are assembled back, tested for like-new conditions and returned to the market for sale. However, in the computer world, the fast paced technology does not give enough time for computers to be remanufactured with such scrutiny. Logically, it is more common for computers to be resold as it is or after upgrading to enhance its performance and remaining life. An upgrade by itself is a very consumer specific activity, and hence it is very hard to average them out. Upgrades can include replacing of the existing used hardware like hard-drives, RAM, disk-drives etc; and/or softwares with new state-of-te-art ones.

The methodology adopted for this analysis is similar to that for other product-studies, where the situation considers a consumer with a choice of either purchasing a new computer which will be the average state of the art new computer of that particular year or he/she may purchase an used, second hand computer, which has already lived through one life. From an energy-analysis perspective, this situation is also equivalent to a consumer looking to replace his old computer with a new one, against the option to continue using his existing computer.

2 Computer After-Market

The computer after-market dictates the different end-of-first-life options for personal computers. Though in this study we are considering the reuse of personal computers, there are other end-of-life options like recycling, landfill, incineration, storage etc, as well. A report by the Environmental Protection Agency (EPA) [8] used data of waste allocation from four to five states of the US and a number of surveys from the Consumer Electronics Association (CEA) and MetaFacts to estimate the end-of-first-life management allocation weights for personal computers, as shown below in Figure 1:

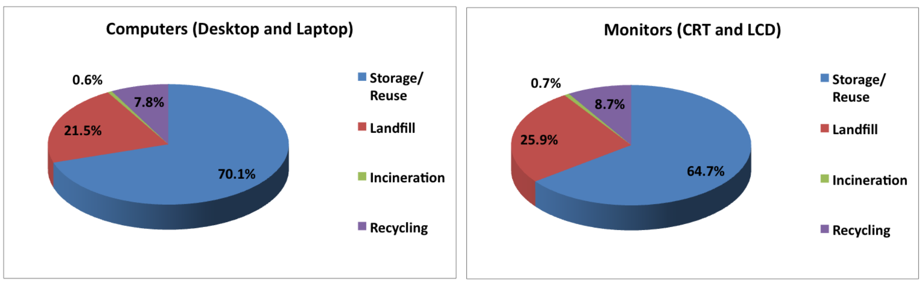

Figure 1: End-of-first-life Options [8].

The data collection methodology was not able to distinguish between storing and reusing the computer, and hence the two options have been lumped together. It is evident that the majority of desktops, laptops and monitors are either reused or put into storage after the end of their first life.

Williams and co-workers have reported the US used-PC market in 1997 to be 5.5 million units [29]. They also combined this statistic with other reports to suggest that this corresponds to a market share of approximately 18 % of the total PC market.

3 Drivers of Change

A consumer seeks to change their personal computer device under two conditions - 1. if the device fails to perform the required functionality (this includes the case where the device has mechanically or / and electrically failed); 2. if the device is obsolete. Unless the device has failed mechanically or / and electrically, there is still some useful life in the device and hence can be put into reuse. In order to understand the potential of reusing, it is important understand the reason behind changing the personal computer device.

Replacement of personal computer devices can be broadly classified into two categories:

- Category A - replacement of a desktop with a laptop, or a CRT monitor with a Flat Panel Display (FPD) monitor.
- Category B - replacement of a functional desktop/laptop/monitor with a new, state of the art desktop/laptop/monitor, i.e. replacement of a similar device.

Though Category A and Category B may have the same potential customer set, the driving force for change is relatively different, and hence the analysis is classified. In the following sections we would like to address both these scenarios and estimate if these changes in technology are friendly for the environment or not. To do so, we shall use the energy used over the life cycle of a computer, as the metric. This is often also known as the Gross Energy Requirement (GER) [19] or the Cumulative Energy Demand (CED) [17]

4 Analysis.

4.1 Introduction

Figure 2 exhibits the increasing sales and increasing market share of laptops and liquid crystal displays ([1]). Both these changes can be attributed to increased functionality, as both the devices occupy lesser space than their competitors, providing the same performance. Increase in notebook computers is also attributed to its portability attribute, however, once purchased, notebooks are often also used for on-desk usage.

Another major reason for the discontinued use of functional personal computer devices is the fast paced improvements in performance characteristics, offering more with every newer generation. To exemplify this, figure 3 [16] shows the considerable improvement in the MIPS (Million Instructions per Second) of Intel Processors over the years. Over a period of 30 years, Intel processors have become more than a million times faster.

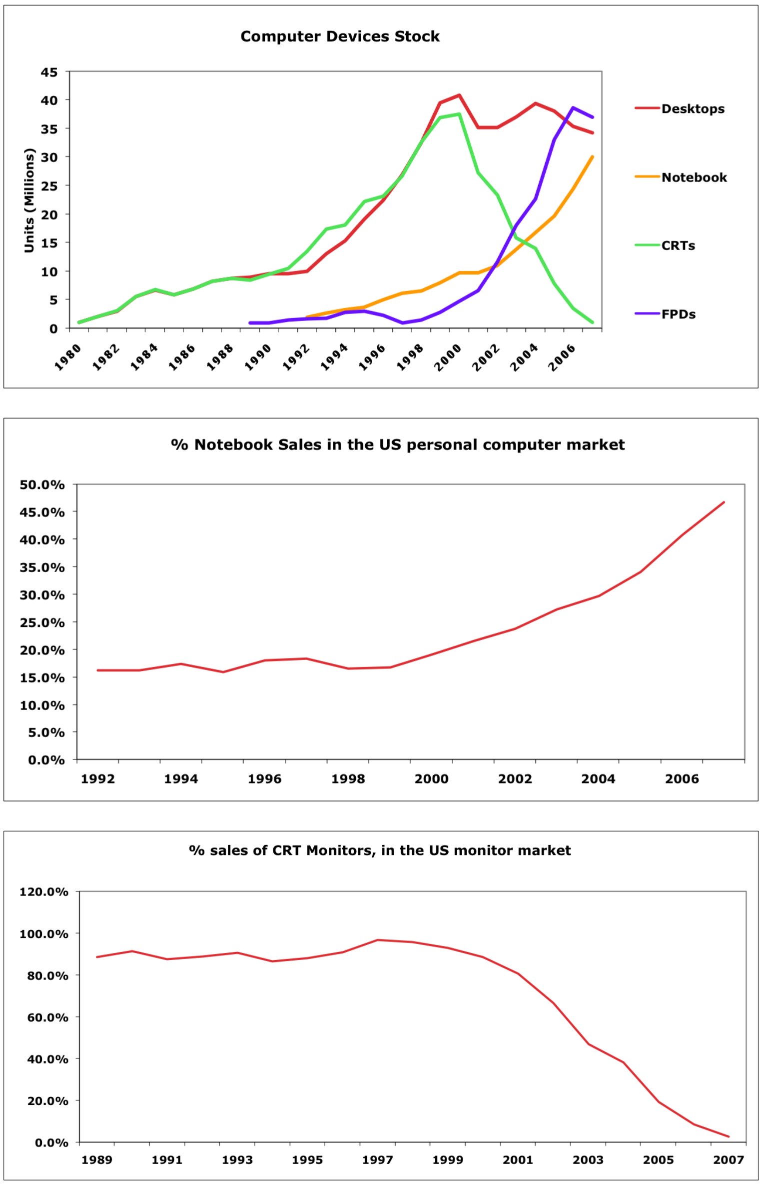

Figure 2: Personal Computer National Stock Trend [1].

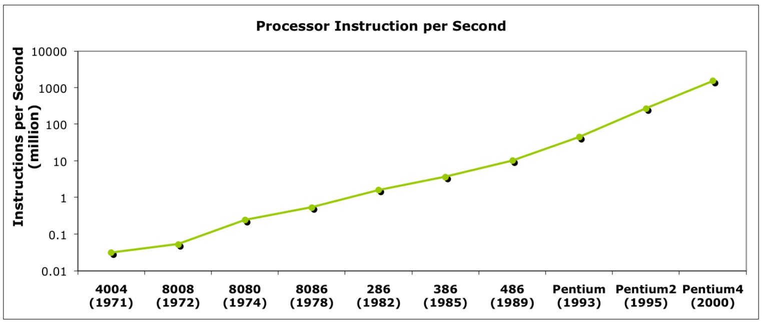

Figure 3: Intel Processor performance characteristic trend[16].

Similar trends can be seen with the primary memory (RAM), storage, Graphical User Interphase (GUI) etc. The wide range of performance characteristics available in the market allow a consumer to assemble a desktop/laptop of their personal configuration, and thus it is hard to find what the average trend is. However, a major driver of the frequent improvements in the hardware is the quickly changing softwares. Microsoft Corporation, the leading Operating System (OS) provider, constantly works on making operating systems which can offer more. The more an operating system has to offer, usually, the more are its hardware requirements. Figure 4 shows the minimum hardware system requirements (memory, storage and processor) for newer generation of Windows, since 1995 (obtained from the Microsoft website, www.microsoft.com/). The OS are arranged from older to newer generations on the x-axis.

Clearly, system requirements have been almost exponentially increasing making personal computer consumers replace their functional devices with newer ones, so as to support the latest OS. However, the fact is that for most applications (browser, Microsoft Office etc), the old computer can itself be used without any functional limitations. Even if abandoned, the old computers can always find place back in the market, in applications that do not entail extensive computing, for instance, with a register at a store, or with many research instruments, which operate on older versions of OS etc.

Therefore, intuitively, from a materials and energy conservation perspective, it seems highly essential to be able to reuse personal computer devices and save the energy expended in the production of the device. However, this intuitive approach may not always be the best for saving energy, as exemplified by the analysis below.

4.2 Data Source and Methodology.

In order to compare the energy requirements during a life cycle of a new computer against an old one, [19] was referred and used as the base case.

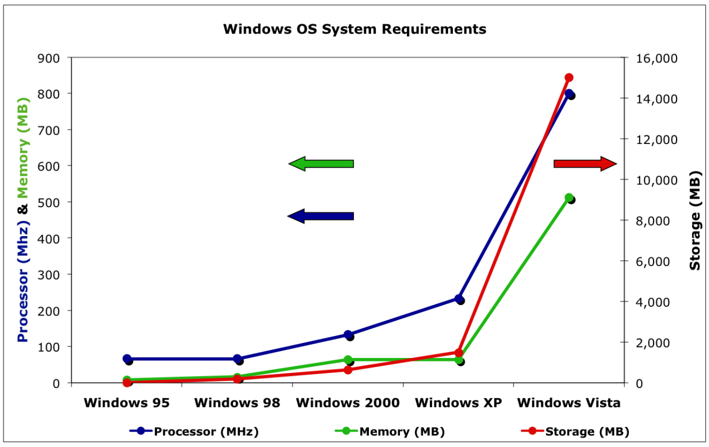

Figure 4: Microsoft Windows Operating System Requirements for different versions, 1995 onwards.

The bill of materials for the different analysis have been self-calulated by [19] who have used a model created by Van Holsteijn en Kemna BV (VHK, http://www.vhk.nl/), using the MEEuP (Methodology study Eco-design of Energy using Products) methodology [11] to generate the Gross Energy Required (GER) for raw material production and component manufacturing. This analysis has been done explicitly by [19] already. The assembly and distribution of the product have not been considered. In the MEEuP methodology, manufacturing energy of the Integrated Circuits and several other electronic components has been included in the raw material production stage, so for this analysis, we are going to use the total energy embodied in the components (raw material production + manufacturing) from [19]

Using this approach and using the assumption that the one time use of a computer is 4 years, the purchase of a 2005 new computer was compared with the reuse of a computer manufactured in 2001. Data for an average computer in 2005 was taken from [19], while for a 2001 computer was taken from [20].

Similarly, a comparison of a new 2009 computer was drawn with the reuse of a computer manufactured in 2005. With the increase in Energy Star qualified computers in the United States, recent computers have become lesser power consuming, thanks primarily to the lesser power consumed in inactive modes (sleep and off) and the more effectual power management. Also, with the increase in Laptop share in the PC market, personal computer device manufacturers are beginning to give more importance to efficiency and efficiency related metrics like energy per instruction for processors [9].

These improvements are opening new doors into innovative energy efficient desktops and other personal computer devices as well. Hence, for 2009, the average personal computer characteristics were assumed to be that of an average Energy Star qualified personal computer device (the sensitivity analysis for this assumption is worked out later). This data was obtained from the Energy Star website [27]. This helps us in using the best case scenario in favor of new computers since every Energy Star qualified personal computers are one of the least energy demanding of their type (at least during the use phase). It should be reminded that the new Energy Star requirements (that are satisfied by the considered personal computer devices [26]) for desktop control units and laptops came into effect July 1, 2009, and those for displays below 30 inches came into effect from Oct 30, 2009.

4.3 Life Cycle Assessment (LCA)

4.3.1 Bill of Materials

The bill of materials (BOM) obtained from [19] are shown in figure 5.

These BOMs represent an average computer of 2005. The following are the configurations:

- Desktop: 3 GHz processor (or equivalent), built-in graphics card, 512 MB RAM, 80 GB HDD
- Laptop: Mobile 1.7 GHz processor (or its equivalent), good 3D graphics performace, 15"-screen, 512 MB RAM and 60 GB HDD
- CRT Monitor: 17"
- LCD Monitor: 17", with a resolution of 1280*1024

These specifications and the BOM are for an average best-selling computer or display in 2005.

4.3.2 Manufacturing

As mentioned before the manufacturing energy was obtained from the model formulated by VHK, using the MEEuP methodology [11].

4.3.3 Use Phase

In order to calculate the energy consumed in the use phase of any product, one needs to know the power consumed during usage and the time for which the product is used.

For a computer (including the monitor) the power consumed depends on the mode of usage. The most popular modes are -

Desktop PC

Material	Weight (g)
LDPE	246
ABS	380.75
PA 6	137.68
PC	264.25
Epoxy	97.9
Flex PUR	1.5
Steel Sheet Galvanized	6312.3
Steel tube/profile	106.5
cast iron	482.5
ferrite	0
stainless 18/8 coil	9.5
Al sheet/extrusion	314.53
Al diecast	15
Cu winding wire	257
Cu wire	33.5
Cu tubesheet	66.5
Powder Coating	1.62
Big Caps and coils	482.5
Slots/ ext. Ports	310
Integrated Circuits, 5% Si, Au	69
Integrated Circuits 1% Si,	95.5
SMD and LED avg	193.5
PWB 1/2 lay 3.75 kg/m sq.	78
PWB 6 lay 4.5 kg/m sq	162.5
solder SnAg4CuO.5	48
Cardboard	2286.5
Total (Kg and MJ)	**12.45253**

Notebook PC

the integrated monitor is included in the balance

Material	Weight (g)
LDPE	43
PP	4
PS	2.6667
EPS	50.333
PVC	23.333
ABS	141.83
PA 6	280.54
PC	267.1
PMMA	36.333
epoxy	2.6667
steel sheet galvanized	489.23
Al sheet/extrusion	37.9
Cu wire	60
Cu tube/sheet	15.2
MgZn5 cast	121.67
Power Coating	4.7933
LCD screen m sq (viewable screen size)	63.167
Big caps and coils	501
Slots/external parts	132.93
Integrated Circuits, 5% Si, Au	46.833
Integrated Circuits 1% Si,	31.167
SMD and LED avg	50.247
PWB 1/2 lay 3.75 kg/m sq.	4.8
PWB 6 lay 4.5 kg/m sq	76.867
solder SnAg4CuO.5	6.9667
Glass for lamps	0.6667
Cardboard	921
Glass for LCD	362.33
Total (Kg and MJ)	**3.7785701**

17" CRT Monitor

Material	Weight (g)
EPS	165
PVC	43.8
ABS	1754.8
PA 6	447.47
PC	0.55
Steel sheet galvanized	126
Al sheet/extrusion	14
Cu wire	222.2
powder coating	6.03
CRT screen m sq (nominal screen size)	90.2
Big cas and coils	37.5
Slots/ ext.. Ports	40
Integrated Circuits, 5% Si, Au	17
Integrated Circuits 1% Si,	13.5
SMD and LED avg	12.5
PWB 1/2 lay 3.75 kg/m sq.	96
PWB 6 lay 4.5 kg/m sq	23.5
solder SnAg4CuO.5	11
Glass for lamps	6.5
Cardboard	1880
Office paper	280
misc glass	11110
Total (Kg and MJ)	**16.39755**

17" LCD Monitor

Material	Weight (g)
LDPE	164
EPS	278.7
PVC	42.8
ABS	679.1
PA 6	422.22
PC	384.75
PAMMA	152.85
E-glass fibre	119.75
Armid fibre	6.5
steel sheet galvanized	1854
Al sheet/extrusion	39
Cu wire	189.6
powder coating	1.03
LCD screen m sq (viewable screen size)	91.3
Big cas and coils	41.35
Slots/ ext.. Ports	36.55
Integrated Circuits, 5% Si, Au	12.85
Integrated Circuits 1% Si,	20.35
SMD and LED avg	10.7
PWB 1/2 lay 3.75 kg/m sq.	30
PWB 6 lay 4.5 kg/m sq	19.6
solder SnAg4CuO.5	7.55
Glass for lamps	26
Cardboard	650
Office paper	54.5
misc glass	307.6
Cast iron	1165
Total (Kg and MJ)	**6.80765**

Figure 5: Bill of Materials [19].

(a) *Idle* - when the computer/montor is on and left by itself (idle). Note that it is hard to quantify the *active* power mode (while using programs), as it strongly dependent on the number of programs, characteristics of programs, computer hardware etc. Thus, the idle power is used for active mode calculations.

(b) *Sleep* - When the computer/monitor is put into some type of intermediate power consuming stage between active and switched off.

(c) *Switched off or standby* - when the computer/monitor is completely switched off but kept connected to the power socket.

Authors of [19] have estimated these values using self-measurements and data cases on a number of devices, so as to generate an average for devices in 2005. Figure 6 gives them in a tabulated fashion. Along with them, are also shown the average values for personal computer devices manufactured in 2001 and 2009, obtained from [20] and [27] respectively.

	Idle (W)	Sleep (W)	Off (W)
Desktop (2001)	70	9	3
Desktop (2005)	78.2	2.2	2.7
Desktop (2009)*	53.16	2.93	1.61
CRT (2001)	61.44	2	0
CRT (2005)	69.5	1.5	1.5
CRT (2009)*	37.00	2.00	1.00
FPD (2001)	34.68	2	2
FPD (2005)	31.4	0.9	0.8
FPD (2009)*	25.08	0.79	0.65
Laptop (2001)	19	3	2
Laptop (2005)	32	3	1.5
Laptop (2009)*	15.78	1.44	0.82

Figure 6: Power Consumption Values for different devices in different modes [19].

Based on summer surveys and existing data cases [19] approximated the usage pattern of these devices. Though these values have been obtained from surveys in the European Union (EU), it is assumed that computer usage in the United States and EU are approximately the same. This is shown in figure 7.

This gives the balanced estimates for the use phase of personal computer devices. Please note that 'desktop' in the above and below text and figures refers specifically only to the control unit and does not include the monitor.

4.3.4 LCAs

Using the above given data, life cycle assessments (comprising of manufacturing and raw material production; and use phase, but devoid of the as-

Computer Usage Pattern	Location	Mode	Hours (hours/day)
Desktop	office	off	9.0
		sleep	8.8
		active	6.2
	home	off	11.8
		sleep	7.9
		active	4.3
Laptop	office	off	8.6
		sleep	8.2
		active	7.2
	home	off	12.2
		sleep	8.0
		active	3.8
Monitor	office	off	6.5
		sleep	10.4
		active	7.1
	home	off	13.2
		sleep	7.2
		active	3.5

Figure 7: Usage Pattern of Personal Computers. For completion, use patterns for both home and office usage are provide, but to avoid redundancy in calculations, only home usage is considered in this study. [19].

sembly, distribution and disposal) for the different devices in consideration are show collectively in the graph below (figure 8)

For simplicity and to avoid repetition, this study only analysis home used personal computer devices only. The analysis for office usage can be conducted similarly.

4.4 Literature Comparison.

- [12, 32] have shown the production energy of a processor (the largest energy consuming step in computer manufacturing) to be an order of magnitude lower than the use-phase energy. This result conforms more with the life cycle assessment used in this study.

Eric D. Williams has published extensively on this topic through several publications [30, 15, 31, 28], and a book [13]. Using the bill of materials from papers published in 1998 [21, 22], estimating the manufacturing energy by combining Process based and Economic input-output methods, and approximating the use pattern of computers of that time, Eric Williams and co-workers have shown the manufacturing (including raw material production) phase to dominate over the life cycle. This is clearly not the case for the LCAs shown above. To understand the reason, we have listed out the key differences found between the two analysis:

- One of the key differences come from the lesser usage assumed for the devices considered, by Williams and Masanet [30, 15, 31, 28, 29]. In

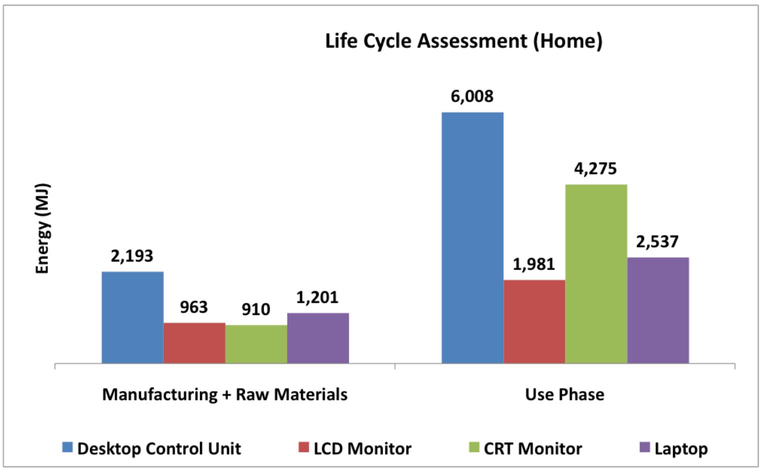

Figure 8: Life Cycle Assessments of Personal Computer devices.

[30, 28, 31], a residential computer is assumed to be used for 3 hrs in a day in active mode, and switched off for the rest, and the life time is estimated to be from 2 to 3 years through surveys. In [29], a survey is used to estimate the length of the first use-time of a computer in Japan, giving 2-3 years to be the most popular replies. In the same, the use pattern in also obtained through a survey indicating a 2.6 hrs/day residential usage with 78% of the users turning off their machines when not in use. Masanet et al. [15] used a report by Kawamoto [10] which estimates a more detailed usage pattern for office computers. Apart from this there exists a variation of 2 - 6.6 years in the length of the first life-time of personal computer devices as further explained in Section 5 (*Assumption 1*). All these estimates come from reports based on studies before 2005, which is the year of consideration in this report and thus the usage pattern from [19] is used for this study (figure 7) as [19] have conducted surveys and literature studies to estimate the use pattern in 2005 specifically, making calculations for this study more accurate.

- In [30, 13, 28], Williams and co-workers estimate the energy used in the production of desktop control units and CRT monitors. In [30], Williams uses a hybrid methodology to estimate the an energy consumption of 7,320 MJ *(using 1 kWh = 3.6 MJ)* for production (just before sale) of a desktop with a 17 inch CRT monitor. With-in this the process-based sum corresponds to only 3,230 MJ *(using 1 kWh = 3.6 MJ)*, which is similar to the estimate used from [19]. Other reports by Williams are similar. It should be mentioned that the hybrid analysis includes the energy consumed in transportation, telecommunication, plastic plumbing fixtures, waste management and other such processes too. For this study, the boundary of analysis only includes process-based energies.

4.5 Environmental impact of Personal Computer changes

Considering the decision of the customer to purchase a new device against a reused one (one lifetime (= 4 years) old); or the abandonment of a function devices (one lifetime (= 4 years) old) for a new device. This entails an energy expenditure equal to the manufacturing energy cost of the new device. Assuming that the new device is more energy efficient, there should be an expected energy saving during the use phase equal to the difference between the use phase energy consumption of the reused device and a new device. Thus it is important to compare life cycle energy assessments so as to estimate the energy savings strategy.

Before comparing new devices with old ones, first lets look at the inherent energy impact of the trends of increasing market share of notebook computers and preference of consumers for LCD monitors over CRT monitors (Figure 2). Figure 9 gives the life cycle energy assessment comparisons between these new technologies (laptops and LCD monitors) and old technologies (desktops and CRT monitors) for the year of 2005. This graph compares the LCAs for all new devices. In other words, for a consumer seeking to buy a new personal computer device, the choice is of of either buying a notebook or a desktop computer, and similarly of either buying a LCD monitor or CRT monitor. The choice of buying a combination of desktop/laptop with CRT/LCD monitor is also considered. This is similar to *Category A* changes, except that it compares two new devices and not a replacement-scenario.

It is observed, that all cases yield energy savings for the new technologies. In other words, the trend of moving from desktops to laptops and from CRT monitors to LCD monitors is inherently an energy saving strategy. Figure 10 exhibits the same in terms of percentage energy savings by choosing the older technology over new in the year of 2005.

Thus choosing a new laptop over a new desktop, or a new LCD monitor over a new CRT monitor leads to relative energy savings over the life cycle of the personal computer device. This choice is for a customer who has decided to purchase new. Before this decision point the same customer faces the choice of purchasing a new personal computer device or an old one. A similar scenario is for the customer who is to decide whether to purchase a new personal computer device or to continue using the existing one.

The typical purchase-to-purchase lifespan for computer products is 4 years (see Section 4.2). Thus an old PC device refers to one built with a state of the art technology 4 years prior to the year of analysis. For example,

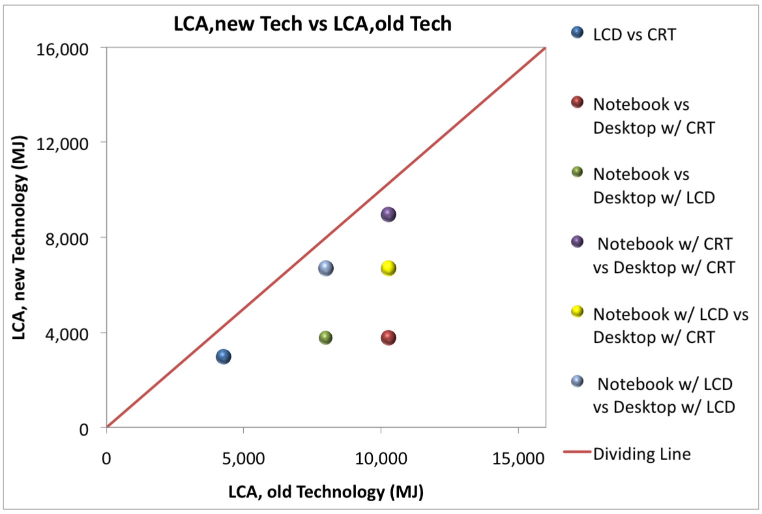

Figure 9: Life Cycle Assessments of Personal Computer devices.

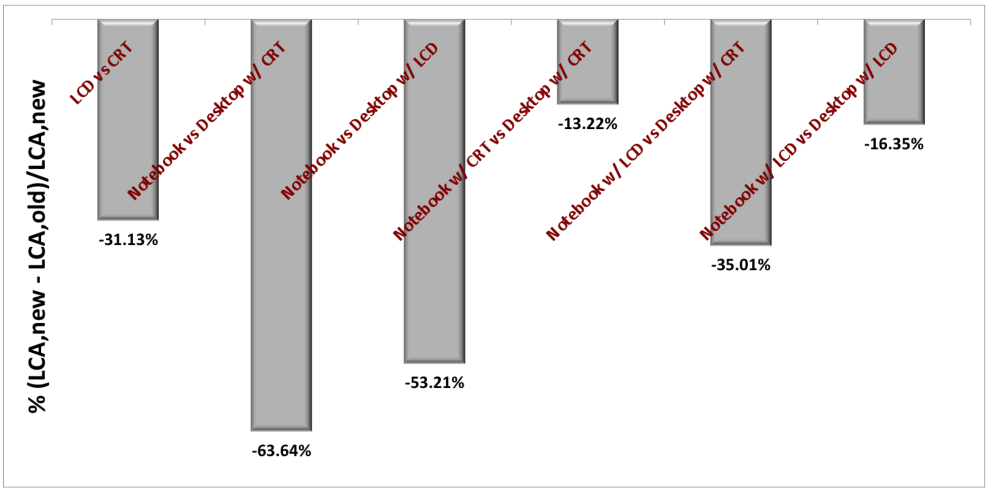

Figure 10: Percentage life cycle energy savings by choosing old technology devices over new. Both choices are for new devices. Negative savings indicate, net relative savings for the new technology.

in this study, the analysis is conducted for the years of 2005 and 2009, and thus old PC devices are from the years of 2001 and 2005 respectively.

For the 4 personal computer devices in consideration (desktop control unit, laptop, CRT monitor, LCD monitor), a life cycle energy assessment comparison for Category A type changes is shown in Figure 11.

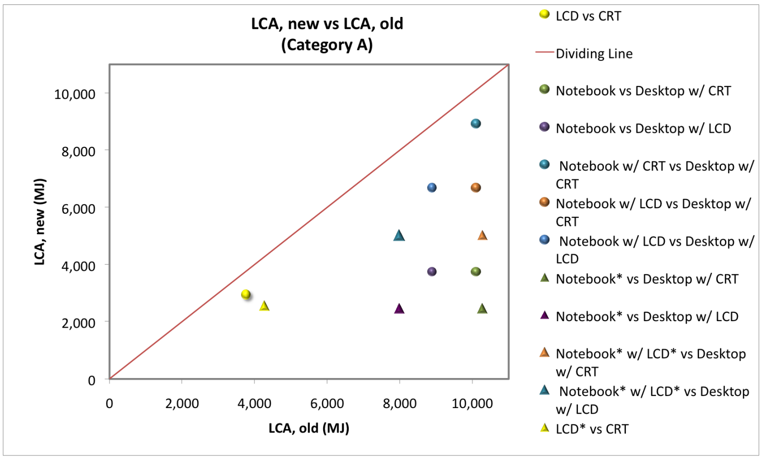

Figure 11: Life cycle energy assessment comparisons between a choosing a new personal computer device with choosing an old (resell or reuse) one (Category A). The analysis is done for two years - 2005 and 2009. Circles depict the 2005 analysis while the triangles depict the 2009 analysis. The astrix ("star") for the 2009 analysis signifies the use of EnergyStar qualified devices for 2009. Hence circles compare the life cycle energy requirements for a new personal computer device of 2005 with that of reusing/reselling a personal computer device originally manufactured and sold in 2001 and that has lived through one life of 4 years. Similarly for triangles. Since, only one CRT monitor model is listed to satisfy EnergyStar analysis [27], and because of the declining use of CRT monitors (see Figure 2) the analysis of comparing for new CRT monitors of 2009 is not conducted.

A greater quantitative understanding for the comparison is the *percentage life cycle energy savings by reusing an old device relative to using new*, shown in Figure 12.

In the case before (Figure 9 and 10) the comparison is similar to Category A type choices but between new devices of 2005. In this case (Figure 11 and 12) the comparison is of Category A type choice between a new device of 2005 / 2009 and the old device that was first produced and put into use in 2001 / 2005 respectively. Even in this case, choosing a personal computer device which is new, i.e. changing with the motive of replacing a 4 year old desktop to a new laptop and/or a 4 year old CRT monitor to a new LCD monitor leads to a relative energy savings strategy compared

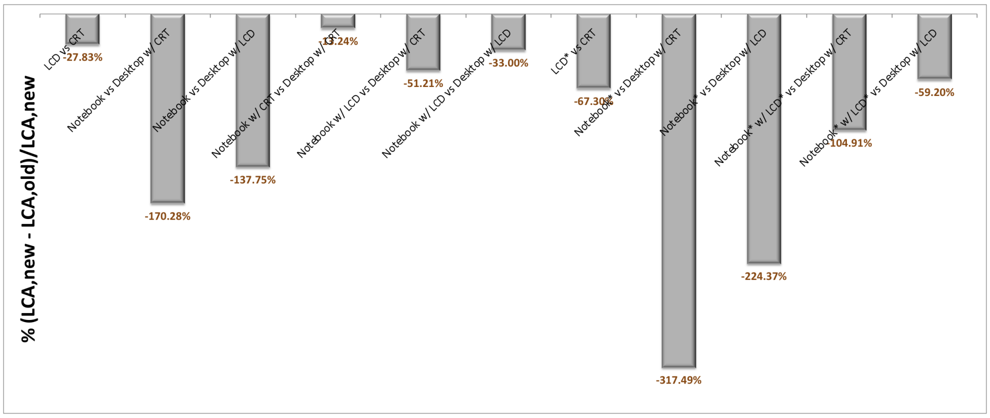

Figure 12: Percentage life cycle energy savings by reusing an old device relative to using new for Category A type changes between the years - 2005 and 2001 (shown in the first 6 bars), and 2009 and 2005 (shown in the last 5 bars. The * (astrix / star) mark indicated the use of EnergyStar qualified personal computer devices for the year of 2009. Since, only one CRT monitor model is listed to satisfy EnergyStar analysis [27], and because of the declining use of CRT monitors (see Figure 2) the analysis of comparing new CRT monitors with old one in 2009 was not conducted.

to reselling/continuing to use the old device. Also like the the case before, changing from a desktop + monitor combination to a laptop yield the maximum savings, indicating the superior efficiency of laptops compared to desktops. It should be reminded that ”Laptops” in the above analysis include desktop replacement laptops, validating the comparison. Figure 12 also shows that the maximum relative savings are obtained for the case of replacing a 2005 desktop + monitor combination with an EnergyStar qualified laptop computer of 2009. This hints of the the relatively high efficiency provided with these devices. Also, in both cases for category A (comparing only new devices and comparing replacement scenarios), the savings calculated are greater than 10% making the result significantly strong.

Hence for category A type changes, choosing the new device is the relative energy savings strategy. Such a strong result for Category A type changes, enhances the curiosity for the the analysis for Category B type changes in which the comparison is in between buying an old or reusing a personal computer device with buying a new personal computer device of the same type. For instance, comparing the life cycle energy assessment of reusing / buying an old desktop (or similarly a laptop/CRT monitor/LCD monitor), which is 4 years old, with the life cycle energy assessment for the decision of buying a new desktop (or similarly a for laptop/CRT monitor/LCD monitor). The analysis is again conducted for both years 2005 and

2009. The results are shown in Figure 13 and Figure 14.

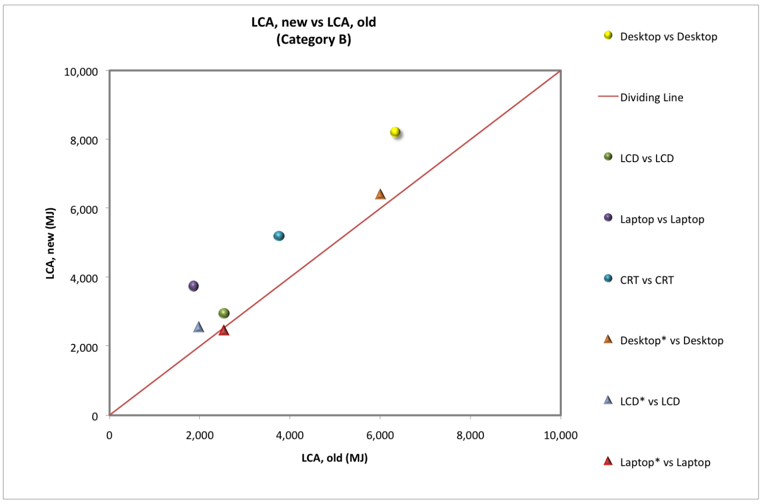

Figure 13: Life cycle energy assessment comparisons between a choosing a new personal computer device with choosing an old (resell or reuse) one (Category B). The analysis is done for two years - 2005 and 2009. Circles depict the 2005 analysis while the triangles depict the 2009 analysis. The astrix (”star”) for the 2009 analysis signifies the use of EnergyStar qualified devices for 2009. Hence circles compare the life cycle energy requirements for a new personal computer device of 2005 with that of reusing/reselling a personal computer device originally manufactured and sold in 2001 and that has lived through one life of 4 years. Similarly for triangles. Since, only one CRT monitor model is listed to satisfy EnergyStar analysis [27], and because of the declining use of CRT monitors (see Figure 2), the analysis of comparing for new CRT monitors of 2009 is not conducted.

In this case, interestingly enough, the results indicate that reusing personal computer devices when making category B type choices is the relative energy savings strategy. Using the reports referenced, choosing to buy new Desktops, Laptops, and Monitors of 2005 in stead of an old one from 2001, or reusing an old one from 2001, can lead to significantly higher life cycle energy consumption. The comparison for 2009 shows that EnergyStar qualified LCD monitors and Desktops are sufficiently more efficient that LCD monitors and Desktops of 2001 such that the savings in the use phase due to higher efficiency overcome the initial relative energy expenditure of manufacturing the new device. If the error associated with Life Cycle assessment is assumed to be 10%, the analysis for desktop and laptops in 2009 is nuanced. It is worth bringing to attention in this study, the data for the three different years of consideration, 2001, 2005, 2009 are procured from three different and independent sources. Personal correspondence with authors

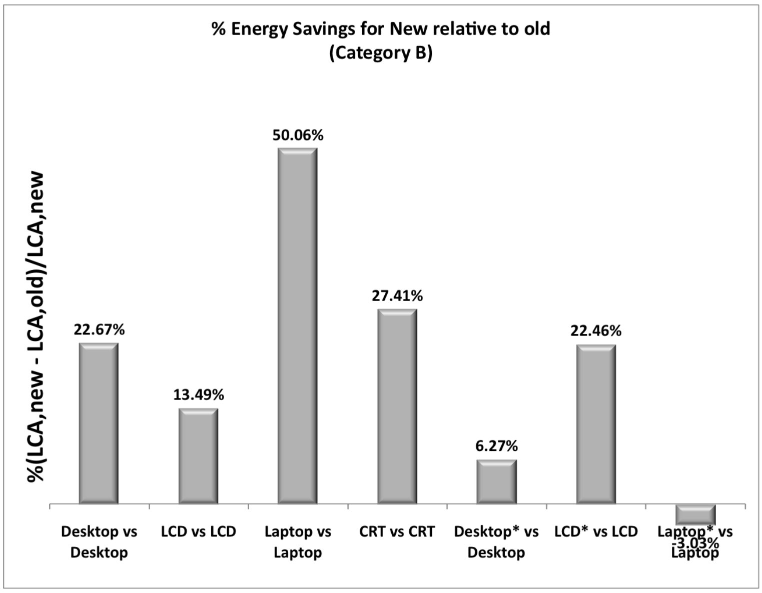

Figure 14: Percentage life cycle energy savings by reusing an old device relative to using new for Category B type changes between the years - 2005 and 2001 (shown in the first 4 bars), and 2009 and 2005 (shown in the last 3 bars. The * (astrix / star) mark indicated the use of EnergyStar qualified personal computer devices for the year of 2009. Since, only one CRT monitor model is listed to satisfy EnergyStar analysis [27], and because of the declining use of CRT monitors, Figure 2, the analysis of comparing new CRT monitors with old one in 2009 was not conducted.

of all three gives confidence in using them, but there still remain few unexplained peculiarities inherent in the description. One such is the power value (32 W) used for Laptops of 2005 from [19] which is relatively higher than that for 2001 (19 W) and 2009 (16 W). While the reasons for this can be guess, but no such literature based evidence was found to explain this. As mentioned, personal communications with the authors of all three sources indicate that the power-measurements for all three sources are done in a similar fashion and thus are comparable.

Thus for category B choices, reusing/reselling LCD monitors in both 2005 and 2009, reusing/reselling CRT monitors in 2005, reusing/reselling desktops and laptops in 2005 is the energy saving strategy. For laptops and desktops in the year of 2009, the comparisons are nuanced.

4.5.1 Discussion

From the study above, it is evident that all new laptop/FPD devices result in a net saving relative to older reused desktops/CRT monitors. In other words, choosing new in Category A scenarios result in net energy savings. One reason for this is the enhanced efficiencies of notebooks and FPD. Grochowski and Annavaram [9] have also discussed the improvement of notebook processors efficiencies in 2004 after the introduction of the Pentium M processors.

Shifting focus on to Category B comparisons, the analysis gets a little more complicated. The graphs depict that in 2005, purchasing a new personal computer device over reusing an old one (originally manufactured in 2001) would use more energy. This can be attributed to the increase in power requirements of the higher performing components in the newer devices. Figure 3 and 4 already hint this. Figure 15 [16, 3] relates Figure 3 to the power consumed for each processor generation. This is the Thermal Design Power (TDP). It is evident how the power consumed by the processors follows its own Moore's Law. Apart from increased power consumed by the processor, other components offering more hard drive space, faster memory access, and better GUI etc. also add to the increase in power consumption of newer devices. The energy analysis thus encourages the reuse of older devices, as long as they satisfy the need and necessities of the consumer.

However, from 2005 to 2009, Energy Star (though voluntarily) has been gaining great publicity. Energy Star sets upper bars on the power consumed by personal computer devices in different modes [25, 26] as evident from figure 13. To add to this, power management (built into operating systems and devices) is also gaining a great deal of importance, which tries to minimize the total energy consumed by a device by efficiently putting it into sleep and standby modes when not in use.

Together, these improvements definitely reduce the relative life cycle energy requirements of new energy star qualified devices over reusing a one-

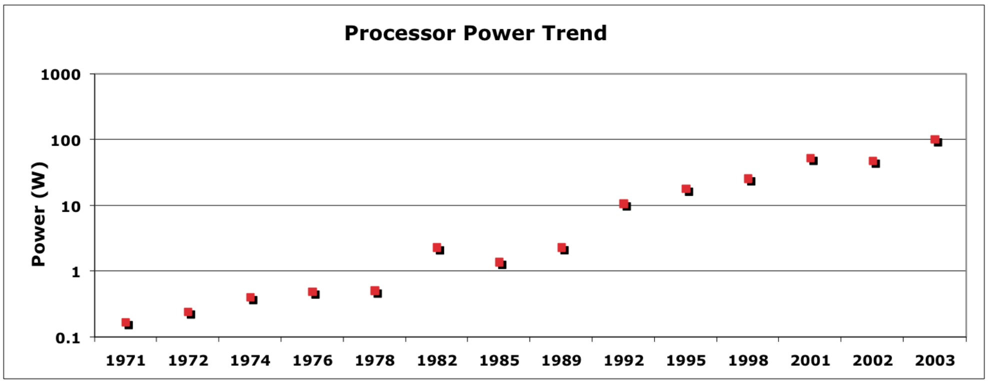

Figure 15: Intel Processor Power Consumption.

lifetime old device as shown in Figure 13 and 14. However, for both Laptops and Desktops, the situation is in proximity to the break-even line (% savings less than 10%), where the energy expended to produce the new device is equivalent to the energy saved by using the new devices relative to reusing the old. Thus to know the impact correctly it is important to get accurate estimations for the energy savings and expenditures.

5 Assumptions.

1. Key-boards, mice and other accessories to a personal computer are not taken into consideration as their environmental impact is assumed to be negligible compared to the monitors/control units/laptops. This is supported by [7]

2. The average lifetime for the use of a computer in the United States is assumed to be 4 years [14, 4, 15] (a 4 year lifespan is also used by Energy Star in their energy indicator models [27]). The total usable life of a computer (including monitor) is taken to be $\geq$ 8 years (as they are usually upgraded after their first life of 4 years), so that a computer when resold can last through an equivalently long second life. Note that a computer monitor can not be upgraded but its total lifetime is assumed to be $\geq$ 8 years. A lifetime use of 4 years maybe different from a few reports, some of which take it to be 3 years [28], some 3.44 years [23] and some from 5.6 - 6.6 years [19]. [7] have assumed the use of a personal computer in China to be for 6 years.

   No concrete report was found which explicitly calculates the total usable life for a computer (including all lives), and hence for convenience, it was assumed that computers, if required, can be used for $\geq$ 8 years, or in other words, they can sustain two equivalent lives of 4 years each.

Researchers at the University of Tennesse and the U.S. EPA [24], have estimated (through industrial surveys) the manufactured life (expected life before mechanical failure) for a LCD monitor to be approximately 45,000 hours and for a CRT monitor to be 12,500 hours. For the use pattern assumed for household usage (which has been the focus of this study), as given in Figure 7, this gives a total lifetime of both types of monitors to be more than 8 years.

3. Some of the reports cited are based on European studies and European computer-device characteristic averages. It is assumed that these hardware averages for Europe would be similar to that for the United States, considering equivalent technological advancements.

4. The use phase pattern for computers has been adopted from [19], assuming that computer usage pattern in the United States is similar to that in the European Union.

5. The assembly and distribution phases are not taken into account in this study. However, later in section 6, approximate values for these stages are considered to evaluate the sensitivity of this assumption. Also, Quariguasi et al [17] reported the transportation energy during computer manufacturing to be approximately 1% of the total production energy, encouraging us to neglect it for the moment.

6. The manufacturing energy of a personal computer device is approximated to be the same in 2005 and 2009. This assumption was made since information for the manufacturing energy of an average 2009 computer could not be found. Sensitivity analysis for this assumption is also considered later.

7. The energy consumed during the upgrade phase between the two lives is assumed to be small and is neglected. This makes the analysis slightly in favor of reusing, and hence the conclusions of using new become stronger on relaxing this assumption.

8. The energy consumed during the maintenance and periodical repair of the device during its use it neglected for simplicity.

6 Effect of Assumptions.

- The 2009 analysis has been conducted for only EnergyStar qualified devices. These devices are considered to be one of the most efficient of their type. If the analysis was to be conducted for average devices, the power consumed by them would be higher. Thus the use phase for the new devices of 2009 would be larger, making the LCA,new to be larger in Figure 11 and 13. Thus all "triangles" (in Figure 11) and "diamonds" (in Figure 13) would move up. However it is worth noting that the data points used for Energy Star qualified devices are averaged from 1,637 models for desktops, 2,035 models for laptops, 435 models for LCD monitors, and thus the general average may not deviate much from the EnergyStar averages used. Thus, for the small shift upward, the "diamonds" would strengthen the conclusions drawn, while the "triangles" (with life-cycle savings larger than 50% for each (see Figure 14) would not move significantly enough to change the conclusion of choosing a new device for energy saving.

- The 2009 analysis has been conducted using the use pattern for 2005. It is expected that the use of computers from 2005 to 2009 has become more extensice. Since the power considered for each 2009 device is lower than that for a 2005 device, making the usage of the devices more extensive is likely to move the data points towards the positive X-axis (as the LCA, reuse will increase more than LCA, new). In other words this will further promote the use of new devices for Category A replacements, and can recommend use of new for some of the Category B replacements too.

- When "idle" mode values are replaced by the more realistic "active" mode values, the data points involving desktops and laptops are expected to shift. However, this shift is impossible to predict without knowing the actual active-mode values. To exemplify, [27] us an "idle" mode power of 84 W and an "active" mode power of 115 W for a conventional desktop computer for its energy savings calculations.

- It should also be mentioned that for data points lying close to the dividing line, the assembly and distribution energy cost (not included in this analysis) should also be taken into account. This would create a distinguishing factor between reusing and reselling the old device (considered equivalent before) as reusing will not have any distribution cost, while reselling would. If this cost is assumed to be the same for new and reselling then the data points would only move in parallel to the break-even diving line, and thus the conclusions would not be affected. If reusing is compared with new, the data points to move upwards (towards the positive Y-axis, as LCA, new would increase, while LCA,reuse would not change). To get a feel for these numbers, the assembly and distribution energy costs for the devices calculated by the VHK model are shown below in figure 16.

  These numbers include transportation, HVAC of warehouses, and selling shops etc, and since this data was calculated for Europe, it was not included in this analysis. However, it can be seen that including the energy cost to assemble and distribute the devices would further promote the reuse of devices from Category B. On the other hand, for

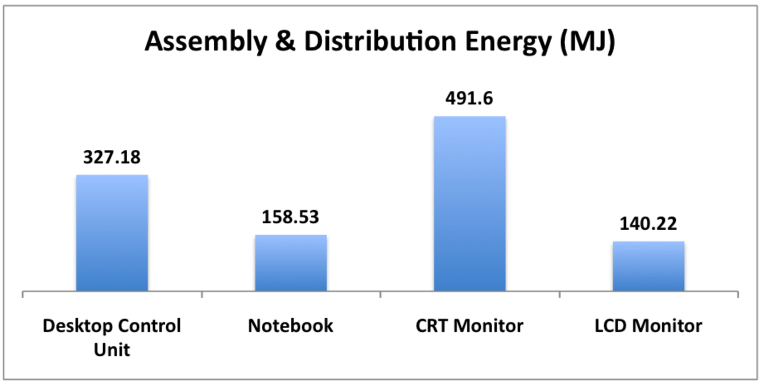

Figure 16: Assembly and distribution energy costs calculated by the VHK model, reported in [19].

Category A replacements, inclusion of data shown in figure 16 would make make the analysis for "LCD* vs CRT" and "Notebook with CRT vs Desktop with CRT" nuanced, while all others would still give appreciable relative energy savings by choosing new. In [30], the energy to assemble a control unit has been estimated to be 578 MJ (after taking 1 kWh = 10.6 MJ [18]) which is in conformity with the above estimates in Figure 16. Unfortunately the referred report by Williams does not give the energy to assemble for all the personal computer devices considered in this study.

- Including the energy used during the upgrade phase (which includes the production of the upgrade-components) will have a similar impact to the inclusion of the assembly and distribution phase. As mentioned before, that an upgrade is very consumer specific and is very hard to estimate. No report was found that evaluated the average upgrade options for computers of 2005 and 2009.

- *Assumption 6* can also have a significant impact on the energy benefits/drawbacks of the use of new personal computer devices. With newer computers incorporating faster processors, larger storage and memory, and better graphics etc., intuitively *assumption 6* seems conservative, i.e. the energy to manufacture newer personal computer devices is expectedly more.

  Unfortunately, we could not find any report which directly calculates the manufacturing energy for the latest 2009 computers. However, to get an idea about the trend, the production of semiconductor devices, which constitute the majority of energy used in manufacturing (as discussed before), was studied for different years. Figure 17 gives the energy to manufacture different processors used previously [6]. It is observed that the energy to manufacture a die is roughly proportional to the area of the die. Also the energy to manufacture a processor is proportional to the area of the wafer used.

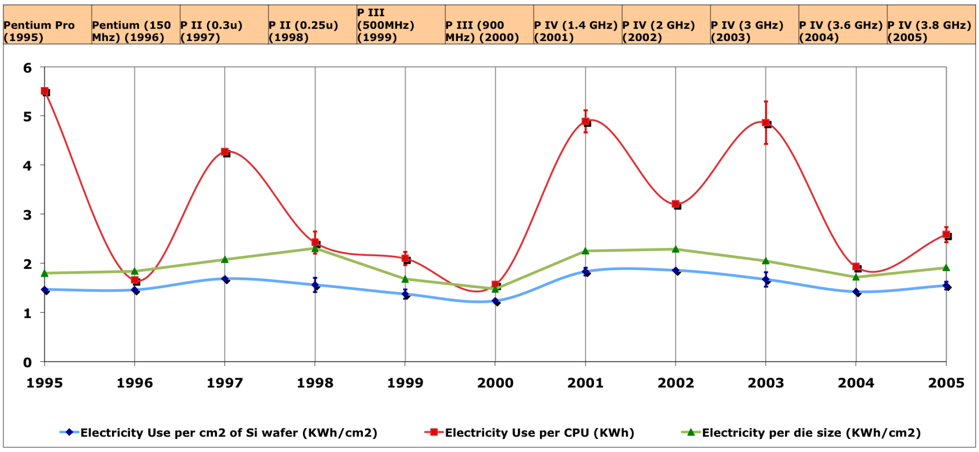

Figure 17: Manufacturing Energy trends for different processors [6].

Figure 18 shows that from 2005 until now the size of the wafer has been predominantly 300 mm [2], and thus there is no change in that respect. However the die size of the new processors (the Energy Star qualified computers specifies their processors, thus hinting the common state of the art processors) has definitely grown (information available on the Intel website) which should incur a greater energy to produce. This is because with a large die size, lesser dice are produced per wafer, and more material is required per die. However, there might be a possibility where a complete change in IC architecture has led to net savings in production energy. No report was found which supports this possibility and thus is could not be accounted for. So, for the moment it can be assumed the energy to produce ICs for new devices in 2009 is greater than that for 2005 (since the die size is larger), and since semiconductors require a majority of the energy used to manufacture a computer, and since other components like hard drives, RAM, have also become more intensive, the possibility of the manufacturing energy of a 2009 computer being higher than a 2005 computer, is likely. This would further shift the "triangle" and "diamond" data points in Figure 11 and 13 upwards (towards the positive Y-axis).

However, no concrete report or estimate of the change in manufacturing energy for personal computer devices from 2005 to 2009 was found and thus it was assumed to be equal.

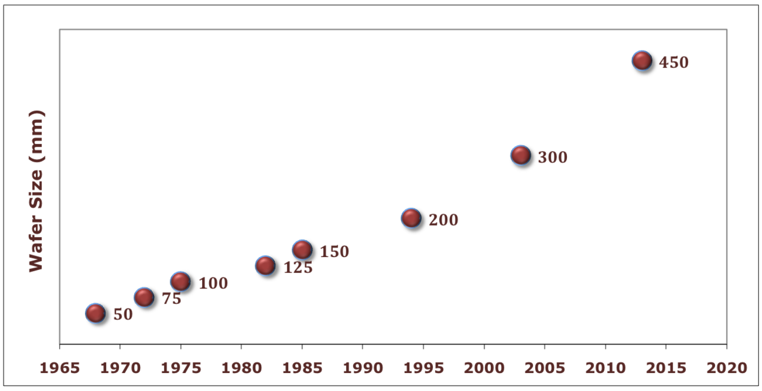

Figure 18: Wafer size trend (a year indicates the year the industrial production exceeded 3 million wafers/year) [2].

7 Conclusions

The above analysis was to evaluate the reusability (a conservative form of remanufacturability, since we assume the reuse life (after a conventional upgrade) to be as long as the first one) of personal computer devices. Personal computer changes were classified into two categories - changing from an old Desktop to a new Laptop, or from an old CRT to a new LCD monitor; changing from an old desktop (or laptop or monitor) to a new desktop (or laptop or monitor) providing better performing hardware, and thus supporting newer softwares.

The conclusions drawn from the analysis are as follows:

- Reuse / reselling of the old personal computer device can lead to both energy saving, as well as energy expenditure relative to choosing a new one. The difference is based on what category the decision analysis fall into (A) or (B), as given above (see Figure 19).
- While reusing in scenario (B) can attain life cycle energy savings close to 50%, buying new in the case of scenario (A) can lead to savings of over 300% (see Figure 19).
- With increasing market share for laptops and LCD monitors, scenario (A) is encountered more often than before and thus promoting purchase of new over reusing old should not be looked upon as against the environment.
- Sensitivity analysis for the assumptions has been conducted. Though the conclusions drawn for some comparisons might become nuanced or change, the conclusions for most comparisons is robust and likely to remain the same even after relaxing the assumption.

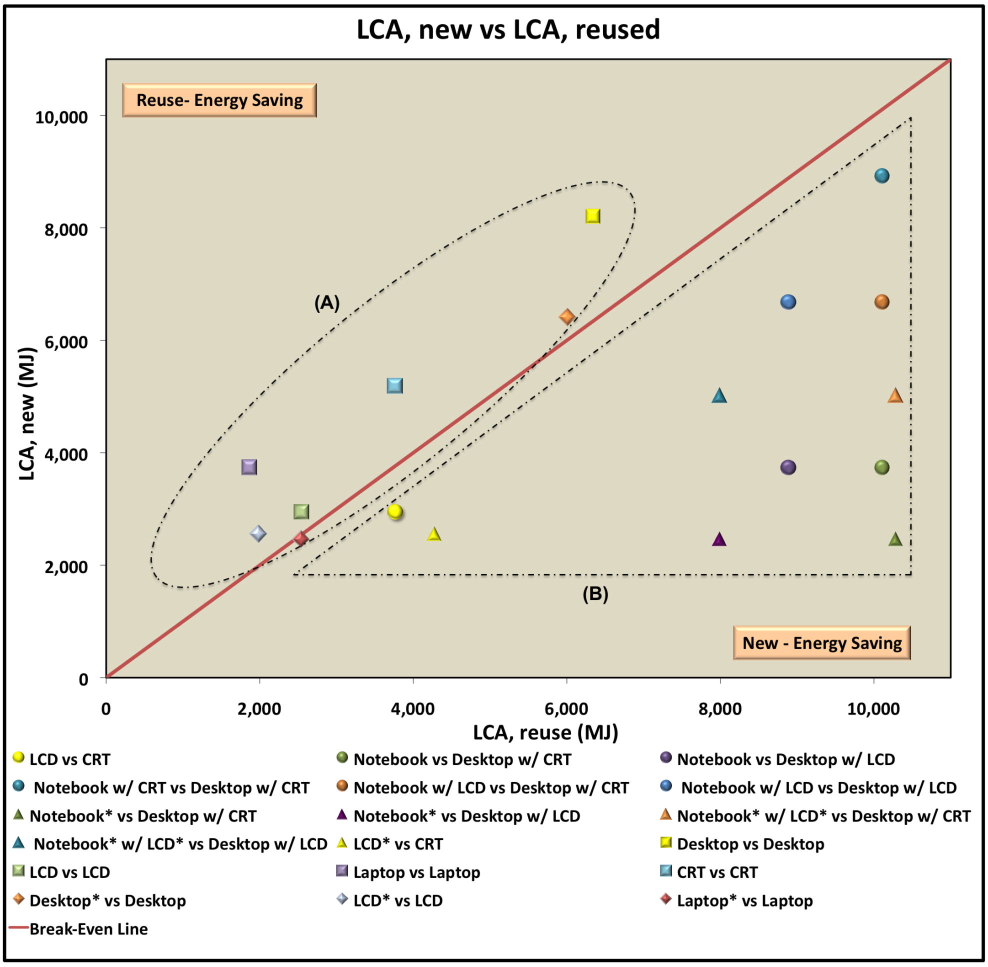

Figure 19: Life Cycle Energy Comparison between reusing / reselling an old personal computer device and buying a new one. Boundaries (A) and (B) enclose data points corresponding to the analysis of category (A) and (B), described in the text. All comparisons without * (circles and squares) are between a 2005 new device and a 2001 reused / resold one, while all with * (triangles and diamonds) are between an EnergyStar qualified 2009 new device and an average 2005 reused / resold device.

- This analysis calls for investigation into appropriate secondary markets (where they are equivalent to new) for reuse of personal computer devices rather that re-introduction into the primary market.

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