

Reusing Personal Computer Devices – Good or Bad for the Environment?

S. Sahni*, A. Boustani*, T. G. Gutowski, S. C. Graves

Abstract — The energy saving potential of reusing / reselling personal computer (PC) devices was evaluated relative to the choice of buying new. Contrary to the common belief of reuse leading to energy savings, with the advent of more efficient laptops and liquid crystal displays (LCD), reuse of an old personal computer device can lead to relative energy expenditure. We found that in certain scenarios this expenditure could be as large as 300% of the lifecycle energy inventory for the new device. As a result, it is essential to assess the reuse of personal computer devices more critically, incorporating the different factors that influence the analysis as discussed below.

Index Terms — Computer, Energy, Life Cycle Assessment, Reuse

I. INTRODUCTION

Personal computer devices have become ubiquitous today. Rising demand for computers has made them one of the major market drivers, forcing other products and technologies to conform to their existence. As a result, computer hardware production volume has grown exponentially over the past decade, with more than 64 million personal computers (desktop and laptop computers) installed in the United States in 2007 alone [1]. The US Census Bureau estimated that more than 62% of the US households in 2007 contain at least one computer. Figure 1 exhibits these trends in the computer market [2]. The rising popularity of laptop computers and LCD monitors is clearly evident. Increased versatility and improved functionality of personal computer devices cause consumers to change their computers before mechanical or electrical failure, leading to thousands of tons of usable devices being abandoned every year. This has increased concerns about hazards associated with electronic waste. The US EPA [2] declares landfilling to be much more common than both recycling and incineration of personal computer devices. However, the most common end-of-life option for desktop computers, laptops, and computer monitors is either reuse or storage; close to 65% of computer monitors undergo reuse or storage after their end of life [2]. Williams et al. have reported the US used-PC market in 1997 to be 5.5 million

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units, which was approximately 18% of the total PC market at that time [3]. Many of these devices are abandoned due to obsolescence, when in actuality most are functional enough for continued use or can at least be resold to serve less intensive computing requirements. Reuse would appear to instantly save on the energy and environmental impacts associated with both production of raw materials and manufacturing of the new device, otherwise purchased. If followed for every computer, these savings would seem to be cumulatively immense. This implies that, from an environmental standpoint, computer devices should be used and continued to be reused (if they satisfy application requirements), until they undergo an irreparable failure or when repair is almost as energy intensive (as repair often includes replacements of failed parts with new ones) as manufacturing a new personal computer device.

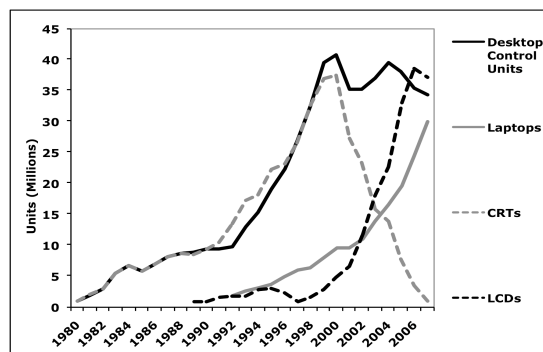


Fig 1: Personal computer national stock trend [2]

This study challenges this claim by analyzing the relative lifecycle energy saving potential of reusing personal computer devices, namely desktop computers, laptops, cathode ray tube (CRT) monitors and LCD monitors versus choosing to buy new ones. The specific questions addressed are:

1. Which consumer action results in less energy consumption: Reuse¹ (use of old units) of personal computer devices or purchase of new ones?
2. On what factors does the reuse / replacement decision depend and what are the implications?

II. METHODOLOGY & DATA SOURCES

The tool used to quantify the energy saving potential of reusing / reselling is Life Cycle Assessment (LCA). Typically LCA involves scoping, life cycle inventory, impact

¹ In this study, Reuse by primary user (within USA) and reselling to a secondary user (within USA) are considered to be same from an energy standpoint, since the intermediate transportation energy is assumed to be negligible. This is discussed in detail in the sensitivity analysis (Section V).

assessment, and interpretation. The comprehensive scope for a product LCA includes raw material processing (from its naturally occurring form), transportation of these processed materials to the manufacturing plant, manufacturing of the product, transportation of the product to the consumer, use of the product, and the final end-of-life stage which may or may not include more transportation. This is also shown in Figure 2. This study tries to incorporate all phases except for product transportation (this is discussed in the sensitivity analysis); however whenever a phase is neglected or avoided, it is clearly mentioned and explained. For instance, when comparing new and reused products, we assume that waste-management associated with the two can be considered to be equivalent. That is, at the end of using the new and the remanufactured product, both have an equivalent potential for recycling, incineration, and landfilling. As a result, the energy associated with these practices is expected to be very similar for the two and hence is not included in the comparisons (this is discussed in greater detail in the proceeding sections). The “dashed” boundary in Figure 2 depicts what the base case encompasses in this study, while the impact of transportation is discussed in the sensitivity analysis (Section V).

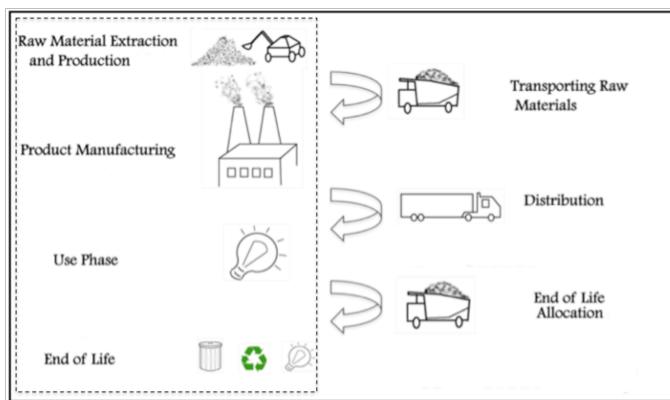


Fig 2: Life cycle assessment scope and boundary condition for this study.

In order to compare the energy requirements during the lifecycle of a new computer against an old one, we refer to a study by IVF Industrial Research and Development [4] as the base case. They have calculated the average bill-of-materials for personal computer devices of 2005. The Methodology Study for Eco-design of Energy-using Products (MEEuP) [5] was used to estimate the production energy requirements. Using the 2005 average power values in different states (Idle, Sleep and Off) of the devices and the assumption that one service-life of a computer is 4 years long [6-9], the use phase energy consumption was estimated. Aggregating all these calculations gave the energy associated with the purchase of a new computer of 2005; we then compare this to the reuse / resell of a computer in 2005, but originally manufactured in 2001 (one lifetime old). Data for an average computer of 2001 was obtained from [10]. Note that for the reuse / resell decision, we neglect the energy to repair / refurbish the computer, which makes the analysis conservative in estimating the energy cost with reusing. Similarly, we compare a new 2009 computer with the reuse of a computer

originally manufactured in 2005 (one lifetime old). With the increase in Energy Star qualified computers in United States and the expected regulation of these standards, we chose the 2009 computers that were Energy Star certified. This makes the 2009 comparison between new computers and reusing / reselling computers slightly in favor of new, but at the same time makes the analysis more relevant to the impending future. We note that since desktop and laptop designs, and configurations change very frequently and since they are usually built to the customer’s specifications, there exists a large variation in the personal computer devices from one time to another. As a result, great care was taken in using references that provided data for the average configurations and power requirements for the particular years analyzed.

Using the above data and methodology, we analyzed the Replacement vs Reuse (Resell) decision of personal computer devices. The consumer choices are broadly classified into two decision scenarios:

- (1) Replacement of a functional desktop/laptop/monitor with a new, state of the art desktop/laptop/monitor respectively, i.e. replacement with a similar, but new device.
- (2) Replacement of a functional desktop with a laptop, or replacement of a functional CRT monitor with a LCD monitor. These replacements correspond to technological upgrades, as has been common with rapidly evolving electrical devices.

III. RESULTS

Using the IVF report [4], the life cycle inventory of new desktop computers, laptops, LCD and CRT monitors was taken to be as shown in Figure 3. It has been broken down into two primary phases: Production, which includes raw material processing and device manufacturing; and Use.

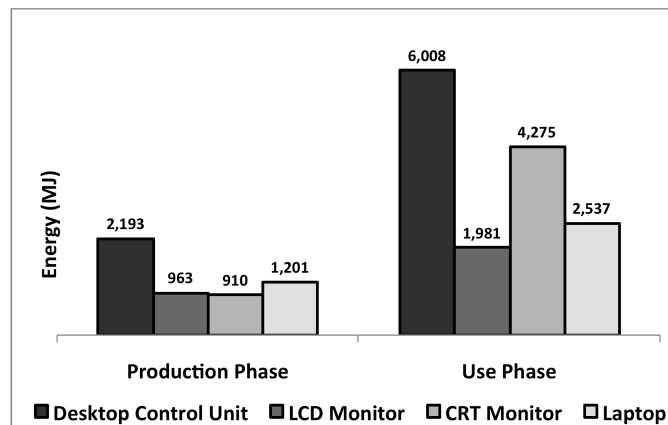


Fig 3: Life cycle inventories (LCI) of average personal computer devices of 2005 [4]

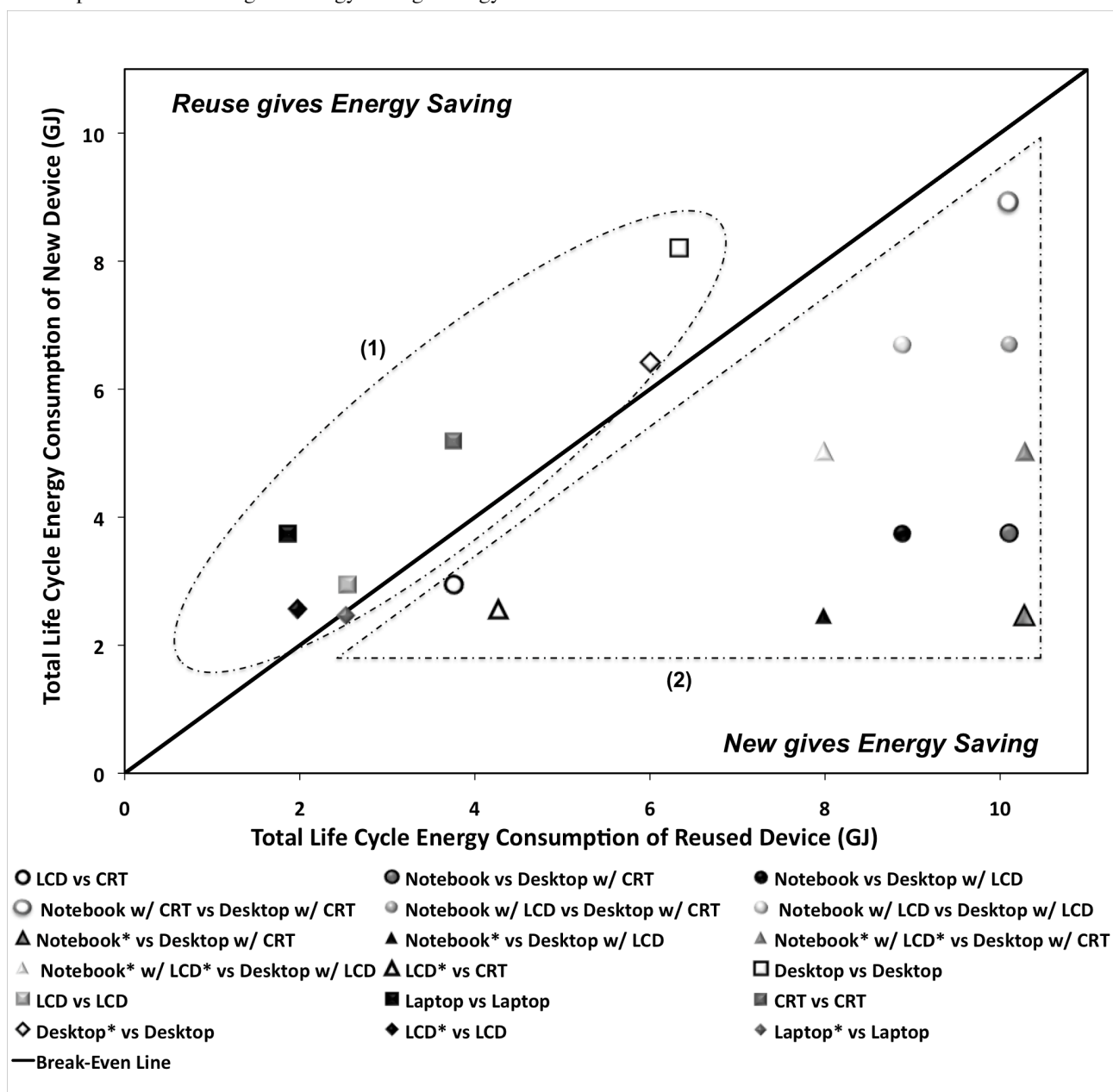
Note that though the production energy costs remain the same, the use phase and hence the life cycle energy consumption depend on whether the device is used for home or office purposes. For this case, we only show the home calculations. A similar analysis can be conducted for office

usage of personal computer devices. The use-pattern for home usage has been taken from [4] (assuming that the use-patterns in US and Europe are similar) and combined with the use powers (for Idle, Sleep and Off modes) to estimate the total use phase energies as shown in Figure 3.

Interestingly, Figure 3 depicts that for all products the use phase consumes more energy than the production phase. This is due to the 4 years service life and the long usage hours of computers. This difference is even greater for office use because of the more extensive usage [4].

Using Figure 3 for new computers of 2005 and data from Roberson et al. [10] for the energy consumed by reusing / reselling a computer in 2005 (2001 model), the life cycle energy comparisons are determined. For the year of 2009, using Figure 3 for the reused / resold computer (2005 model) and Energy Star [6] for the new computer (2009 model), the life cycle energy comparisons are again computed. Figure 4 below provides a comprehensive plot of the analysis. Looking at the graph the following inferences can be drawn:

Fig. 4: Life Cycle Energy Comparison between reusing / reselling an old personal computer device and buying a new one. Boundaries (1) and (2) enclose data points corresponding to the analysis of type (1) and (2), 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 Energy Star qualified 2009 new device and an average 2005 reused/resold device. The upper-left triangular half to the break-even line indicates reuse as the energy saving strategy while the lower-right half corresponds to new being the energy saving strategy.



- Reuse 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 the decision scenario – (1) or (2), as described in Section II.
- While reusing in Scenario (1) can attain life cycle energy savings as high as 50% (when choosing to reuse a laptop computer of 2001 against buying a new 2005 laptop), reusing in the case of Scenario (2) can provide relative energy expenditures of over 300% (when choosing to reuse a 2005 desktop with CRT monitor over buying a new Energy Star certified Laptop of 2009).
- With increasing market share for laptops and LCD monitors [2], Scenario (2) occurs more often than before. Thus promoting the purchase of new over reusing old can be favorable for reducing net energy consumption. At the same time, these trends along with the increasing popularity of Energy Star certified devices could further discourage the reuse of personal computer devices from an energy saving perspective.
- Even within the decision to buy a new computer device it is much more beneficial to buy a LCD over a CRT (energy savings of 31%) or a laptop over a desktop with either kind of monitor (energy savings of over 50%). This also holds true when choosing to use a new external LCD monitor with the new laptop. In other words the trend of moving from desktops to laptops and from CRT monitors to LCD monitors results in lower energy consumption.

IV. DISCUSSIONS

The above analysis shows that reusing personal computer devices can be both energy saving and energy expending. By choosing to reuse, assuming the reuse / refurbish / repair / upgrade phase does not consume any energy and provides an equally long second life, the relative saving before use is the energy required to manufacture the new device, which is 20-30% of the total lifecycle energy requirements of the product (Figure 3). Thus as long as the new product is not significantly more efficient² in the use phase, reusing is the relative energy saving strategy. Figure 4 shows this to be true for all Scenario (1) comparisons where the efficiency gain is not significant enough to overcome the energy expenditure in manufacturing the device. However, a complete revolution in architecture of the device like in the case of Scenario (2) comparisons between a laptop and desktop or a LCD monitor and a CRT monitor, has made new devices much more efficient; as a consequence, the initial energy expenditure in the manufacturing phase is more than countered by the more efficient use phase leading to a net energy saving. Thus with the increasing popularity of laptops and LCD monitors (Figure 1), choosing new over reuse is not necessarily bad for the environment.

Ideally it is important to understand the drivers behind this trend. However, this becomes very complex for desktops and laptops because of the independent innovations for their

components. While the total power required by the device depends on the assemblage of the different software and hardware, one of the key components for each are the operating system and the processor respectively. The operating system by itself determines the hardware requirements. Microsoft Windows operating system (OS) requirements for Processor Speed, Memory and Storage have been rising exponentially with every new OS release [11]. Similarly possessing speed (instructions per second) has also risen exponentially with subsequent versions of Intel processors [12]. Added hardware requirements and processing speed are likely to require added power [12]. However, with increasing popularity of laptops, Intel Corporation has also introduced more energy efficient processors for mobile applications, which require much lower energy per instruction [13]. As a result laptop computers consume much lower energy compared to their desktop equivalents. Along with this, advanced power management has also helped reduce the use phase power consumption of devices. In the case of monitors, a complete change in technology has driven the sharp improvement in efficiency from CRT to LCD monitors. This along with the reduced size makes LCD a preferred technology for battery powered mobile devices like laptops.

While the above analysis brings out some interesting conclusions, it is also important to compare and understand the difference between this study and other similar studies. Some researchers [14, 15] have shown the production energy of a processor to be an order of magnitude lower than the use phase energy. This more or less conforms to the life cycle assessment used in this study. At the same time, E. D. Williams et al. as well as E. Massanet have published extensively on this topic [8, 9, 16-18] and have shown the production phase (manufacturing and raw material processing) to dominate over the life cycle. This is clearly not the case for the LCAs shown above (see Figure 3). One of the key differences is the lower life-time utilization (2 to 3 years total use-life with 2.6-3 hours/day usage) assumed for the devices considered by Williams and Massanet [3, 9, 15-17]. Another reason for the same is the methodology adopted to estimate the manufacturing energy for desktop control units and CRT monitors. They utilize a hybrid methodology to estimate the combined energy to manufacture the control unit and the CRT monitor while this study follows the process-based approach [16, 17, 19]. Thus, their estimates are close to double of what has been used in this study. However, their estimations for the process-sum (from the process analysis and not including I-O analysis) are a good match giving confidence in the data used.

V. ASSUMPTIONS AND SENSITIVITY ANALYSIS

The following are the key assumptions made in this study:

1. Key-boards, mice and other accessories to a personal computer are not considered as their environmental impact is assumed to be negligible compared to monitors / control units / laptops. This is supported by Duan et al. [19].
2. The average lifetime for the use of a computer as home is assumed to be 4 years [6-9]. The total usable life of a computer (including monitor) was taken to be ≥ 8 years, as they are usually upgraded after their first life

² The use phase efficiency of new should be more than ((% production phase contribution) / [fractional use phase contribution]) relative to old, which is equal to 25-43% assuming a 20-30% production phase.

of 4 years. So we assume that a computer when resold can last through an equivalently long second life. This is different from some other reports as discussed above. No report was found which explicitly calculates the total usable life for computers. However, researchers at the University of Tennessee and US EPA [20] have estimated 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, this gives a total useful life in excess of 8 years for both monitor types.

3. Computer hardware and use-pattern for particular years have been assumed to be the same in both United States and Europe.
4. The 2009 analysis has been conducted using the use pattern for 2005 due to lack of data for 2009.
5. The use phase energy is based on Idle state calculations due to lack of data and since quantifying the Active state would be a complex task.
6. The manufacturing energy for a personal computer device is assumed to be the same in 2005 and 2009. Though researchers like Williams et al. [21] have quantified the trend for processor manufacturing, unfortunately no such data is available for the entire PC.
7. The energy consumed during the repair and / or upgrade phase is taken to be negligible. This makes the above analysis slightly in favor of reusing, and hence the conclusion of choosing new becomes stronger on relaxing this assumption.
8. The assembly and distribution phases were not taken into account in the study.
9. The energy consumed during the maintenance and periodic repair of the device during its use are neglected.
10. We assume that the PC devices operate “like-new” all through their use phase. That is, there is no deterioration in the performance of the device with use. This is also true when they are reused / resold.
11. As mentioned before in Section II that the waste-management options (landfill, recycle, incinerate, not reuse) for the new and old device are assumed to be similar so that they cancel each other when comparing the two versions.

Given below is the impact of relaxing some of the above assumptions:

It is crucial to understand the impact of Assumption 2. A use life of 4 years seems practical for home applications. A longer use life will further enhance the savings associated with more efficient devices, while these savings would be less if personal computer devices were replaced more frequently than 4 years. Figure 5 shows the percentage life cycle savings of reusing over choosing new when the use life of 2 years, 4 years and 6 years is considered. It is observed that the energy savings / expenditure for most comparisons is large enough to include the variation due to use-life ($\pm 50\%$) enhancing

confidence in the inferences drawn in Section III. A similar sensitivity is expected for a $\pm 50\%$ variation in usage-hours as well as device power consumption.

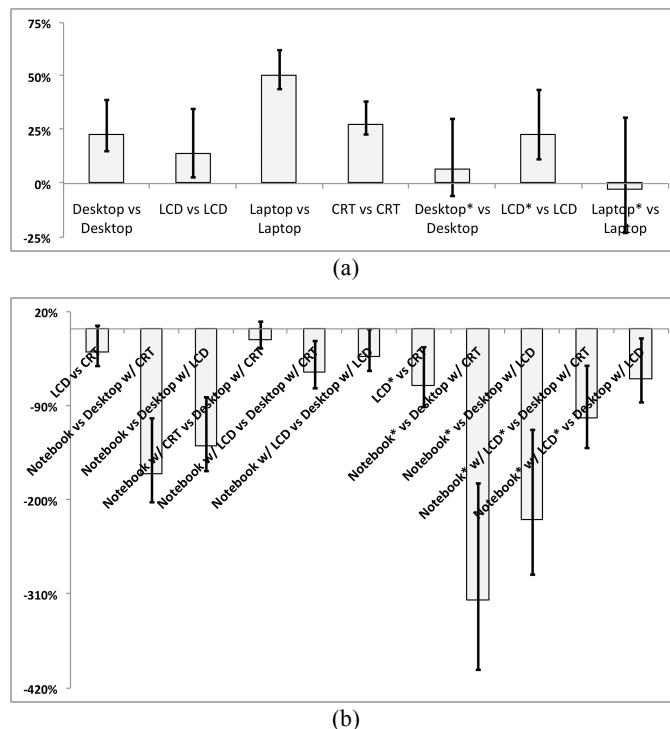


Fig. 5: Life cycle energy savings by choosing to reuse over replacing with new for (a) Scenario (1); (b) Scenario (2) comparisons. The columns represent the results for 4 years, while the upper and lower ends of the error bars represent the results for use-life of 2 years and 6 years respectively.

Assumption 4 is conservative and in favor of reusing, since we expect that the use of computers from 2005 to 2009 has increased per consumer. Since the power for each 2009 device considered is lower than that for a 2005 device, relaxing this assumption is likely to promote use of new devices for Scenario (2) comparisons even more and can even recommend use of new for some of the Scenario (1) replacements.

Relaxing Assumption 5 may cause a significant shift in the data points corresponding to desktops and laptops. However, this shift is hard to predict without knowing the actual Active-mode values. To exemplify, [6] gives 84W as the Idle mode power consumption and 115W to be the Active mode power consumption for a conventional desktop computer.

Assumption 6 can also have a significant impact on the energy benefits / drawbacks of the use of new personal computer devices. It is true that newer computers incorporate faster processors, larger storage and memory, and better graphics etc.; however no study was found that either qualitatively or quantitatively compares the manufacturing energy of a 2005 computer with a 2009 computer. As a result this study assumed them to be equal.

If transportation energy is to be taken into account (Assumption 8), the resell and reuse scenario become different, as reselling is expected to have the added energy

cost of transporting the device from its previous user to the purchaser (this may be via a retail channel). At the same time there would be added transportation energy consumption for the new product. Through personal communications with Dell Inc [22] it was learnt that, due to the international assembly and supplier distribution, the transportation energy consumption over the life cycle of new personal computers can be as high as 600 to 700 MJ per device. If we assume that the transportation energy costs associated with reselling are negligible (compared to that from new) since it is within the domestic market (we are not considering export of old devices), then by relaxing this assumption all the data points in Figure 4 will move up by 600-700 MJ (and close to 1200-1400 MJ for desktop / laptops with external monitors). It is observed that this would only make the LCD versus CRT (white circle with black boundary) and laptop w/ CRT versus desktop w/ CRT (white circle with grey boundary) scenarios nuanced and not change the conclusion for any other comparisons. In fact for all the Scenario (1) comparisons, the result of reusing would get further accentuated. This exhibits the robustness of the conclusions for several of the Scenario (2) comparisons (where choosing new is the energy saving strategy), leaving a large margin for error.

We note that the 2009 analysis has been conducted for only Energy Star qualified devices. These devices are considered to be one of the most efficient of their type. If the analysis were to be conducted for the average stock (including those not certified by Energy Star), the power consumed would be higher. This would shift the “triangles” and “diamonds” in Figure 4 upwards. However, it is worth noting that the Energy Star averages include 1637 models for desktops, 2035 models for laptops and 435 models for LCD monitors. This combined with consumer awareness of Energy Star makes it unlikely that the impact of relaxing this assumption will be substantial, at least in the future.

VI. CONCLUSION

The above analysis evaluated the reuse / resell energy saving potential of personal computer devices. Personal computer device end-of-life replacement scenarios were classified into two categories – 1. Replacing an old desktop with a new desktop and similarly for laptops, CRT and LCD monitors or 2. Changing from a desktop to a new laptop, or from an old CRT to a new LCD monitor.

We found that reuse / reselling of old personal computer devices can lead to both energy saving and energy expenditure relative to choosing a new state-of-the-art one. The difference is based on whether the scenario falls into Scenario (1) or (2). Reuse / resell (domestically) saves energy for the former and expends for the later. With the trend towards increasing market share of laptops and LCD monitors, choosing new over reuse should not be looked upon as necessarily bad for energy saving. While lack of data is overcome with a few given assumptions and a detailed sensitivity analysis, the main result to take from this study is that the environmental benefits associated with reuse of computer devices, as their end-of-life option, requires greater investigation and political control.

REFERENCES

- [1] <http://www.rer.co.uk/>, “Yearbook of World Electronics Data,” Reed Electronics Research.
- [2] US-EPA, “Management of electronic waste in the United States: Approach Two (EPA530-R-07-004b),” 2007.
- [3] E. Williams and T. Hatanaka, “Residential computer usage patterns in Japan and associated life cycle energy use,” *IEEE International symposium on electronics and the environment*, pp. 177-182, 2005.
- [4] A.K. Jönbrink and M. Zackrisson, *Lot 3: Personal computers (desktops and laptops) and computer monitors: Preparatory studies for Eco-Design Requirements of EuPs*, IVF Industrial Research and Development Corporation, 2007.
- [5] R. Kemna, M.v. Elburg, W. Li, and R.v. Holsteijn, “Methodology study eco-design of energy-using products – MEEuP methodology report,” 2005.
- [6] *Energy Star*. Available from: <http://www.energystar.gov>.
- [7] B. Choi, H. Shin, S. Lee, and T. Hur, “Life cycle assessment of a personal computer and its effective recycling rate,” *The International Journal of Life Cycle Assessment*, vol. 11, (no. 2), pp. 122-128, 2006.
- [8] R. Kuehr and E. Williams, *Computers and the environment: understanding and managing their impacts*: Kluwer Academic Pub, 2003.
- [9] E. Masanet and A. Horvath, “Enterprise strategies for reducing the life cycle energy use and green house gas emissions of personal computers,” *IEEE International symposium on electronics and the environment*, pp. 21 - 26, 2006.
- [10] J. Roberson, G. Homan, A. Mahajan, B. Nordman, C. Webber, R. Brown, M. McWhinney, and J. Koomey, “Energy use and power levels in new monitors and personal computers,” *Lawrence Berkeley National Laboratory, Berkeley, CA*, 2002.
- [11] *Microsoft Windows System Requirements*. Available from: <http://www.microsoft.com/>.
- [12] S. Chickamenahalli, “Power electronics research efforts at Intel,” *The Applied Power Electronics Conference and Exposition, 2008 Presentation, Austin*, 2008.
- [13] E. Grochowski and M. Annavaram, “Energy per instruction trends in Intel microprocessors,” *Technology@ Intel Magazine*, vol. 4, (no. 3), pp. 1-8, 2006.
- [14] S. Raoux, D. Dornfeld, N. Krishnan, D. Clark, S. Boyd, and A. Somani, “A Hybrid Life Cycle Inventory of Nano-Scale Semiconductor Manufacturing,” *Environmental science & technology*, vol. 42, (no. 8), pp. 3069-3075, 2008.
- [15] M. Yao, A. Wilson, T. McManus, and F. Shadman, “Comparative analysis of the manufacturing and consumer use phases of two generations of semiconductors,” *IEEE International symposium on electronics and the environment*, pp. 97-103, 2004.
- [16] E. Williams, “Revisiting energy used to manufacture a desktop computer: hybrid analysis combining process and economic input-output methods,” *IEEE International symposium on electronics and the environment*, pp. 80-85, 2004.
- [17] E. Williams, “Energy intensity of computer manufacturing: hybrid assessment combining process and economic Input-Output methods,” *Environmental science & technology*, vol. 38, (no. 22), pp. 6166-6174, 2004.
- [18] E. Williams and Y. Sasaki, “Energy analysis of end-of-life options for personal computers: resell, upgrade, recycle,” *IEEE International symposium on electronics and the environment*, vol. 2003, pp. 187, 2003.
- [19] H. Duan, M. Eugster, R. Hischier, M. Streicher-Porte, and J. Li, “Life cycle assessment study of a Chinese desktop personal computer,” *Science of the Total Environment*, vol. 407, (no. 5), pp. 1755-1764, 2009.
- [20] M. Socolof, J. Overly, L. Kincaid, D. Singh, and K. Hart, “Preliminary life-cycle assessment results for the design for the environment computer display project,” *IEEE International symposium on electronics and the environment*, pp. 290-297, 2000.
- [21] L. Deng and E. Williams, “Measures and trends in energy use of semiconductor manufacturing,” *IEEE International symposium on electronics and the environment*, pp. 1-6, 2008.
- [22] E. Colon, *Personal Communication*. Dell Inc., 2009.