Laptop Computers:

How Much Energy Do They Use and How Much Can We Save?

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Executive Summary

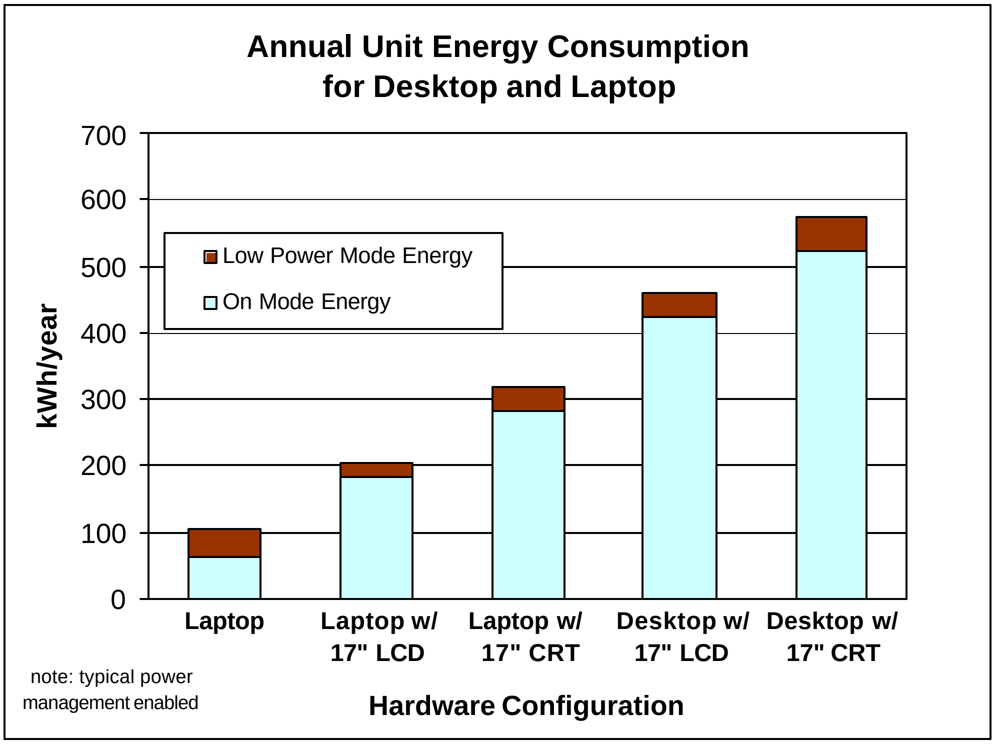
Today in the United States there are over 200 million computers in use in business and residential settings. The annual national energy use of computers and their associated monitors is approximately 85 billion kWh per year, or approximately 2.8% of the total US electricity use. Due to their portability, improved performance, and reduced purchase costs, laptop computers are becoming an increasingly popular choice for residential and commercial consumers alike. Laptops employ the latest developments in computer technology due to the need to prevent overheating and to maximize battery life.

To date, there has been little work done to assess and compare the energy efficiency of laptop computers. To this end, NRDC and its consultant, Ecos, have prepared this report. The purpose is to assess the approximate energy efficiency differences between laptops and desktops and among various models of each type in order to determine how much energy the U.S. might save by switching to more efficient designs. In the process, we discuss various ways to characterize computer efficiency on a component basis and system basis, and conclude with recommendations for future research in this field.

The Savings Opportunity

While the fastest desktop computers continue to outpace the fastest laptops in absolute speed and processing power, it is now very common to find affordable desktop and laptop computers with roughly comparable performance, especially when running the common software applications found in most offices. As illustrated below, today's conventional desktop computer with a conventional cathode ray tube (CRT) monitor uses more than five times as much energy as a laptop (570 kWh/yr vs. 100 kWh/yr). Therefore, replacing a desktop system with a laptop system could save a user over 450 kWh/yr – nearly $40 annually.

Monitor choice greatly impacts the overall system energy usage. For example, simply switching from a CRT to the increasingly common LCD (liquid crystal display) yields the desktop computer user annual savings more than 100 kWh/yr. Likewise, much of the energy savings of a laptop is negated if it is connected to an external CRT monitor. This figure also shows that even if power management is enabled, the majority of the energy consumption happens while the computer is in the *on* mode, not in the various low power modes like *monitor sleep*, *hardware sleep*, and *off*.



The annual energy consumption of computer hardware combinations varies widely. The economic and environmental implications of replacing the most inefficient configurations with more efficient configurations are discussed in the following section.

Environmental Impacts

The table below puts some of the potential energy and environmental impacts into perspective, demonstrating the significant benefits that can be attained from particular shifts in the current computer marketplace. The section below provides an initial attempt to quantify the potential savings that can be achieved for laptops through further improvements in their design and technology.

Scenario	Annual kWh Saved	Annual Dollars Saved	Annual Tons CO_2 Saved
25% of US desktops with CRTs are replaced with laptops	20 billion kwh	$1.6 billion	13 million tons
25% of US desktop systems shift from CRTs to LCDs	10 billion kwh	$0.8 billion	6 million tons

Key Efficiency Differences

In order to investigate efficiency differences between laptop computers, we used two different approaches:

1) comparing individual components, which included the power supply, battery charging system, display, central processing unit, and power management software.

2) comparing overall product speed and performance per unit of energy consumed while utilizing system performance benchmarking software.

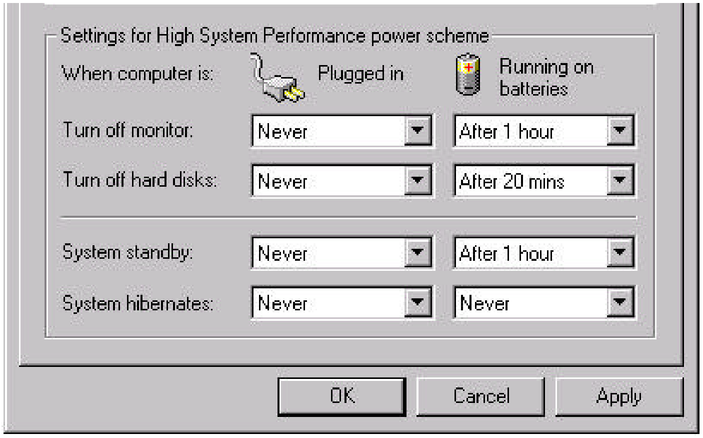
Power Supplies - Our measurements showed that laptop power supplies are remarkably efficient, typically achieving nearly 90% efficiency at peak load. This is far higher than efficiencies typically found in power supplies used in desktop computers and other consumer electronic products. The best designs could maintain efficiencies nearly that high over most of their operating range, while others declined in efficiency fairly dramatically at partial load, where the system operates a substantial portion of the time.

Battery Charging Systems - Our measurements did not reveal any major efficiency differences in battery charging systems across the various laptop models tested, though differences in battery *capacity* and run-time were significant. The need for portability appears to keep most such battery components fairly similar. *Smart charging* technology allows batteries to automatically inform the charger regarding their temperature and state of charge. On average, about 20% more AC energy is required to operate a computer in battery mode and then recharge it, compared to simply leaving it plugged in. By contrast, we have found the battery charging systems used in other consumer products to be much less efficient.

Displays - Laptops' LCD displays vary widely in the amount of information (pixels) they can display per watt of power consumed. Some of this is attributable to differences in screen brightness, size, and performance, while the rest is likely due to differences in the technologies employed. Some displays, for example, provide better off-angle viewing or more accurate rendering of colors and moving images than others, but may consume more power to do so.

CPUs - The three largest central processing unit (CPU) manufacturers for laptop computers -- Intel, AMD, and Transmeta -- all have recently released chips that improve computer energy efficiency significantly. Most of these designs are "mobile" processors only, meaning their efficiency features (the ability to run at lower speeds and voltages during periods of inactivity) are specifically intended for laptop computers. This includes Intel's Pentium M chips (Centrino system) and AMD's "PowerNow!"-equipped Athlon processors. Transmeta's Crusoe is predominantly a laptop processor, but has also been utilized in NEC's new PowerMate Eco desktop system. In most cases, the manufacturer's motivation for selecting the more efficient chip is to maximize the amount of time a user can use the laptop between battery charges.

Power Management - Power management software allows a computer to lower power to various components after periods of inactivity. The largest savings typically result from dimming or switching off the screen, reducing processor speed, shutting down the hard drive, or putting the entire computer into "sleep" mode after longer periods of time. This sleep capability varies widely across various operating systems, computer manufacturers, and component types, and is frequently not fully enabled by the user. In most operating systems, maximum performance is synonymous with *AC state* and slower performance is synonymous with *battery state*, meaning that large savings opportunities can go untapped when computers are plugged into AC power.



Settings for High System Performance power scheme

When computer is:	Plugged in	Running on batteries
Turn off monitor:	Never	After 1 hour
Turn off hard disks:	Never	After 20 mins
System standby:	Never	After 1 hour
System hibernates:	Never	Never

This power management window, available to the user through Windows 2000 software, allows the user to set different power management functions based on whether the computer is plugged in (*AC state*) or running on batteries (*battery state*).

What Is the Impact of More Efficient Laptop Components?

In the chart below, the efficiency differences of various components are summarized. Also given are the estimates of the annual national energy savings if the most efficient components were adopted. The savings are quantified in two different duty cycle scenarios: the Road Warrior scenario, which refers to a laptop as it is used by a business traveler, and the Desktop Replacement scenario, which refers to laptop that is plugged in most of the time. The potential savings for each component overlap somewhat so cannot be simply added together, but they do approximate the energy benefits that are associated with improving the efficiency of each component individually.

Component	Possible Efficiency Improvement	National Annual Energy Savings: Road Warrior (GWh)	National Annual Energy Savings: Desktop Replacement (GWh)
Display	From 64,000 pixels/watt to 128,000 pixels/watt	260	550
Power Supplies	From partial load efficiency of 56% to 85% From full load efficiency of 80% to 90%	210	520
CPU	From Intel P3 Max Performance to P3 Battery Optimized	180	520
Power Management	From 50%of laptops PM enabled to 70% laptops PM enabled	20	220
Battery System	From 80% to 85% efficiency	30	9

Applying Benchmarking Software to Assess System Performance

Looking at the individual components can make comparisons unnecessarily complicated and not entirely accurate, since the laptop components operate together as a system. Also, the simple measures of battery life frequently published in computer magazines are not meaningful comparisons of the relative efficiencies of two laptops. One laptop can achieve a longer battery life than the other by simply running slower or having a larger battery. Using benchmarking software tools to compare functional performance per unit of AC energy consumed can help to improve the fairness and relevance of efficiency comparisons across a range of laptop and desktop computers. This type of system metric measures the efficiency of the interaction of all the components.

Because there is currently no benchmarking software that is ideal for an energy efficiency metric, Ecos evaluated three different benchmarking tools: BAPCO's MobileMark 2002, Futuremark's PCMark 2002, and PC World's PC WorldBench4. MobileMark and PC WorldBench4 were chosen because of their claims to represent 'normal' office user performance while PC Mark was chosen because it is easy to use. Unfortunately, we were unable to gather meaningful energy consumption values that related to the performance score for PC Worldbench4, and as a result, only MobileMark and PCMark were used to generate system efficiency metrics.

The resulting laptop system efficiencies, as defined using MobileMark software, are listed in the table below. These data represent initial efforts by Ecos to assess the validity of this type of system level approach and other benchmarks could change the relative performance ranking of the laptops tested. Nevertheless, these data indicate that large system efficiency differences exist among laptop computers with different configurations (larger scores indicate greater efficiencies). Even within one form factor (thin and light) we see that the highest score (6.3) is more than three times the lowest score (1.9).

Laptop Tested [1]	**CPU Power Management Enabled?**	**MobileMark Performance Score**	**MobileMark Battery Life (hours)**	**Measured Energy to Charge Battery (AC Watt-hours)**	**System Efficiency[2] (Performance/ Watt)**
IBM T23 **(Intel P3 Mobile)** **Thin and Light**	No	111	3.3	58.8	**6.3**
IBM T40 **(Intel Centrino)** **Thin and Light**	Yes	95	4.2	66.1	**6.0**
Sharp MM-10 **(Transmeta Crusoe)** **Ultra Portable**	Yes	60	2.5	35.2	**4.3**
Fujitsu S-Series Lifebook **(AMD Athlon 4)** **Thin and Light**	Yes	94	2.4	58.6	**3.9**
MiTAC **(AMD Athlon 4)** **Thin and Light**	No	66	2.2	77.1	**1.9**
Toshiba Tecra 8100 **(Intel P3)** **Desktop Replacement**	NA[3]	50	2.4	67.0	**1.8**

Using this type efficiency metric, a laptop like the IBM T40 can achieve a high efficiency score by attaining a relatively good performance score while using an average amount of AC energy. Alternatively, the Sharp laptop arrived at a better than average efficiency score with a relatively low performance score because it consumed a comparatively small amount of AC energy.

We also employed PC Mark to compare desktops to laptops. Efficiency was calculated in a similar way as the MobileMark benchmark: total performance score (CPU+memory+hard drive) divided by the AC watt-hours consumed during the test. The range of scores for the laptops was 532 to 3696 and for desktops was 295 to 519, where a higher score indicates better performance. Note that the most efficient desktop we measured, the NEC Powermate Eco PC, achieved a score comparable to that of the least efficient laptop we measured.

Conclusions

Our preliminary research suggests three important conclusions:

- Laptops offer the potential for major energy savings relative to desktops. **The best laptops are at least 5 times more energy efficient than the worst desktop systems (computer and CRT monitor).** However, highly efficient laptop components could be readily incorporated into desktop designs, preserving the basic form factor and functionality of a desktop while saving energy and space and reducing noise from cooling fans. However, the present trend is the reverse,

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[1] Tested in Ecos Consulting's Colorado laboratory between 12/02 and 7/03.

[2] System Efficiency = (MobileMark Performance Score) * (MobileMark Battery Life) / (Measured Energy to Charge Battery)

[3] There is only one power mode for this CPU.

with each new desktop computer model incorporating faster, higher power CPUs and video cards.

- While there are clearly significant energy efficiency differences in the components of computers, those technologies change rapidly and interact closely, making it difficult to drive overall improvements in system efficiency with component-based specifications. Employing instead benchmarking software and an AC watt-hour meter to capture overall product efficiency in *on* mode offers key advantages. It allows manufacturers to choose combinations of individual components and software to achieve the greatest energy savings at the lowest cost, and reduces the need for frequent updates to the technical details of an efficiency specification. The next step to further understand and quantify these system level differences is to create, with input from stakeholders in the computer industry, a benchmark specifically for energy efficiency.

- Specifications such as ENERGY STAR® that currently recognize efficient computers in the marketplace should be revised to include consideration of *on* mode energy use – the most important single fraction of overall energy use. Based on our preliminary measurements, separate specifications for laptops and desktops are warranted. A similar methodology should be employed in each, however, so buyers understand the savings they could achieve by purchasing not just a more efficient desktop and screen, but a highly efficient laptop instead

Introduction

At the request of the Natural Resources Defense Council (NRDC), Ecos Consulting has been researching the energy efficiency of electronic devices such as power supplies, battery chargers, and computer monitors since 2001. This paper continues that research by exploring energy efficiency aspects of laptop computers, which represent portable combinations of the three technologies above. We consider not only the opportunities for energy savings by switching from one laptop computer to another, more efficient design, but also the relative energy use of laptop and desktop computers. Laptops present opportunities for substantial energy savings through integration of:

- highly efficient, compact power supplies
- highly optimized, smart battery chargers
- advanced screen backlighting designs
- mobile computer processors able to drop into low-power states when needed
- efficient support circuitry
- software enabled to manage and control all energy-saving features automatically

Through such integration and optimization, laptops also point toward significantly greater opportunities for energy savings in the future, both by persuading desktop computer users to switch to laptops, and by steadily migrating the energy efficient features of laptops into traditional desktop computer designs.

A laptop is more than just desktop components arranged into a portable-sized package. Because of weight and battery life considerations, laptops frequently utilize different and more costly versions of the technology commonly found in desktops. In addition, they tend to offer fewer opportunities for customization, because they lack a means of adding the types of internal expansion cards typically used in desktops. Additionally, with improvements in integrated circuit technology, laptops are now more comparable to desktops in performance capabilities. An average user that is surfing the Internet, word processing, or listening to music on the computer is not going to notice a significant performance difference between a laptop and a desktop, but the power demands of the two systems are quite distinct.

The potential for future energy savings in the laptop computer has been largely overlooked, because at first glance it seems that all laptops should be inherently energy efficient due to their limited storage capacity for electricity. Indeed, energy efficiency is essential for computers operating in battery-powered state, to maximize battery life. But it is certainly not automatically the case that all laptops always operate efficiently during the much longer periods of time when most of them are plugged into the wall and operating off of AC power. The efficiencies of AC/DC power conversion and battery charging, for example, strongly influence overall computer efficiency without affecting battery life at all. Similarly, some laptops have increases in screen brightness, processor speed, and fan operation that occur when laptops are plugged into AC power. These boost power use substantially without in any way affecting battery life or being identified in the legions of reviews and comparisons published by computer magazines.

In Chapter 1, we take a look at laptops on a national level, examining market trends and comparing energy consumption to conventional desktop systems (computer and monitor). In this chapter, we also define for the reader key operational terms such as *on* and *sleep* modes, and build a model duty cycle, which provides hours of use for each power mode. This duty cycle is used throughout the paper in order to calculate possible annual national energy savings associated with improving the efficiencies of certain laptop components.

In Chapter 2, we focus on the energy efficiency of specific laptop components, discussing the range of efficiencies and the possible energy savings associated with a move to the most efficient technologies. This section concludes with a summary that illustrates the degree to which laptops can improve their energy efficiency. Chapter 3 provides the results of Ecos' investigations of benchmarking a laptop system, which is an alternative approach to the component-by-component analysis. The last section, Chapter 4, presents a summary of findings, suggestions for further research and resulting policy recommendations.

Chapter 1 - The Big Picture

Laptop Market Trends

No longer simply niche products, laptop computers represent a large and growing fraction of total computers in use, especially as desktop computer sales have flattened over the last year. Laptops represent about 18 percent of total personal computers now in use in the US,[1] and the laptop's market share is expected to increase in time, making the energy efficiency analysis of laptop computers increasingly important. One market research firm found that in the fourth quarter of 2002, the worldwide desktop PC market grew only 2.5 percent over fourth quarter 2001, while the worldwide laptop market grew 17.6 percent over fourth quarter 2001. This growth was driven largely by the US and western European markets.[2] This trend continues into the middle of 2003. For the first time in May of this year, the dollar value of laptop sales moved past the dollar value of desktop computer sales.[3]

There are many reasons for this growth trend. The most important development has been the simultaneous downward price movement and the increased functionality of laptops. Although in general laptop consumers pay approximately twice the price of a similarly configured desktop system with monitor, there are many capable new laptops (1 to 2 GHz, 128 MB, 20GB, CD ROM, 56K modem, Ethernet) being sold for $600 to $1000.[4] In addition, laptops are becoming the preferred choice of students and travelers that now have access to wireless LAN connections in libraries and cafés. There is a style and functional trend associated with the purchase of laptops; people like the small and portable form factor.

Laptops fall into three classes that describe their functional capability and relative size: ultra-portable, thin and light, and desktop replacement. The first class, ultra-portable, describes laptops that compromise some amount of computing performance for a petite form factor. These laptops, which are the smallest on the market, tend to operate at the lowest power levels. Thin and light laptops, which represent the second class, have solid computing performance with a form factor that is manageable for a frequent traveler. The present trend in the marketplace is toward producing more of the third class of laptop, the desktop replacement. This class has the greatest computing capability but is the heaviest and largest of the laptops. Their power consumption levels, which are the greatest among laptops, are still much lower than an average desktop. These laptops, such as the Apple's PowerBook and the Toshiba's Satellite P25-S507, with 17-inch screens, desktop processors, and stereo sound, are aimed at consumers who are looking for a performance driven mobile computer. Although it is important to be aware of the

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[1] Please see Appendix B for details of stock estimate.

[2] Kiagawa, Mikako and Charles Smulders, Gartner Group, "Mobile PC Sales Growth Greatly Outpaces Desktop PCs," 1/29/03, available at www.gartner.com.

[3] "Laptops Take Center Stage, Buyers Face More Decisions." Mike Musgrove. Washington Post 9/3/03, p. F1.

[4] See www.laptopexchange.com and www.dell.com.

design variations that exist among laptops, these products all serve similar functions therefore will be addressed in this paper as one group.

Figure 1 - Laptop Computer Size Variation

Figure 1 - Although the form-factor of the laptop computer varies widely in the current market, laptops have gotten progressively smaller with time. The class of these computers (from top to bottom) is ultra-portable, thin and light, and desktop replacement.

Definitions - Laptop States and Modes

Throughout this report, various terms will be used to describe the functional status of a laptop. The status of a laptop is defined by two parameters: a power source state and a power mode. Because of the inconsistency in the literature concerning the names of these states and modes, the authors have chosen to develop a set of clearly defined terminology and have applied it consistently throughout the report.

The laptop can be in one of two power source states. These states do not describe how much electricity the laptop is consuming or how fast it is operating, but merely where its power originates:

- *AC state*- The laptop is plugged into the familiar household alternating current (AC) outlet.
- *battery state*- The laptop is not plugged into the AC outlet and is operating on battery power.

Within either of these states, the laptop can be in the following power modes, listed in decreasing order of typical power consumption:

- *max on* – The laptop is on and the screen is set to full brightness. The computer is performing some intensive computing operation, such as opening a program, downloading e-mail, finding a web-site, saving a file, or searching a directory. This power mode only occurs over intervals of a few seconds or less, so it represents a small amount of the total time that a laptop is used.
- *on* – The laptop is on and the screen is set to full brightness.[5] The computer is performing only minimal computing, with or without user input. In this mode, the user could be running a word processing or spreadsheet program or playing solitaire. In these situations, the computer's power draw does not change meaningfully whether the user is entering data or not, so both situations are included in this mode.
- *monitor sleep* – The laptop is on and the screen is powered down. This low power option is available through the power management (PM) software and is automatically enabled after a certain time period of user inactivity (ranging from minutes to hours). The likely scenario under which the computer would enter is mode is the following. The user is attending to other non-computer work and is not typing or otherwise using the computer so the screen on the computer automatically turns off, which sends the laptop into *monitor sleep* mode. The laptop quickly returns to *on* mode when the computer detects a key press or a mouse movement.
- *hardware sleep* – This power mode is accessed either by choosing the "Standby" option from the Windows Start menu, or by enabling a automatic timer in the PM software that sends the laptop into *hardware sleep* mode after the user has not been typing or otherwise using the computer for some period of time. This period of time selected by the user is usually longer than the time period designated by the user for transition into *monitor sleep* mode. In order to get the computer to return to *on* mode from *hardware sleep*, a particular button (usually the power button) must be pressed. The computer returns to *on* mode more slowly than *monitor sleep*, but more quickly than starting up from the *off* mode.[6] Different PM software has different names for this mode and in all cases the monitor is off in this mode.
- *off* – The laptop is switched off by manually pushing the power switch or by choosing "Shut Down" from the Windows start menu. In order to get the computer to *on* mode from this mode, the user must start up the computer using the power button. If the computer is in *AC state* in this mode, a small amount of power continues to be consumed even if the laptop battery is fully charged.[7]

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[5] The brightness level of the display in *on* mode was chosen because an informal survey of laptop users indicated that they typically set their screen at full brightness while working. In addition, most laptops are shipped with screen is at full brightness, even if the brightness is adjustable by the user. The brightness of the screen does affect power consumption of a laptop significantly, which will be discussed in the section entitled "Displays" (Chapter 2).

[6] Intel's Instantly Available Personal Computer (IAPC) initiative and others like it from other chip manufacturers are designed to reduce this time discrepancy, making it possible for users to employ hardware sleep more routinely with minimal time spent waiting for computer operation to resume.

[7] Although not addressed separately in this report, "hibernate" is a form of off and has nearly identical power requirements as the *off* mode described here. For more information about hibernate and how it

The top row in Table 1 in the following section, “National Energy Consumption of the Laptop (Duty Cycle),” provides the reader with an estimate of the power usage in each of these modes.

There are a number of battery charging conditions that can occur in the *AC state* and can influence the total power consumed in each mode listed above. Power draw for battery charging varies widely depending on the state of charge, so is not amenable to categorization in the same way as operating mode (see “Battery System” in Chapter 2 for an additional discussion of this). To keep the complexity of measurement and discussion manageable, we made all power measurements in each mode with either no battery installed or a fully charged battery, effectively removing battery charging as a variable in determining the power consumption of the operational modes.

In order to completely describe the status of the laptop, a state and a mode must be specified. For example, if a user is typing in a word processing program and has the laptop plugged into the wall outlet, this laptop would be in *AC state*, *on* mode. If only a power source state is referred to, without a mode specification, then it is assumed that the discussion refers to all power modes within that power source state.

National Energy Consumption of the Laptop (Duty Cycle)

The energy consumption of laptop computers has likely been underestimated in previous studies for a number of reasons:

- Energy efficiency analysts have paid most of their attention to other office equipment that is always plugged in and only runs in *AC state*, often assuming that the laptop is an insignificant and rarely used accessory of the office.

- The power values of the laptop computer that are quoted in the literature are lower than the averages that we obtained through measurement of 2002-2003 models. The older studies may need to be updated to reflect the increasing capabilities (and power use) of newer machines.

- The duty cycle of the laptop computer, or how much time it spends in the various power modes of *on*, *off*, *monitor sleep*, etc., is not well established or known, leading researchers to make guesses about their use patterns.

- Analysts have previously assumed that laptops always have their power management (PM) functions enabled. Laptop users we informally surveyed said that their laptops spend much of the time in *AC state* with minimal PM functions enabled. PM functions were more likely to be enabled when laptops were running

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relates to off please see: Bruce Nordman, "The Power Control User Interface Standard", prepared by Lawrence Berkeley National Laboratory for the California Energy Commission, Public Interest Energy Research Program, P500-03-012F, LBNL-52526. December 2002.

in *battery state.* No laptop users informally surveyed said that they allowed their laptop to go into *hardware sleep* mode although some users enabled the *monitor sleep* mode to increase battery life.[8]

- Finally, and most importantly, the *battery state* of the laptop and the energy penalty associated with its portability has been overlooked. Analysis up to this point has ignored the *battery state* when considering the duty cycle calculation. This oversight results in an underestimation of the energy consumed because the amount of energy that is put into a battery during the charge cycle is always larger than the amount that can be extracted from it when it is powering the laptop.

Given these deficiencies, NRDC and its consultant Ecos have decided to develop their own estimate of laptop energy consumption using a bottom up approach. Inherent in our analysis are some assumptions on operating hours and user behavior. As better data become available on these parameters, analysts can simply revise the spreadsheets we developed to calculate updated numbers.

To calculate total national energy consumption for laptops, we used four primary sets of data: the average power consumption in each of the various modes, the amount of time per year one laptop spends in each power mode (duty cycle),[9] the energy consumption associated with one battery charging cycle, and the number of charging cycles experienced per year. Adding the product of the first two factors and the product of the last two factors yields total annual energy use per computer, or its unit energy consumption (UEC).[10] This value, when multiplied by the total number of computers in use, yields the total national energy use for laptops.

Of these values required for the calculation of the energy consumption, the least is known about the duty cycle of the laptop. Therefore, we will examine two different duty cycle scenarios: the Road Warrior scenario, which approximates the use of a business person on the road or of a college student working at home and at the library, and the Desktop Replacement scenario, which considers a laptop used primarily to replace a desktop in an office setting. In brief, the Road Warrior will more frequently use the laptop in *battery state* while, in the Desktop Replacement scenario, the laptop is generally plugged in and run using an AC outlet and not the batteries (*AC state*).

In the Road Warrior scenario, we assume that the laptop will be used for one short business trip per week, with one day of preparation for departure and 2 to 3 days on the road. The user has minimal PM options enabled, such that the laptop goes into *monitor*

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[8] Users are likely to disable hardware sleep because they are concerned about reliability (real or perceived) of the machine if they allow the laptop to go into hardware sleep or because network administrators are unable to access the machine remotely if it is in *hardware sleep* mode. For more information, please see Bruce Nordman, December 2002.

[9] Also known as "operating pattern."

[10] The energy consumed by one laptop in one year is described by the following equation where *n* is the number of modes, E in the energy (in watt hours) required for one full charge of the battery and N is the number of charge cycles: $UEC = [\sum_n Watts_n * Hours_n] + E * N$

sleep mode after some relatively long period of time of being idle. Based on this scenario, we assume for one week a total of 24 hours are spent in *AC state - on* mode, 6 hours are spent in *AC state - monitor sleep* mode, 10 hours would be in *battery state* with any mode enabled, and the laptop would undergo 5 charge cycles. Of the remaining time, we assume 32 hours are spent in *battery state - off* mode (unplugged and drawing no electricity from the AC outlet). The remaining 96 hours are spent in *AC state - off* mode (plugged into the AC outlet and drawing some electricity.)

In the Desktop Replacement scenario, we assume that the laptop is functioning primarily as a desktop. Because of its portable capabilities, the user may occasionally use the laptop in *battery state* while in meetings. We modified duty cycle numbers from Arthur D. Little's estimation of a desktop duty cycle, changing three hours a week of *AC state - on* mode to three hours per week of *battery state* and adding in 1.5 charge cycles per week. The Desktop Replacement scenario assumes that, like a desktop in an office setting, the standard PM functions are enabled. Therefore, this user scenario will allot more time in *monitor sleep* mode and *hardware sleep* mode than the Road Warrior scenario.

Table 1 shown below contains details of the values used to calculate the unit energy consumption (UEC) of a laptop computer under the two scenarios. In developing these values, Ecos measured the power consumption of approximately 30 laptops in their laboratory at each the operating modes. In addition to the power values, researchers also recorded (when possible) laptop class, manufacturer, model number, year purchased, purchase price, display pixel configuration, display size (diagonal inches), operating system, CPU manufacturer, and CPU model.

Based on our calculations, a laptop that was operating under the Road Warrior scenario would consume 60 kilowatt hours per year (kWh/yr) and a laptop operating under the Desktop Replacement scenario consumes 106 kWh/yr. When this is multiplied by the US laptop stock, we obtain estimates of the annual energy consumption of laptop computers in the US (Table 2). Assuming the Road Warrior scenario, 2.2 Tera-watt hours are consumed per year. This is the equivalent of $188 million worth of electricity that produces about 1.5 million tons of CO_2 emissions in the process of generation.

In the Desktop Replacement scenario the energy consumption is higher: 3.9 Terawatt hours are consumed per year, which is the equivalent of nearly $330 million, and results in 2.6 million tons of CO_2 emissions in the generation process.[11] Both of these energy consumption estimates are much higher than previous estimates. For example, Arthur D. Little's[12] estimates are five and ten times smaller than the Road Warrior and Desktop Replacement scenarios, respectively.

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[11] Estimates assume 0.085 dollars/ kWh and 1.341 pounds of short tons of CO_2 per kilowatt-hour of generation.

[12] Roth et al. p.29.

Table 1 - The Unit Energy Consumption (UEC) of a Laptop Under Two Duty Cycle Scenarios

Type	On	Monitor Sleep	Hardware Sleep[13]	Off	Unplugged	Battery Mode[14]	Charge
Power consumption of average laptop (watts)[15]	23	14	2	2	0		
Energy consumed in one charge cycle (watt-hours)[8]							66
Road Warrior usage time (hours/year)	1,248	312	0	4,992	1,664	520	
Road Warrior # of charge cycles/year							260
Desktop Replacement usage time (hours/year)[16]	2,606	2,369	375	3,254	0	156	
Desktop Replacement # of charge cycles/year							78
Road Warrior Total UEC (kW-h/year):							60
Desktop Replacement Total UEC (kW-h/year):							106

Table 2 - Total Annual National Energy Consumption of Laptop Computers Under Two Duty Cycle Scenarios: Road Warrior and Desktop Replacement.

Scenario	Residential and Commercial US Stock (millions)[17]	UEC (kWh/year)	Total Annual Energy (TW-h)
Road Warrior	37	60	2.2
Desktop Replacement	37	106	3.9

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[13] In most laptops, *hardware sleep* power values are slightly higher than the *off* mode power values. The power values associated with these two modes are identical because averages taken from the sample are rounded to the nearest watt.

[14] It is important to note that the energy to charge the laptop battery is an add-on to the total energy consumed in different laptop modes because charging can take place in any mode in the *AC state*. An average of 66 watt-hours are consumed every time the battery is charged. This coupled with the number of times that the battery is charged per year gives the energy consumption of the laptop battery charging system.

[15] Power and energy consumption averages were obtained through Ecos measurements of over 30 current model laptop computers.

[16] Modified from Kurt W. Roth, Fred Goldstein et. all. *Energy Consumption by office and Telecommunications Equipment in Commercial Buildings. Volume 1: Energy Consumption Baseline.* Prepared by Arthur D. Little for The U.S. Department of Energy. January 2002, p. 29.

[17] This stock calculation assumes the average laptop life is 2 ½ years. Further details of this stock calculation can be found in Appendix B.

Figure 2 – Annual Laptop Energy Consumption by Power Mode

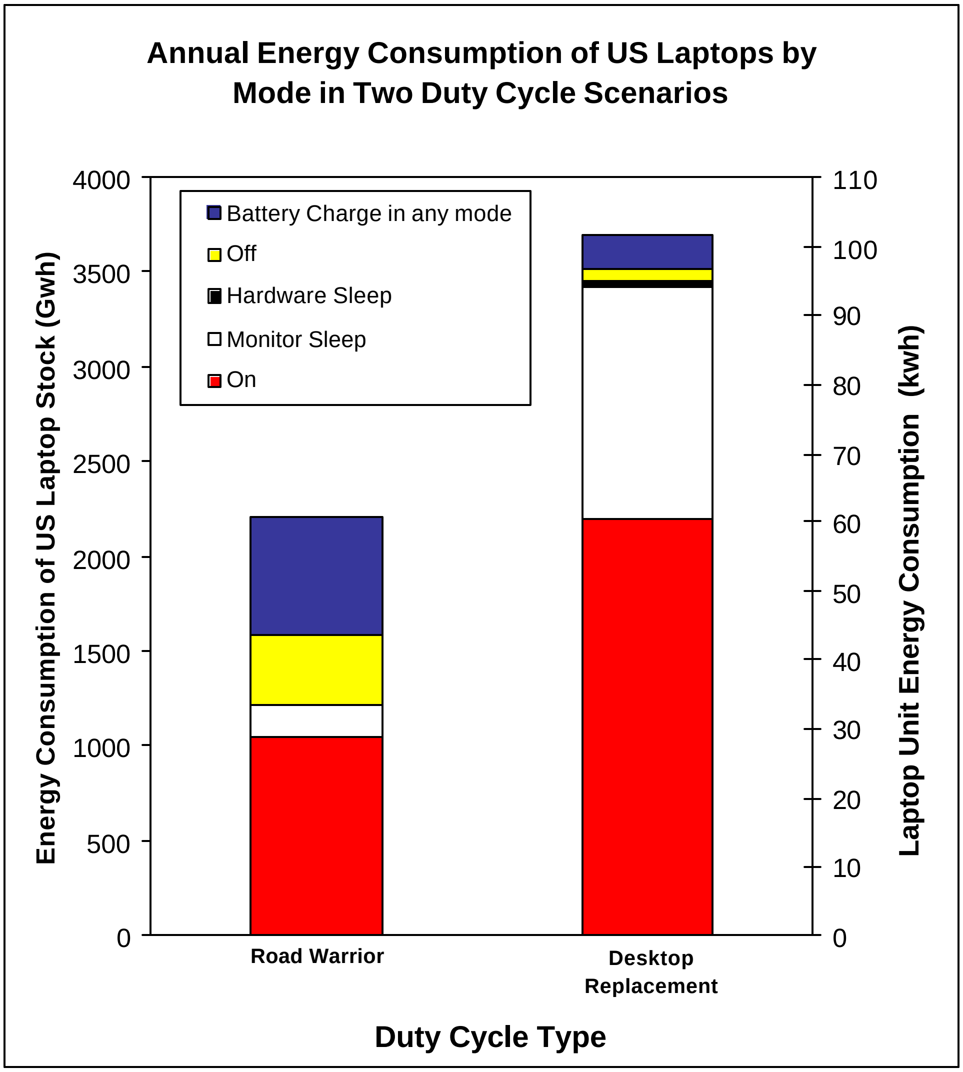

Figure 2- A breakdown the annual national energy consumption of laptop computers by mode reveals that some operational modes consume more than others. Note that in the highly mobile Road Warrior scenario, over 25% of the total annual energy is used to charge the battery.

Taking the data from Tables 1 and 2, we prepared a side-by-side plot of the annual national energy use of the Road Warrior and Desktop Replacement (Figure 2). The total energy consumption is broken down into energy spent in various relevant operational modes as well as energy spent for battery charging. A relatively small amount of energy over the annualized duty cycle is consumed in the low power modes (*hardware sleep, monitor sleep, off*). This is because users are unlikely to take full advantage of low power modes and as a result, laptops spend little time in these modes. This user behavior is partially due to obstacles associated with computer networking in *hardware sleep* mode, and partially because of difficulties with the power management user interface.[18]

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[18] For more information, please see Chapter 2, "Power Management Software."

Because of the complexity associated with enabling low power modes, there is an absolute dominance of the *on* mode in overall energy consumption of laptops, regardless of whether the products are used for highly mobile applications (Road Warrior) or primarily office (Desktop Replacement) purposes.

The Energy Consumption of Laptops and Desktops

Using known power values for the desktop, the laptop, and the two most common types of monitors, as well as the desktop duty cycle detailed in the previous section (Table 3), we can calculate the annual energy consumption of computer systems with various hardware configurations (Table 4). These hardware combinations were chosen based on the nature of the two computer technologies. Most desktop computers must operate with an external screen, either the liquid crystal display (LCD), which is characterized by its relatively slim profile, somewhat limited viewing angle, and flat screen, or the cathode ray tube (CRT), which is characterized by its large, roughly cubical shape, and wide viewing angle. The LCD is a newer technology and is generally a more efficient technology than the CRT display. CRTs traditionally have a curved screen, but the latest models often incorporate a flat viewing screen. Unlike most desktops, laptops have an internal screen and therefore can operate with or without an external screen. We therefore examined five possible form factors: laptop, laptop with LCD, laptop with CRT, desktop with LCD, desktop with CRT (Figure 3).

Table 3 - Hardware Power Values and Duty Cycle Assumptions

Type	On	Monitor Sleep	Hardware Sleep	Off	Unplugged
Power consumption of 17" LCD (watts)[19]	40	4	3	1	0
Power consumption of 17" CRT (watts)[20]	76	8	4	3	0
Power consumption of laptop using internal screen (watts)[21]	23	14	2	2	0
Power Consumption of laptop using external screen (watts)	14	14	2	2	0
Power consumption of desktop (watts)[22]	61	61	34	3	0
Usage Time of computer system (hours/year)[23]	2762	2369	375	3254	0

Table 4 - Unit Energy Consumption (UEC) of Five Hardware Configurations

Configuration	Total UEC (kwh/year)	On Mode Energy Consumption (kwh/year)	Low Power Mode Energy Consumption (kwh/year)	Percent of Total UEC Spent in On Mode
Laptop[24]	104	64	40	61%
Laptop w/ external 17" LCD[25]	203	182	21	90%
Laptop w/external 17" CRT	319	282	37	88%
Desktop w/ external 17" LCD	460	423	36	92%
Desktop w/ external 17" CRT	576	523	53	91%

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[19] LCD power mode values are derived from an average of 35 models reported by manufacturers to EPA, ENERGY STAR ®, compiled by ICF. 2001.

[20] CRT power mode values are derived from an average of 236 models reported by manufacturers to EPA, ENERGY STAR ®, compiled by ICF. 2001.

[21] We assume that the laptop is always operating in *AC state* for the purposes of this comparison.

[22] Desktop power mode values are derived from an average of 20 models, measured by Travis Reeder of Ecos Consulting and Jonathan Koomey of LBNL, 2001.

[23] Kurt W. Roth, Fred Goldstein et. all..p.29.

[24] This is slightly lower than the earlier UEC calculation associated with the desktop replacement duty cycle because in this case there is no energy spent charging the battery. It is assumed that the laptop only operates in *AC state*.

[25] Note that the laptop with 17" LCD configuration is **NOT** equivalent to the energy consumption of a standard laptop plus the energy consumption of an LCD. This is because when the laptop is operating with an external LCD screen, the user can shut off the internal laptop LCD screen.

A number of useful observations can be made about Figure 3:

- Today a conventional desktop computer with a CRT monitor uses more than five time the annual energy that a laptop uses (580 kwh/yr vs. 100 kwh/yr)

- In some cases, the user may elect to hook their laptop up to an external monitor when in the office. Even in this case, a laptop with a 17-inch external LCD consumes 60% less energy in a year than a desktop computer with a 17-inch CRT screen.

- Desktop systems using an LCD monitor instead of a CRT monitor will use 20% less energy yielding an annual savings of 100 kWh/yr.

- Finally, note the majority of the energy consumption in all cases happens while the computer is in the *on* mode, not in the various low power modes like *monitor sleep*, *hardware sleep*, and *off*. Further implications of details concerning *on* mode power consumption will be discussed in a later section entitled "Policy Recommendations" (Chapter 4).

Figure 3 - Annual Unit Energy Consumption for the Average Desktop and Laptop

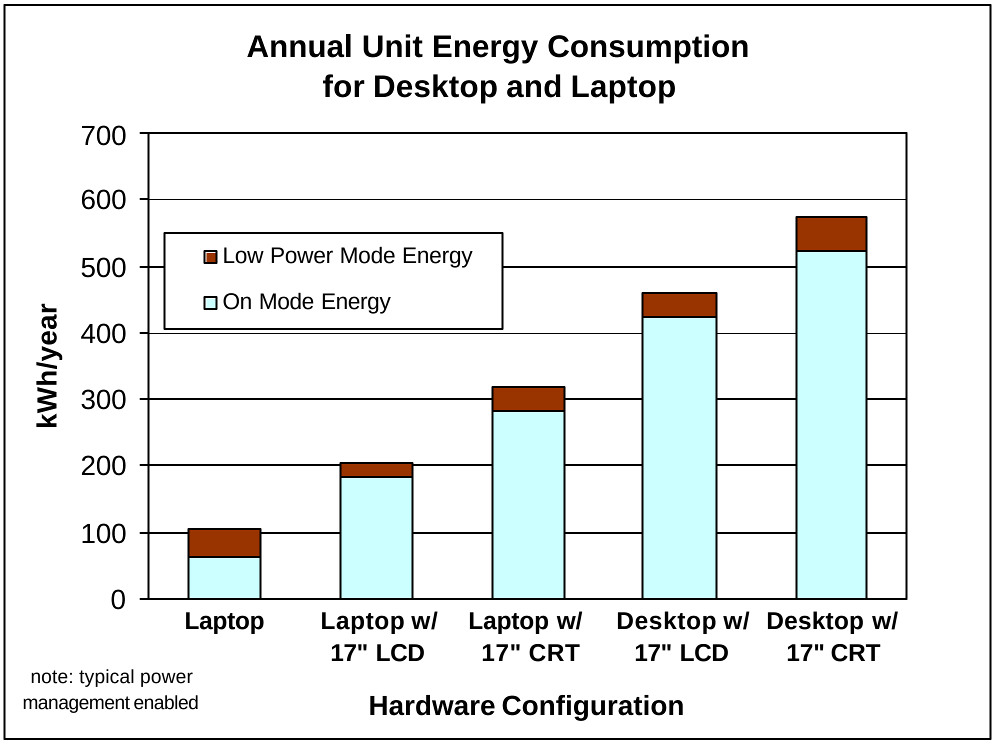

Figure 3 - Leading the pack in energy efficiency is the laptop computer; one unit consumes approximately 110 kWh per year functioning as a desktop replacement. Compare this to the desktop with CRT configuration that consumes five times that amount of energy in one year, takes up more real estate in the office, and produces more heat and fan noise.

The table below puts some of the potential energy and environmental impacts into perspective, demonstrating the significant benefits that can be attained from particular shifts in the current computer marketplace (Table 4). Two scenarios where there are significant potential for energy savings are: replacing desktop-CRT systems with laptop computers (or computers with laptop-like power requirements), and replacing desktop-CRT systems with desktop-LCD systems.

Table 4 - Estimated Potential Energy Savings for Two Replacement Scenarios

Scenario	**Annual kWh Saved**	**Annual Dollars Saved**	**Annual Tons CO_2 Saved**
25% of US desktops with CRTs are replaced with laptops	20 billion kwh	$1.7 billion	13 million tons
25% of US desktop systems shift from CRTs to LCDs	5 billion kwh	$0.4 billion	3 million tons

Variations in Laptop Energy Consumption

Not only is there a difference in energy consumption between laptops and desktops, there is also substantial variation in energy consumption among laptops themselves. The unit energy consumption (UEC) of the most energy-consuming laptop (maximum power) and the UEC of least energy-consuming (minimum power) laptop that were measured by Ecos are charted below under two duty cycle scenarios (Figure 4). Power values and duty cycle assumptions can be found in Table 5.

Figure 4 - Differences in Laptop Annual Power Consumption

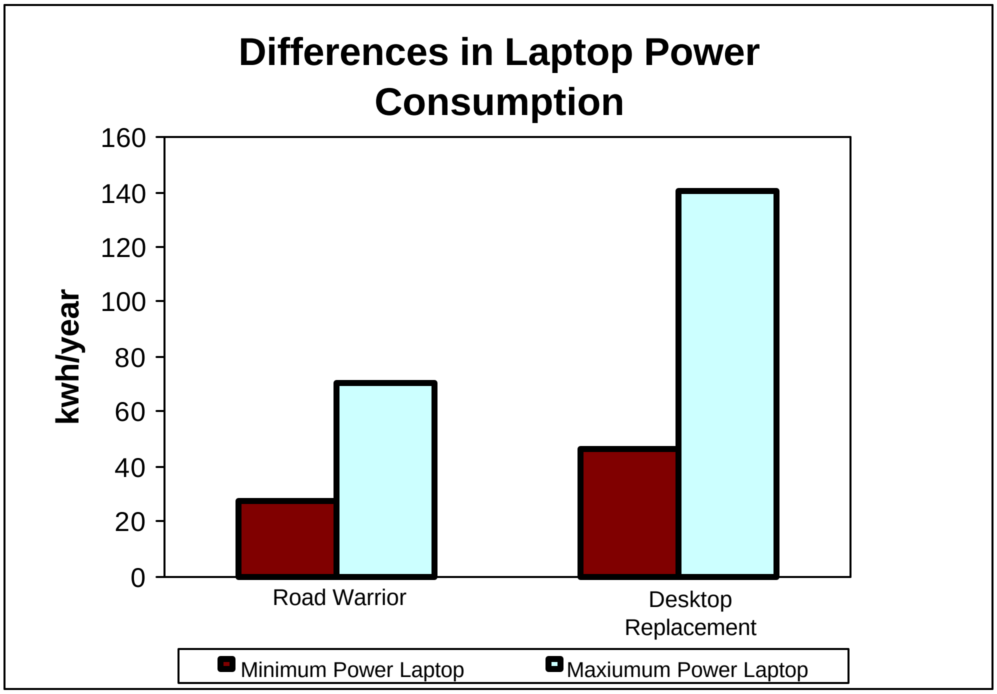

Figure 4 - Under both duty cycles (Road Warrior, and Desktop Replacement), the maximum power laptop consumes more than 60% more energy over the course of a year than the minimum power laptop. Although these power measurements do not account for performance differences between the two laptops,[26] they do help illustrate how widely annual laptop energy use can vary depending on the design of the machine and its usage pattern.

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[26] A measure of performance per watt-hour of energy consumed that does take into account the performance differences between laptop systems is addressed in System Benchmarking (Chapter 3).

Table 5 – Maximum and Minimum Laptop Power, Duty Cycle Assumptions, and UEC Values

Type	On	Monitor Sleep	Hardware Sleep	Off	Unplugged	Battery Mode	Charge
Power consumption Maximum Power Laptop (watts)	29	22	2	2	0		
Power consumption Minimum Power Laptop (watts)	11	5	1	1	0		
Energy consumed in one charge cycle (watt-hours)							66
Usage time: Road Warrior (hours/year)	1248	312	0	4992	1664	520	
Road Warrior: # of charge cycles/year							260
Usage time: Desktop Replacement (hours/year)[27]	2606	2369	375	3254	0	156	
Desktop Replacement: # of charge cycles/year							78
Maximum Power Laptop Road Warrior Total UEC (kW-h/year):							**70**
Maximum Power Laptop Desktop Replacement Total UEC (kW-h/year):							**140**
Minimum Power Laptop Road Warrior Total UEC (kW-h/year):							**27**
Minimum Power Laptop Desktop Replacement Total UEC (kW-h/year):							**46**

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[27] Modified from Kurt W. Roth, Fred Goldstein et. all. p.29.

Chapter 2 - Laptop Components: How much energy does each major component use?

When a laptop is running in *AC state*, electricity from the wall outlet is converted to low voltage DC (direct current) in an external power supply or AC adapter (Figure 5). This kind of current is necessary to run the chips and other digital electronics in the laptop. In the power supply, approximately 15% of the AC energy is lost as heat in the process of converting AC to DC. The electricity that has been converted to DC then supplies the whole of the laptop, which includes the battery charging system (if the battery is at less than 100% of capacity), the monitor, and other hardware. The monitor is, on a component basis, the biggest energy user, consuming approximately 30% of the total power when the computer is in *on* mode.

In *battery state* (represented by the gray line in Figure 5), the laptop hardware is running from the energy stored in the battery. Note that running the laptop from *battery state* is inherently less efficient than running the laptop from *AC state* because there are energy losses associated with storing electricity chemically in the battery pack. Every time the battery is charged, an average of 20% of the energy is lost in the process due to the circuitry of the charging system and the chemical losses in the battery. This 20% energy 'penalty' becomes more significant the more time the user spends in the *battery state.*

Battery run times are currently quite limited and generally range from 1 ½ hours to 3 hours, though the newest and most advanced systems can achieve 5 hours or more. Sometimes laptops will run at lower power states in *battery state*, by clocking the CPU[28] at a slower rate or dimming the screen. These low power modes can be built into the hardware of the system, but more often they are controlled by the power management software of the computer, which can be adjusted by the user.

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[28] CPU, or the central processing unit, is the "brain" of the computer responsible for processing all the tasks of the computer. Three of the largest processor makers for personal computers are Intel, AMD, and Transmeta.

Figure 5 - Interrelationship of Laptop Components

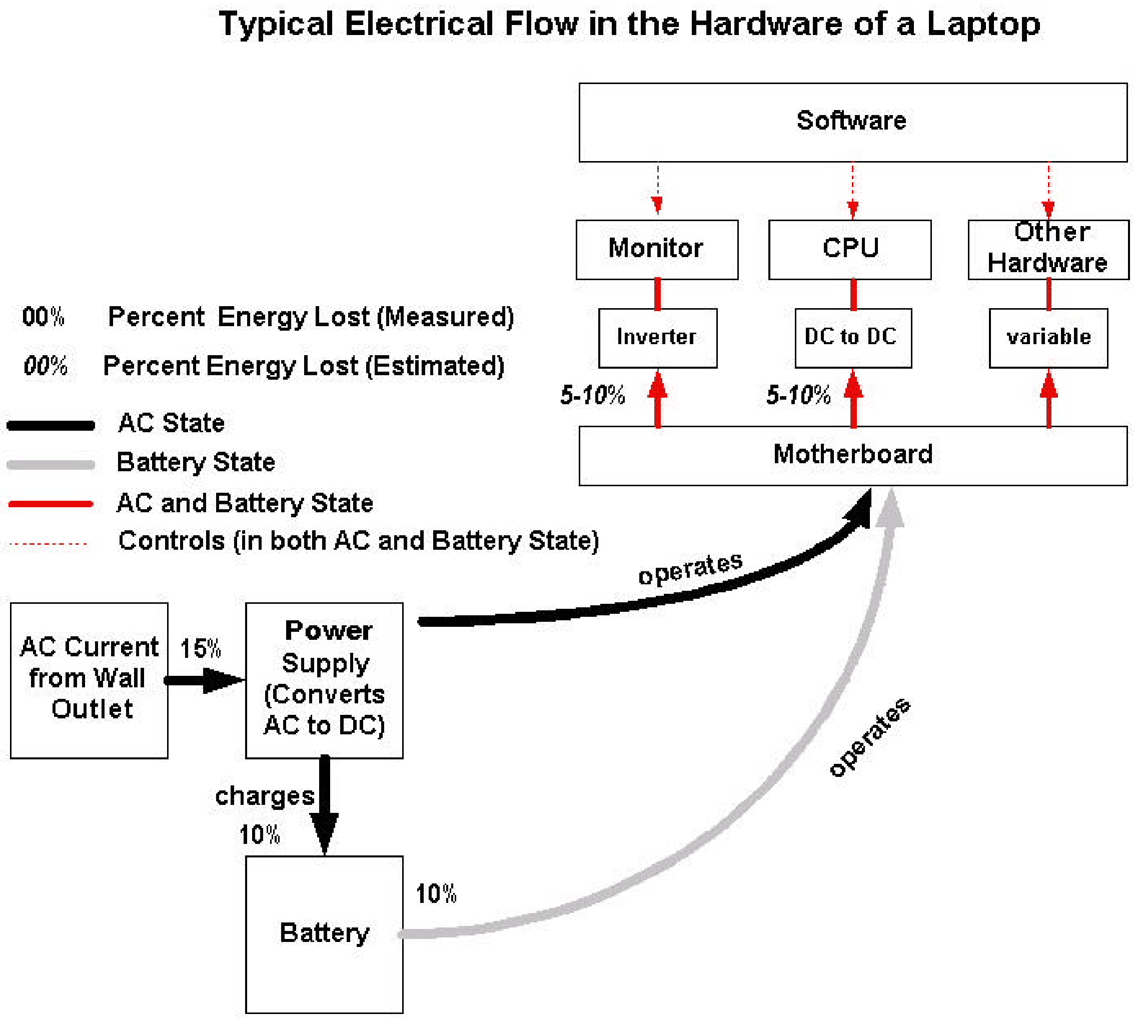

Figure 5 - Unlike the desktop computer, the laptop has the option to run from two different sources of energy, a wall outlet (*AC state*) and a battery supply (*battery state*). There are many factors that determine energy consumption in each state, including power management software settings and inherent hardware configuration.

30% of the power is allocated to the display system, which is the largest sole consumer of energy in a laptop. The remaining 70% of the power is consumed in the hardware of the computer, including the CPU, support circuitry on the motherboard, data storage/retrieval (memory, hard drives, floppy drives, and CD-ROM drives), the video card, communications hardware, a cooling fan, and battery charging/monitoring circuitry.[29]

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[29] For a more detailed discussion of how power losses occur in each component, see Jerzy Kolinski, Ram Chary, Andrew Henroid, and Barry Press, *Building the Power-Efficient PC: A Developer's Guide to ACPI Power Management*, Intel, 2001, pp.136-137.

Most of these devices require a voltage substantially lower than the 15 to 20 volts DC typically provided by the power supply. As a result, much of the power supply's output is routed through subsequent DC-to-DC converters, each with their own efficiency losses (perhaps 5 to 10%), before it is finally in a form usable by the computer's components.

Memory requires continual refreshing with an electronic signal to ensure that data will be retained. Hard drives, CD-ROM drives, and floppy drives are also inherently inefficient, since they require substantial amounts of electricity to "spin up" and maintain operating speed. Other approaches to information storage, including compact flash, require neither regular memory refresh nor mechanical rotation of a physical storage media. If these low power types of technologies replaced more power demanding memory technologies, they have the potential to contribute to energy savings in future laptop and desktop computers.

On top of all of the hardware is the software, which controls and utilizes the monitor, CPU and other hardware. Software allows the user to interact more easily with the computer and includes the operating system[30] and application programs (word processing programs, games, and internet browsers, for example). Of particular interest in this discussion is power management software, which gives users the capability to manipulate the power consumption of their laptop through various shut-off and low power techniques.

Since each of these components has unique efficiencies, we will now more thoroughly discuss these efficiencies component by component: power supply, battery system, display and CPU. Following that will be a discussion of power management software and its capacity to reduce energy consumption of the laptop computer, and then the implications of wireless technology. The concluding section will summarize and illustrate the range of differences found in the set of laptops surveyed and will estimate the energy savings and environmental benefits associated with potential improvements in component hardware.

Power Supplies

Ecos measured the efficiency of nine laptop power supplies from a variety of manufacturers. The measurements were made using five different static loads[31] across a range of possible output power levels for each power supply. The most efficient, least efficient, and average of the set of power supplies are plotted in Figure 6. Overall, the power supplies for the laptop computers were fairly efficient, compared to external power supplies that Ecos has measured for other NRDC investigations,[32] probably because of size and weight considerations.[33]

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[30] Operating System, or OS, is the software that manages all the other programs that are present on the computer. The most common OS is Microsoft Windows, but other operating systems include Linux, Unix, and Apple.

[31] We used variable resistors capable of dissipating the required power levels.

[32] Laptop power supplies represent the upper bound on the range (20%-85%) of external power supply efficiency.

[33] Inefficient power supplies weigh more. For more details, see Chris Calwell and Travis Reeder, *Power Supplies: The Hidden Opportunity for Energy Savings*, a report prepared for the NRDC, June, 2002.

Note that all laptop power supplies achieves a peak load efficiency of roughly 85 to 90%, but part-load efficiencies vary substantially. This is significant because laptop power supplies operate at part load a large percentage of the time: in *on*, *hardware sleep,* and *monitor sleep* modes as well as while charging the battery in *off* mode.

If all of the power supplies in US laptops were as efficient as the IBM model (20% more efficient when the laptop is in *monitor sleep, off, and hardware sleep* mode and 10% more efficient when in *on* mode), we estimate that this change alone would amount to savings of 210 GWh (million kWh) for the Road Warrior duty cycle and 520 GWh for the Desktop Replacement duty cycle (Table 6). Assuming a national average electricity rate of 8.5 cents per kWh, this translates to electricity savings of 17 million dollars for the nation's computer users under the Road Warrior scenario and approximately 44 million dollars for the nation's computer users under the Desktop Replacement scenario.

Table 6 - Possible Annual US Energy Savings with Efficient Power Supplies

Duty Cycle Type	**Possible Energy Savings (Gigawatt-hours)**
Road Warrior	**210**
Desktop Replacement	**520**

Figure 6 - Laptop Power Supply Efficiency

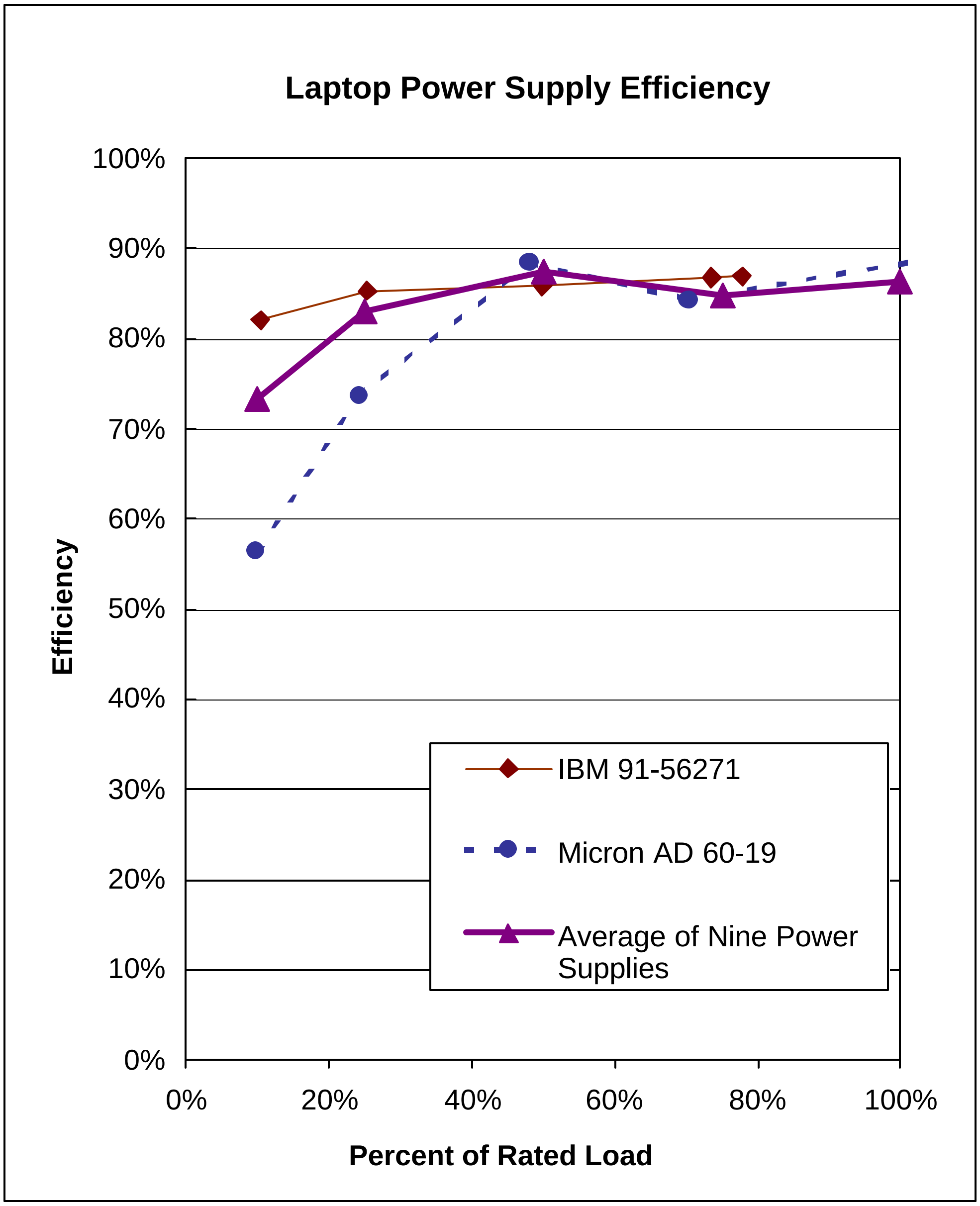

Figure 6 - Plotted above are power supply efficiencies that represent the average, upper bound, and lower bound of the set of power supplies tested by Ecos. Although laptops vary from one another, the operational modes ranges can be approximated. *Off*, *hardware sleep*, and some portions of battery charging are in the less than 10% rated load range. *Monitor sleep* mode is between 15 and 25% of the rated load, *on* mode is between 30 to 50% of the rated load, and *max on* is 50 to 75% of the rated load. Because laptops spend most of their time at these lower load levels, laptops that have less efficient power supplies waste significantly more energy than those with the most efficient power supplies (Table 6).

Battery System

The battery of a laptop can be charged in *AC state* and any operational mode: *max on*, *on*[34], *monitor sleep, hardware sleep,* and *off*. In fact, the battery system, when plugged in, will automatically charge the battery in any of these modes if the battery is at less than 100% capacity. The lithium ion (Li-Ion)[35] battery chemistry found in virtually all new laptops does not require the topping charge necessary for other chemistries to keep the battery at full charge, and therefore has periods when no power is required of the battery charging system. In addition, laptops incorporate 'smart' battery systems. In these systems, the battery tells the charger how and when it wants to be charged. Although this technology increases the cost of the system, it gives the user better battery life performance.

Because there are inherent inefficiencies in the system that charges and discharges the battery, there is an added energy penalty every time users run their laptops in *battery state.* In other words, it takes more energy to do a set of tasks in *battery state* than it does to do exactly the same set of tasks in *AC state*.[36] This is not because the hardware consumes more energy in the *battery state*, but rather because there are power losses, both chemical and electrical, associated with putting energy into the battery. There are also electrical and chemical losses associated with discharging the battery (taking energy out). These types of losses are readily observable in the form of heat, increasing the temperature of the battery and the laptop housing. Ecos was able to determine the sum of these losses: an overall efficiency of the battery system itself.

Because chargers made to handle standard sized rechargeable batteries such as AA batteries were found to be quite inefficient (between 6% and 40%),[37] it seemed important to investigate the efficiencies of the laptop computer charging mechanisms for an opportunity for energy savings. For a complete discussion of specifics and methodology of the investigation, please see Appendix E. Efficiencies of laptop battery chargers were found to be between 76 and 81%. Because it is necessary for chargers in laptop batteries to charge quickly and efficiently and also because of thermal constraints, battery chargers in laptops seem to be incorporating technology that has multiple benefits for the user and is also extremely efficient. These charging systems represent some of the best technology that is available on the market today.

This energy loss associated with the charging system is more pronounced the more time that the laptop spends in the *battery state.* The US total energy loss associated with the Road Warrior duty cycle is 130 GWh, while the loss associated with the Desktop Replacement duty cycle is 40 GWh.

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[34] For more details concerning the differences between charging the battery while in *on* modes and *off* mode in the *AC state*, please see Appendices E and F.

[35] For more details concerning the Li-Ion chemistry, please see Appendix D, "Details of Laptop Battery Design."

[36] This assumes that it is possible to set the hardware power levels, and PM options to be the same in each state.

[37] Measurements made by Ecos Consulting for NRDC 2002-2003.

Table 7 - Annual US Energy Consumed by Laptop Battery Charging System

Duty Cycle Type	**Energy CONSUMED by Battery System (Gigawatt-hours)**
Road Warrior	**130**
Desktop Replacement	**40**

Displays

Laptop displays consume 30% of the total energy supplied by the power supply or the battery and represent a substantial efficiency paradox by themselves. On the one hand, they cut power use and physical size by perhaps 50 to 80% relative to the external cathode ray tubes (CRTs) that preceded them. On the other hand, they still exhibit profound, fundamental inefficiencies in their basic design. The power that feeds the display starts at the AC wall plug and is converted in the power supply to DC. But displays require AC power to operate their fluorescent backlights, so the portion of the power that runs the display must undergo a second inefficient conversion from DC *back* to AC in an inverter, at an efficiency of perhaps 80% to 90%. Of that AC power, about 30% to 40% is successfully converted to visible light in the cold cathode fluorescent backlights, with the rest becoming heat.

Then, because of the inherent opacity of most liquid crystal technologies, 95% of that light is absorbed in the crystals themselves, rather than passing through them to emerge as useful visible light of a particular color.[38] In total, then, perhaps only 1% (84%[39] * 30% * 85% * 35% * 5%) of the energy content of the electricity drawn from the wall is actually available in the pattern of visible light emitted from its display that we call "information." If, to be generous, we consider only the efficiency of the entire chain of components in the display system, rather than the computer as a whole, we would still have to conclude that the system only converts about 2% to 3% of the electrical energy consumed by it into visible information.

A wide range of display efficiencies, expressed as pixels per watt, exist in laptop computers. The difference between the power consumed when the computer is on and the monitor is off (*monitor sleep* mode), and the power consumed by the computer when it is on and the monitor is on (*on* mode), is the amount of power that is drawn by the monitor. Dividing the number of pixels in the monitor by the watts required to run the monitor gives the efficiency of the device.[40] When calculated in this manner, with the monitors on maximum brightness,[41] a wide range of monitor efficiencies was found: from 27,000 pixels per watt on a Toshiba Satellite (800 x 600 pixels on a 12 inch screen) to 186,000 pixels per watt on a Dell Inspiron (1600 x 1200 pixels on a 15 inch screen).

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[38] Poor, Alfred. "LCD Monitors: Technology Update" at www.extremetech.com. © 2001 Ziff Davis Media Inc. January 2, 2002. (http://www.extremetech.com/article2/0,3973,10082,00.asp)

[39] Estimation of power supply efficiency.

[40] DC Power only, net of power supply efficiency losses.

[41] The monitors were measured with high power (high screen brightness) because it is our experience that when laptop users are in *AC state*, they have the screen on the highest brightness setting.

This is a wide range of efficiencies, but it is more instructive to compare those screens that have the same resolution capacity. For example, we compared two computers that have a pixel arrangement of 1024 x 768, a fairly standard pixel configuration. A Fujitsu C-series Lifebook has an efficiency of 64,000 pixels per watt, while an IBM ThinkPad T20 rates achieves 128,000 pixels per watt. Using this comparison, we can estimate the possible energy savings if all laptops in the US had screens that were as efficient as the IBM ThinkPad T-20. If all laptop displays were this efficient, we estimate that this would amount to savings of 260 GWh for the Road Warrior duty cycle and 550 GWh for the Desktop Replacement duty cycle (Table 8).

Table 8- Possible Annual Energy Savings With Transition to Efficient Monitors

Duty Cycle Type	**Possible Energy Savings (Gigawatt-hours)**
Road Warrior	**260**
Desktop Replacement	**550**

LEDs, or light emitting diodes, will provide an alternative way to backlight an LCD in the future. In fact, LED backlit screens are scheduled to be introduced by Lumileds as a commercial product in 2003. LEDs are a low voltage, energy efficient solid-state lighting technology that will eliminate the need for an inverter and will improve color rendering and vibrancy. LEDs have the potential to also increase laptop durability and longevity, and eliminate mercury content in the displays (Figure 7).

Figure 7- Linear Strip LED Backlight for an LCD Monitor[42]

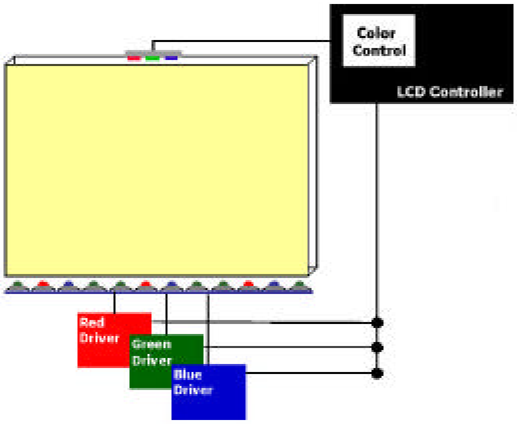

Figure 7- Lumileds' LCD backlight combines red green and blue LEDs in a linear strip and would replace the cold cathode fluorescent lamps that are now used in the LCD display systems of laptops. The LED driver – controller system carefully controls the output of the LEDs to maintain color quality. Other benefits of this system over the conventional system include a reduction in motion blur and an increase in color rendition.

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[42] Figure can be found on the Lumileds website: http://www.lumileds.com/pdfs/techpaperspres/SID-BA.pdf .

Other approaches like OLEDs (organic light emitting diodes) may bypass the backlighting approach altogether, creating the light efficiently and directly from each pixel instead of lighting a largely opaque crystal from behind. OLEDs displays do not currently have the operating life to accommodate heavy display use of the laptop, but they are being introduced in 2003 in Kodak's digital cameras.[43]

Microprocessors

Vitally important to the power consumption of the laptop computer is the central processing unit or CPU. The more time the computer spends in *max on* mode, the more important the power consumption characteristics of the CPU become. The CPU consumes the most power when it is being rigorously utilized, and less power when it is doing minimal processing.

The frequency at which the chip is clocked, which has been traditionally associated with the speed at which information is processed, is directly related to the power consumption of the chip.[44] As chips have increased their clocking speed over time in pace with Moore's law, which predicts a doubling of processing speed every 18 months, so has their power consumption increased (Figure 8). Notice that the Intel 486 consumed about 5 watts at peak operation, and the latest generation desktop processor (the Intel Pentium 4) consumes 75 watts at peak operation. Without changes in current technology, the next generation processor would bring us to the hundreds of watts range. Given the physical limits imposed by heat dissipation requirements and battery storage capacity, fundamental changes to chip technology appear essential in future processor generations.

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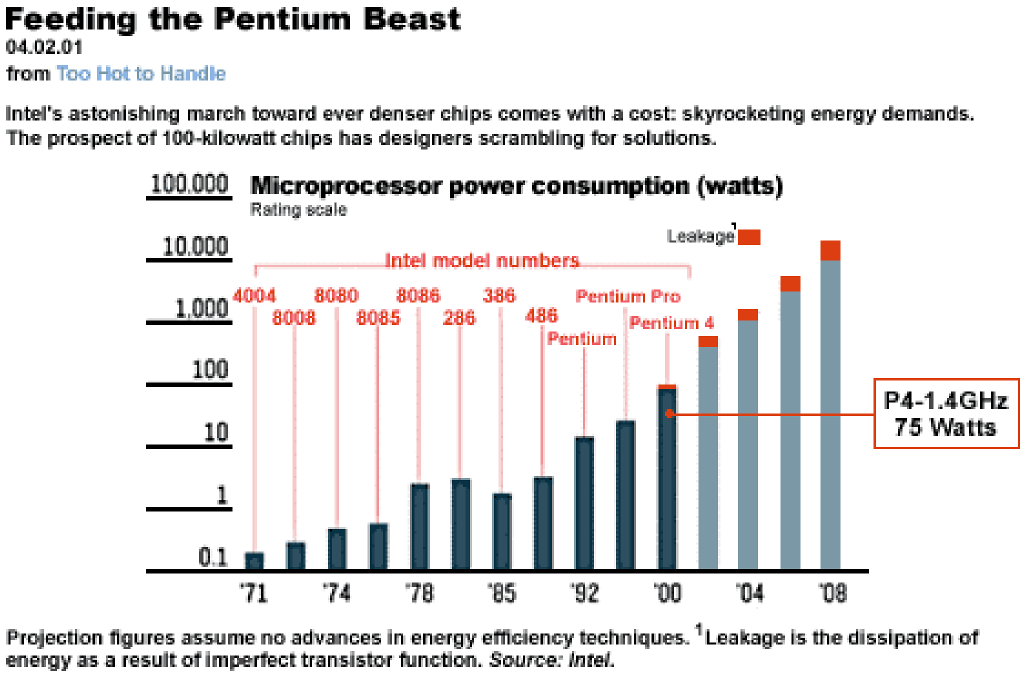
[43] Graydon, Oliver. "Digital Cameras Get Organic Displays," at www.optics.org. 3/7/03 © IOP Publishing Ltd. Accessed 3/10/03 (http://optics.org/articles/news/9/3/5/1).

[44] For more details concerning the relationship between frequency and power as well as other factors that affect the power consumption of a central processing unit, please see Appendix C.

Figure 8- Projected Increases in Microprocessor Peak Power Consumption If CPU Efficiency Is Not Improved[45]



Feeding the Pentium Beast

04.02.01

from Too Hot to Handle

Intel's astonishing march toward ever denser chips comes with a cost: skyrocketing energy demands. The prospect of 100-kilowatt chips has designers scrambling for solutions.

Projection figures assume no advances in energy efficiency techniques. [1]Leakage is the dissipation of energy as a result of imperfect transistor function. *Source: Intel.*

Figure 8- If Moore's Law keeps it pace with Intel chips, doubling processing speed every 18 months, the potential for energy consumption by the CPU itself is extraordinarily high. Notice the vertical axis is a logarithmic scale, with each step a factor of ten larger than the previous step. Currently, Intel's CPU is at 75 watts with its Pentium 4 chip, with the next generation projected to bring power consumption to around 500 watts. Intel has, in 2003, presented an alternative for mobile computing, the Centrino processor, which promises strong performance and energy efficiency in one package.

Recognizing a need for reduced power consumption in order to increase battery life, Intel has introduced in 2003 a processor called Centrino, which is reportedly highly optimized for energy efficiency. This marks the first time that a CPU has been packaged with other components (such as wireless capability) in order to optimize performance. The CPU itself can be found without the Intel chipset and wireless hardware under the name of Pentium M and according to reviews carries many of the benefits of the total Centrino package. [46]

Although the Centrino is clocked at speeds of 1.3 to 1.6 Ghz, its performance is actually improved over the Pentium 4 and Pentium 4 Mobile (a mobile version of the P4) that boast higher clock speeds.[47] The Centrino not only has a lower maximum clocking speed, but also lowers power consumption by cutting the voltage and frequency of the processor depending on the demands placed on the processor. There are a variety of

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[45] "Too Hot to Handle," *Forbes*, April 2, 2001. See also Stephen Ohr, "Intel Exec: Power Consumption is Major Issue," *EE Times*, February 6, 2001.

[46] According ZDnet review: "Centrino: born to run." http://www.zdnet.com/products/stories/reviews accessed 3/14/03.

[47] According to ZDnet review: "Centrino: born to run."

voltage/frequency combinations for different demand levels. This ability to control the voltage and frequency of the chip reportedly enables longer battery life: the IBM Think Pad T40 has been measured to have a 7-hour battery life under certain conditions.[48]

AMD, the second largest CPU producer, has taken a somewhat similar approach to lowering the power consumption of its laptop processors and also has the potential for reduced power consumption and battery life extension. AMD now has a new technology in its mobile chips called PowerNow! that enables 3 different operational modes. The high performance operational mode allows peak frequency and voltage for the chip and maximizes performance within thermal limits. The second mode, the automatic mode, allows core voltage and frequency to more closely match the application needs and conserve power. The third mode is the power saver mode, where the chip operates at the lowest possible voltage and frequency to maximize energy savings. The Power Now! options, although available with Windows XP, are not available with all operating systems. For example, Windows 2000 does not recognize or utilize the stepping mechanism of the Power Now! technology without the PowerNow! applet installed. These features will likely be enabled in future versions of Windows and represent another promising opportunity to contribute to energy savings in the *AC state*, and battery life extension in *Battery state*[49].

A relatively small company called Transmeta employs two design strategies for its CPUs, one fundamentally different from Intel and AMD, and one also utilized on different scales by both Intel and AMD. Unlike the other two companies' designs, Transmeta's processor is a software-hardware hybrid, employing a reduced instruction set to cut the number of transistors needed to process complex instructions rapidly. Transmeta's chips can power down to a wide range of clock frequency and voltage combinations, similar to the latest Intel and AMD technology. They achieve about two-thirds the processing speed of a pre-Centrino Intel chip when run at equivalent clock frequencies, but use far less peak power (from 2 to 6 Watts), which is particularly attractive to mobile users who are concerned with battery life extension. Transmeta's actual processing capability relative to the Intel and AMD designs tends to be somewhat less. However, laptop and desktop computers are not necessarily utilizing the capabilities of the latest generation processors in any case, so somewhat slower designs that cost significantly less and use far less power may have real advantages in the marketplace.

Power Management Software

All the laptops that Ecos surveyed had some type of power management (PM) software that allows the user to select various parameters that are related to energy consumption. For example, the user can specify a period of inactivity that should pass before various components of the laptop power down. The user determines when, for example, the display on the laptop should power down, allowing the laptop to enter *monitor sleep* mode. Other "power down" parameters include turning off the hard disks while in *on*

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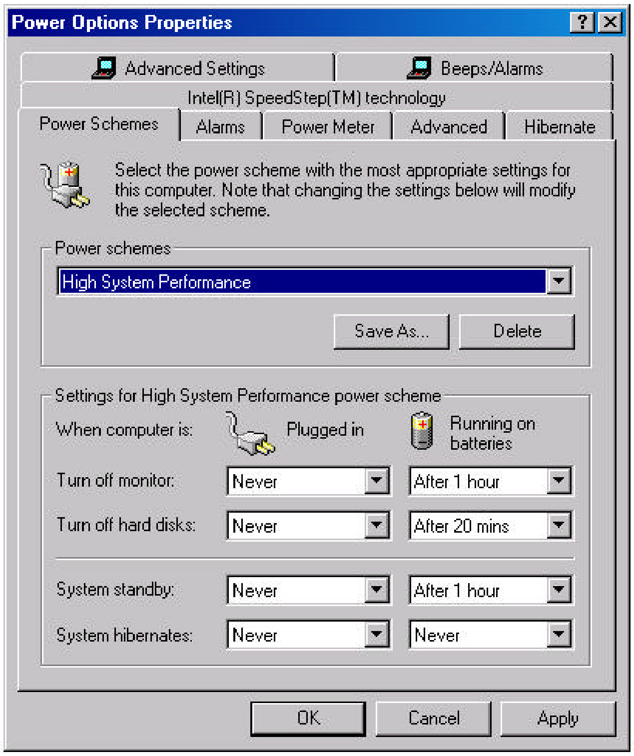
[48] According to ZDnet review: "Centrino: born to run."

[49] For more review information, please see http://www.tomshardware.com/mobile/20030102/index.html

mode,[50] and sending the laptop into *hardware sleep* mode. *Hardware sleep* mode has a significant wake-up time and requires the user to initiate the wake-up sequence.

Monitor sleep and *hardware sleep* initialization options represent the baseline of power management available through the latest versions of Windows, including Windows 2000 and Windows XP. An example of the screen interface offered through Windows and as taken from a model T23 IBM Think Pad is shown in Figure 9. Notice that the user chooses a certain set of parameters in the *AC state* and in the *battery state.* This basic form of power management does not include options such as automatic screen brightness, a key component to energy consumption considering screens consume approximately 30% of the total power of an average laptop when it is in *on* mode.[51]

Figure 9- "Shut-Off" Power Options Standard on Latest Windows Systems



Select the power scheme with the most appropriate settings for this computer. Note that changing the settings below will modify the selected scheme.

Power schemes: High System Performance

Settings for High System Performance power scheme

When computer is:	Plugged in	Running on batteries
Turn off monitor:	Never	After 1 hour
Turn off hard disks:	Never	After 20 mins
System standby:	Never	After 1 hour
System hibernates:	Never	Never

Figure 9 - This interface allows the user to change the period of time that passes before a computer goes into various low power modes. This user has chosen to take a more rigorous approach to power management in the *battery state* than in the *AC state*, directing the laptop to never go to low power modes when the computer is plugged into the wall, but setting various time periods for entry into three different low power modes. Please note that the specific settings in the bottom half of the window can be adjusted independently and do not necessarily match the power scheme indicated.

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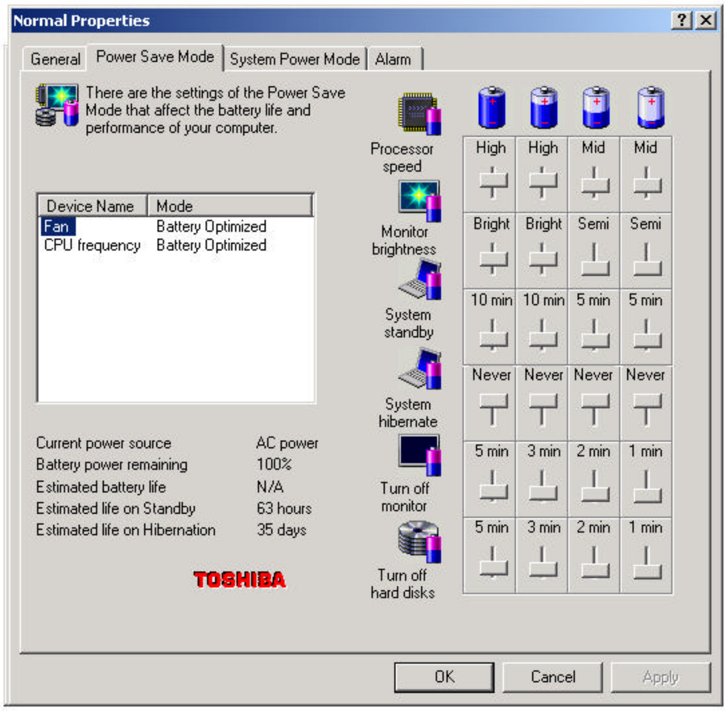
[50] This power mode was not incorporated into the duty cycles in this report because of its relative unimportance in the duty cycle of the average laptop.

[51] This is partially because the VESA (www.vesa.org) protocal does not specify this type of communication between the PC and display.

Other power management options are available, depending on the sophistication of the software and the capabilities of the various components. These parameters vary according to manufacturer of the laptop and the operating system employed. The user may be able to select display brightness and even CPU settings that affect clock and voltage values.[52] All of these settings have the capacity to reduce the energy consumed by the laptop. For example, when a laptop is equipped with a Pentium III Mobile processor, the user has the option to choose the speed of the CPU: either to maximize performance or maximize battery life. This CPU setting is available in *AC state* and in *battery state.*

Figure 10, the Toshiba Power-Saver software found on the Tecra 8100, is an example of software that has multiple parameters to adjust power consumption. Although this is the screen that enables the user to set *battery state* parameters, this software has the capacity to adjust the power management in both *AC* and *battery state*s, potentially enabling a user to save energy. At the same the time, due to the complex nature of the interface and the number of adjustable parameters, this interface is not necessarily straightforward to the average computer user.

Figure 10 - Multiple Parameter Power Management Software



There are the settings of the Power Save Mode that affect the battery life and performance of your computer.

Device Name	Mode
Fan	Battery Optimized
CPU frequency	Battery Optimized

Current power source	AC power
Battery power remaining	100%
Estimated battery life	N/A
Estimated life on Standby	63 hours
Estimated life on Hibernation	35 days

Processor speed	High	High	Mid	Mid
Monitor brightness	Bright	Bright	Semi	Semi
System standby	10 min	10 min	5 min	5 min
System hibernate	Never	Never	Never	Never
Turn off monitor	5 min	3 min	2 min	1 min
Turn off hard disks	5 min	3 min	2 min	1 min

Figure 10 - This software, provided with Toshiba laptops and more sophisticated than the Windows standard, gives users more control of power management, enabling them to save energy and prolong battery life. Notice that the user has the opportunity to change screen brightness levels, an option unavailable in the Windows software.

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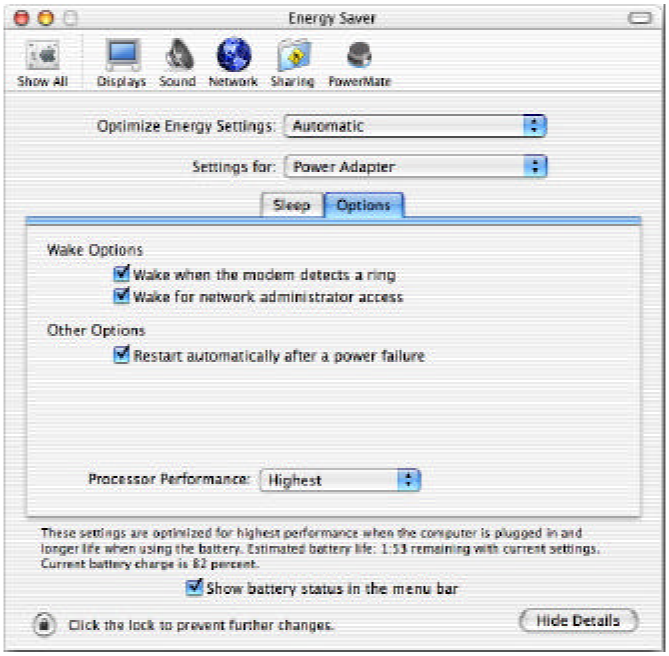
[52] For a more detailed discussion of CPU differences and capabilities, see section entitled "Microprocessor."

Windows and Apple both offer a PM options that allowing the computer to wake from a low power mode if an administrator wants to access the laptop over the network. These options, although useful in theory, are rarely used in practice on networked computers.[53] The Apple Powerbook G4 interface refers specifically to this type of option (Figure 11). Implementing precise and effective power management over a network has the potential increase energy savings.

Figure 11 - PM Software on an Apple Powerbook G4



Optimize Energy Settings: Automatic

Settings for: Power Adapter

Wake Options

☑ Wake when the modem detects a ring
☑ Wake for network administrator access

Other Options

☑ Restart automatically after a power failure

Processor Performance: Highest

These settings are optimized for highest performance when the computer is plugged in and longer life when using the battery. Estimated battery life: 1:53 remaining with current settings. Current battery charge is 82 percent.

☑ Show battery status in the menu bar

Click the lock to prevent further changes.

Figure 11 - This PM software, available on the Apple G4 Powerbook is relatively straightforward compared to the Toshiba interface (Figure 10). Most users would be able to and set the PM options to their liking.

In order to illustrate the importance of even minimal power management (for example initializing *monitor sleep* and *hardware sleep* modes), assume that all the power management modes that were built into the two duty cycle scenarios outlined in Chapter 1 were disabled. If these modes were unavailable, the laptop would instead be in *on* mode during periods of inactivity by the user rather than being in *monitor sleep* or another low power mode, consequently consuming far more power. If the computer were in *on* mode instead of the various other low power modes, there would be an additional 100 GWh of energy consumed for the Road Warrior duty cycle and an additional 1.1 TWh for the Desktop Replacement duty cycle.

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[53] Bruce Nordman, LBNL, personal communication. 9/03.

Table 9 - Annual US Energy Savings as a Result of
Enabling Minimal Power Management in all Laptops

Duty Cycle Type	**Energy Saved Through Conventional Power Management (Gigawatt-hours)**
Road Warrior	**100**
Desktop Replacement	**1100**

Power Management Software and *on* Mode

Power management options that enable "power down" timers, allowing the user to enter *monitor sleep* and *hardware sleep* modes, both in laptop computers and in desktop computers, are important aspects of power management and save a significant amount of energy. At the same time, laptops and other computers consume the most amount of energy when they are on, either in the *on* mode or the *max on* mode. Because the user is asking the computer to perform tasks in both of these modes, power management will only be effective if the PM options do not affect the performance of the computer as perceived by the user. By changing the processor speed settings of a chip capable of such manipulation, the user will be able to save energy (or lengthen battery life), and yet will not notice any performance differences if they are doing standard computing tasks, such as Microsoft Office or internet and email applications.

Power measurements of a Think Pad T23 with a Pentium III Mobile chip were taken under two conditions of *AC state* operation. In the first condition, the laptop processor speed was set to "maximum performance." In the second condition, the laptop processor speed was set to "battery optimized performance." Maximum performance power measurements indicated an increased consumption by two more watts, indicating that battery optimized condition increases efficiency by about 15% in *max on*, *on*, and *monitor sleep* modes. As expected, there was no difference in the *hardware sleep* or the *off* modes.

In addition, there were no performance difference noticed when a series of average tasks in both conditions were undertaken by the researcher. Below is a representative list of tasks undertaken while attempting to assess performance difference:

- Open and modify a standard 5 page Microsoft Word document.

- Open and browse in Microsoft Internet Explorer. Go to the web page www.google.com and perform an Internet search. Open and then immediately close the first three links on the page of search results.

- Open an Adobe Photoshop Elements and perform standard tasks associated with manipulating a picture file.

- Compose and send e-mail in Microsoft Outlook.

The time required to perform all of the tasks was roughly the same, and the energy savings percentage was roughly equal to the power savings percentages measured directly while in the modes of *on*, *max on*, and *monitor sleep*.

This *on* mode potential with power management software and corresponding CPU hardware can reduce the power consumption of an average laptop by two watts in the *on* and in the *monitor sleep* modes. If all US laptops operated with this type of *on* mode power management, we estimate that this would amount to savings of 180 GWh for the Road Warrior duty cycle and 510 GWh for the Desktop Replacement duty cycle.

Table 10 - Potential Annual US Energy Savings Resulting from
On Mode Laptop Power Management

Duty Cycle Type	**Potential Energy Savings (Gigawatt-hours)**
Road Warrior	**180**
Desktop Replacement	**510**

Wireless Technology Effects on Laptop Power Consumption

As the usage of notebook computers continues to stretch beyond the confines of the home and office, the energy efficiency of the notebook computer is going to become more important to the manufacturer in order to extend battery life and make laptops truly portable devices. Business users will have the need to access the Internet and e-mail in airports, convention centers, and hotels. Educational institutions are expected to adopt these wireless systems for use in their libraries and lecture halls. Once these kinds of options become available to students and business users alike, the use of laptop computers is expected to increase further. Wireless LAN (WLAN) is expected to be the preferred method of infrastructure, although some transmission will potentially occur over the cellular infrastructure.

Wireless transmission technology itself will also increase the power drawn while the computer is in operation. In order to estimate this effect, a T30 IBM Think Pad laptop computer with an Orinoco wireless card from Lucent Technologies was metered while it was in operation. The wireless card, engaged and transmitting information, added approximately one extra watt to the power consumption of the *on* mode of the laptop computer. This represents approximately 5% of the raw power consumption of that mode. Although this may seem insignificant, as wireless systems with more powerful transmission requirements are developed, the power requirements of the wireless card could rise substantially and could also contribute to an increase in other power requirements of the laptops, such as the power consumption associated with the cooling fan to dissipate the heat associated with the wireless transmission components.

Enabling wireless hardware increases laptop power consumption in the *on* mode by 5%. If all the laptops in the US incorporated this technology today, we estimate that this would increase power consumption by 60 GWh for the Road Warrior duty cycle and 170 GWh for the Desktop duty cycle.

Table 11 - Annual Laptop Energy Consumption Increase as a Result of Wireless Technology

Duty Cycle Type	**Additional Energy Consumption (Gigawatt-hours)**
Road Warrior	**60**
Desktop Replacement	**170**

Summary: Laptop Component Energy Savings Estimates

In the summary chart below (Table 12), the efficiency differences of the various components are summarized. Also given are estimates of how much energy would be saved if the most efficient technologies were adopted. An analysis component-by-component indicates that the display system, power supplies, and CPU warrant the greatest potential for energy savings in the laptop computer, especially in the *on* mode. The battery system is relatively efficient compared to other battery technologies, with minimal improvement possible. Low power modes currently possible to enable through power management have already been well established in the workplace.[54] The potential savings for each component overlap somewhat so cannot be simply added together, but do approximate the energy benefits that are associated with improving the efficiency of each component.

Table 12 - Summary of Component-by-Component Analysis

Component	**Possible Efficiency Improvement**	**National Annual Energy Savings: Road Warrior (GWh)**	**National Annual Energy Savings: Desktop Replacement (GWh)**
Display	From 64,000 pixels/watt to 128,000 pixels/watt	260	550
Power Supplies	From partial load efficiency of 56% to 85% From full load efficiency of 80% to 90%	210	520
CPU	From Intel P3 Max Performance to P3 Battery Optimized	180	520
Power Management	From 50%of laptops PM enabled to 70% laptops PM enabled	20	220
Battery System	From 80% to 85% efficiency	30	9

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[54] Networking level PM has the potential to generate more savings than the PM savings detailed in table 12, but this type of estimate is outside of the scope of this report.

Chapter 3 - System Benchmarking

Various components in the laptop computer have different efficiencies, yet comparing one laptop against the other by measuring each component (screen, battery system, CPU) separately is laborious and potentially not necessary. Ecos investigated the possibility of using a software-based system benchmark to compare the performance and energy consumption of one laptop to another. This type of measurement is more realistic, because it allows the laptop to function as a system. In addition, because of the fast-paced nature of technological breakthroughs in the portable computing market, the process of comparing laptops system-to-system is more feasible than attempting to compare each component, the technology of which could be obsolete within the year.

Recommended Benchmarking Software

A known way to make a system-level comparison between laptop computers is to use benchmarking software that runs on top of an OS platform. Power management software and other energy efficient components of a laptop computer are only worth implementing and incorporating when they have minimal impact on the performance of the laptop as it is perceived by the end user. Obviously, a consumer is not going to want to implement PM options or other power saving hardware that mean the laptop is going to take a longer time to open programs, has a screen that is so dim it strains the eyes, and is constantly turning off the screen in order to save power. A benchmark-based metric therefore must include a measure of performance of the system as well as a measure of energy efficiency.

Ideally, an energy efficiency benchmark would be easy to use and to run, would subject the system to tests that mimic a 'normal' user workload, and would be capable of running in *AC state* and *battery state*. Because there is currently no benchmarking software that meets all of these criteria (see Table 13), Ecos evaluated three different benchmarking tools: BAPCO's MobileMark 2002, Futuremark's PCMark 2002, and PC World's PC WorldBench4. MobileMark 2002 and PC WorldBench4 were chosen because of their claims to represent 'normal' user performance while PC Mark was chosen because it is easy to use. Unfortunately, because PC WorldBench4 restarts between each section of its test, we were unable to gather meaningful energy consumption values that related to the performance score. As a result, energy efficiency metrics were only developed using MobileMark 2002 and PCMark.

Table 13 - Representative Sample of Available Benchmarking Software

Software	Data Outputs Available			Notes
	‘Normal User’ Performance Score	**‘Maximum Output’ Performance Score**	**Battery Life Score**	
BWS Batterymark (Ziff-Davis Media)			X	battery life measured with ’normal user’ workload
Hyper Threading Performance Analyzer (Competitve Systems Analysis, Inc.)	X			
MobileMark 2002 (Futuremark Corporation)	X		X	simultaneous testing of performance and battery life
PCMark (FutureMark Corporation)		X	X	separate scores generated for CPU, HDD, and memory
PC WorldBench4 (PC World Communications, Inc.)	X			shuts down and restarts between each test
Passmark Peformance Test v. 4.0 (PassMark Software)		X		
SANDRA standard 2002.68.97 (3B software)		X		
SpeedRun 1.1 (Danicsoft)		X		speed performance score

Because the performance metric given by MobileMark2002 is most strongly representative of the performance perceived by the laptop user, it is a more meaningful metric than other benchmarks, such as PC mark, that measure maximum performance capabilities of a computer. Maximum performance is more relevant to users that constantly tax a computer system. At the same time, due to the fact that the software mimics the workload of an average user, the MobileMark benchmark is more complicated to install and run on a laptop than other benchmarks (including PC mark), and cannot be easily done on a laptop that is simultaneously being used for other applications. In addition, MobileMark can only be run in *battery state*, which makes a comparison of the energy consumption between *battery state* and *AC state* impossible.

PC mark, on the other hand, runs the computer through a series of intensive tests, seeking to find the maximum aptitude of the laptop performing various tasks. These tasks are common tasks that are performed by a user in a home or office setting, but these tests do not as closely follow an actual workload of a laptop user as MobileMark’s tests. Even so, PC mark, through methodologies different than that of MobileMark, provides some indication of energy efficiency and performance of a laptop. The results of each benchmark will be discussed separately below.

The purpose of system benchmarking in the context of this report is to test the feasibility of such a laptop efficiency metric and begin a conversation about the possibility of measuring energy efficiency through a system benchmarking process. In these early stages, no definitive conclusion can be made about the relative rankings of laptop computers and processors or the exact amount of energy savings resulting from improvement laptops according to this metric. Our sample sizes, detailed in later discussion, are too limited to attempt that kind of analysis.

MobileMark

The test sequence for a laptop using MobileMark 2002 is as follows: The battery of a laptop is fully charged, and then the laptop is unplugged from the wall outlet, beginning the test sequence. While running in *battery state*, a 'ghost' user that is simulated by the program goes through a sequence of operations that are typical of a business type user. The types of tasks that are performed include, but are not limited to:

- Modifying a Microsoft Excel file
- Modifying a Microsoft Power Point presentation
- Composing e-mail in Microsoft Outlook
- Running a virus scan
- Opening and modifying a picture in Adobe Photoshop

The speed at which keystrokes are entered mimic the manner in which a human user would enter them, and there are pauses in the program that would simulate pauses that a human user might make because of interruptions or other work demands. This ghost user sequence runs until the battery is exhausted and the computer consequently turns off. Starting the computer back up in *AC state* gives a data file with information about the configuration of the system, the battery life, and two performance metrics: a response time and a relative performance metric.

MobileMark values of performance and battery life are generated in the *Battery state.*[55] The energy required to charge the battery from fully empty to fully charged is therefore the amount of energy consumed to achieve a performance score as measured by MobileMark. Losses in the power supply, battery charger, screen, etc. are all incorporated into this metric. To measure amount of energy consumed from the grid to charge the battery, the battery is fully recharged in *off mode, AC state* while the computer is connected to a watt-hour meter.

Laptop system efficiency, as defined using MobileMark software, is the product of the MobileMark performance score and the battery life divided by the energy consumed as a result of the test.

$$\text{System Efficiency} = \frac{\text{MobileMark Performance} * \text{Battery Life}}{\text{Charge Energy}},$$

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[55] Please note that MobileMark2002 cannot make measurements of performance in the *AC state*.

where MobileMark Performance is unitless, Battery Life is in hours, and Charge Energy is in AC watt-hours. In this case, System Efficiency is reported in performance/watt and larger scores indicate greater efficiencies.

Under this type efficiency metric, the relationship between performance and energy become more important than the value of either individually. For example, a laptop like the IBM T40 (Table 14) can achieve a high efficiency score by attaining a relatively good performance score and using an average amount of AC energy. Alternatively, a laptop, like the Sharp, arrived at a better than average efficiency score with a relatively low performance score because it consumed a comparatively small amount of AC energy. This type of metric equally rewards performance and low energy consumption so that a laptop is permitted to use more energy if there is a performance benefit to that energy use.

Table 14 – MobileMark 2002 System Efficiency of Six Laptops

Laptop Tested	CPU Power Management Enabled?	MobileMark Performance Score	MobileMark Battery Life (hours)	Measured Energy to Charge Battery (AC Watt-hours)	System Efficiency[56] (Performance/ Watt)
IBM T23 **(Intel P3 Mobile)** **Thin and Light**	No	111	3.3	58.8	**6.3**
IBM T40 **(Intel Centrino)** **Thin and Light**	Yes	95	4.2	66.1	**6.0**
Sharp MM-10 **(Transmeta Crusoe)** **Ultra Portable**	Yes	60	2.5	35.2	**4.3**
Fujitsu S-series Lifebook **(AMD Athlon 4)** **Thin and Light**	Yes	94	2.4	58.6	**3.9**
MiTAC **(AMD Athlon 4)** **Thin and Light**	No	66	2.2	77.1	**1.9**
Toshiba Tecra 8100 **(Intel P3)** **Desktop Replacement**	NA[57]	50	2.4	67.0	**1.8**

These results in Table 12 represent our initial efforts to assess the validity of this type of system level approach with MobileMark software. Nevertheless, these data indicate that there could be wide variations in efficiency in *battery state*, even among laptops with similar processors. Within one form factor (thin and light) we see that the highest score, achieved by the IBM T23 (6.3) is more than three times the lowest score (1.9), achieved by the Toshiba Tecra.

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[56] System Efficiency = (MobileMark Performance Score) * (MobileMark Battery Life) / (Measured Energy to Charge Battery)

[57] There is only one power mode for this CPU.

PC Mark

The test sequence for PC Mark is as follows. The laptop is plugged into an AC watt-hour meter with battery fully charged and in *on* mode, *AC state*. The starting watt-hour value is recorded and the test is initialized by the researcher through the software window. The series of tests that measure CPU, memory, and hard disk access begin. The researcher observes the tests and when finished (approximately 10 minutes in duration), the final watt-hour value is recorded. The sum of the performance scores divided by the energy consumed during the tests in watt-hours is the efficiency score of each computer (Table 15).[58]

Table 15 - PC Mark Efficiency Metric for Six Laptops and Two Desktops

Computer Tested	PC Mark Scores (no units)			Energy Consumed	Efficiency Score
	CPU	Memory	HDD	(watt-hours)	(sum PC mark/ Whrs)
IBM T40 (Intel Centrino)	4916	4622	520	2.72	3698
Fujitsu S-Series Lifebook (AMD Athlon 4)	4148	2165	439	3.55	1902
IBM T23 (Intel P3-M)	3578	2186	367	3.94	1556
Sharp MM-10 (TM Crusoe)	1646	1472	222	3.24	1031
MiTAC (AMD Athlon 4)	2230	1259	399	5.62	692
Toshiba Tecra 8100 (Intel P3)	1844	1220	224	6.18	532
NEC Eco desktop (TM Crusoe)	1688	1487	328	6.75	519
Custom desktop (AMD Athlon)	2953	2826	1314	24.00	295

Because the performance scores are unitless, they are only meaningful when considered in relationship to the scores of other computers that have undergone the same benchmark. The IBM T40 had the best efficiency score of 3698, 2 times that of the Fujitsu, 3.5 times of the efficiency score of the Sharp notebook, and 7 times the efficiency score of the Toshiba Tecra 8100. Note also that the NEC desktop system (which includes a laptop-style motherboard and a Transmeta Crusoe processor) achieved roughly comparable performance and energy use as the Toshiba laptop system, even with desktop functionality and a larger LCD screen. The custom AMD desktop achieved a high performance score, but consumed 24 watt-hours during the test (compared to an average of 5 watt-hours by the other systems). This higher energy consumption led to an efficiency score that is 1/6 of the Fujitsu efficiency score.

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[58] It is possible that another method for summing these performance scores could be considered, but a complete discussion of the possibilities will not be addressed in this report.

Chapter 4 – Summary and Recommendations

Summary of Key Findings

Below is a summary of our key findings as a result of this investigation.

Laptops use significantly less energy than desktops. Over the course of an annualized duty cycle, laptops consume about 65 to 80% less energy than desktops. This is particularly significant because the computing performance of laptops is now roughly comparable to that of a desktop system in typical applications run by the average user. The potential for energy savings associated with replacing desktops with laptops is substantial. If 25% of the desktops with CRTs in the U.S. were replaced with laptops, the annual savings would be 20 billion kWh.

Energy consumption varies widely among laptops. In *on* mode, the laptops we tested ranged from approximately 11 watts to 31 watts of power use. Even when including the energy consumption in other modes, the most efficient laptop we tested uses only about one-third as much energy per year as the least efficient laptop we tested. So energy can be saved first by using a laptop instead of a desktop, and then by choosing an efficient laptop among the available choices.

Laptops utilize relatively efficient power supplies, but their efficiency still varies at part load. Power supply efficiency is definitely important to all aspects of AC power consumption by laptops. Most laptop power supplies are already highly efficient at peak or near-peak loads. Their peak efficiencies of 85 to 92% are among the highest we have measured in the consumer power supply market. However, laptop power supplies exhibit wider variation in efficiency at part load, where laptops spend most of their operation time. Laptops are also likely to show differences in their internal DC-to-DC converter efficiencies. In total, improving the efficiency of power conversion circuitry in laptops to the best designs currently in use could save hundreds of Gigawatt-hours of electricity per year.

Laptops employ comparatively efficient battery chargers. Battery chargers in laptop computers do not appear to vary significantly in the designs employed, with nearly all relying on lithium ion technology and smart charging circuitry. Charging efficiency averaged about 80%, which is significantly higher than the efficiency of most consumer-oriented chargers for nickel cadmium and nickel metal hydride systems. If anything, we would welcome the migration of laptop battery charger circuitry to other consumer products, given the efficiencies and high storage capacities demonstrated in our test samples.

Display efficiencies vary dramatically in laptops. Display efficiency has a significant impact on overall power use, because laptop displays consume approximately 30% of the total power while the computer is in *on* mode. Some of this is undoubtedly due to differences in brightness and performance, but other substantial differences seem to result from the technologies themselves.

Opportunities exist to save energy with more sophisticated CPU technology. Because of the variety of tactics taken by various CPU manufacturers, CPU design is likely to account for an increasing share of the efficiency differences among laptops. Moreover, the opportunity for energy savings in desktops from use of highly efficient mobile CPUs is quite significant.

on mode power management offers opportunities to save energy; further improvements can be made to increase energy savings. Power management software is essential to achieving reasonably long battery life in laptops, but is greatly underutilized when laptops are plugged in. While it is relatively straightforward to enable *monitor sleep* and *hardware sleep* modes on most residential computers, it can be more challenging to enable reductions in CPU speed and voltage and screen brightness in a standardized way. Instead of those features routinely occurring under operating system control, they often rely on proprietary control software that each laptop manufacturer provides with varying degrees of usability.

Wireless functionality will likely increase energy consumption. Wireless technology, although not yet widespread in the marketplace, generally increases laptop power consumption by a few watts in the *on* and *monitor sleep* modes. As wireless technology becomes more popular in the near future, this could have significant impacts on the energy consumption of laptops.

System efficiency benchmarking reveals wide ranges among laptops. Laptop systems' *on* mode energy efficiency can be measured using benchmarking software and an accurate watt-hour meter. Metrics that measure battery life and provide a score preference for it yield a metric of performance per watt of power consumed on average during the test. Other benchmarks provide a performance score per kwh of energy consumed to run the complete test. This second approach can be applied both to laptop and desktop computers, and automatically credits those computers fast enough to complete the benchmarking testing more rapidly than average. Both approaches suggest that there are substantial, quantifiable differences in the energy efficiency of computers that can be readily observed with benchmarking software.

Recommendations for Further Research

In light of the findings that were uncovered as a result of our research, Ecos recommends the following paths of pursuit for future work:

Modify existing benchmarking software to make it more suitable for energy efficiency testing. In the course of our investigation, we found no benchmarking software that was a perfect solution for testing the system energy efficiency of the laptop computer. We would recommend that future efforts focus on working with leading benchmarking companies and other key players to develop a benchmark that evaluates products fairly, is easy to use, and is potentially applicable to both laptop and desktop computers.

Uniformly characterize system energy efficiency on a large set of laptops. Once benchmarking software and other testing methodology has been developed, it would be instructive to use benchmarking software to test a wider variety of systems in order to reveal in more detail manufacturers' methods for addressing energy efficiency.

Thorough investigation of laptop display efficiencies. It would be good to more systematically investigate the differences in designs of the LCD screens. This is especially interesting because of the wide range of current display efficiencies discovered through preliminary, basic calculations. New technologies, such as OLEDs and LCDs with LED backlights, could potentially offer energy-saving alternatives to the current laptop display technology.

Explore incorporating laptop battery charging technology into other consumer electronics. The technology in the laptop battery chargers is quite energy efficient compared to other battery charging systems. An investigation of the possibility of incorporating some aspects of this technology into other battery charging systems has the potential to lead to significant energy savings.

Further duty cycle analysis. Many duty cycles of laptop computers are reasonable, but more work needs to be done to establish what is truly an average duty cycle for the laptop computer.

Related on mode research effort in desktop computers. As a result of our findings, we also recommend a parallel research effort to investigate implications for desktop computers. It seems plausible, based on initial findings, that desktops could be become significantly more efficient by borrowing design features and technologies from laptops, even if they maintain their overall form factor and functionality. The NEC Eco PC is an example of combining the form factor of a desktop with the energy efficiency of a laptop. This will become more important as desktop computer power consumption in the *on* mode continues to increase, and harnesses a growing market interest in smaller desktop computers.

Research into desktop video card power consumption. Over the course of our research on laptop computers, we became aware that high-end desktop computer video cards (the type marketed for gaming and movie applications) can consume 50 to 75 watts by themselves, with coming generations expected to draw even more power. Such cards also appear to draw a fairly steady amount of power regardless of the intensity of the application. Further research is warranted to measure the power consumption of video cards and recommend possible "sleep" features or other low power capabilities when minimal graphics processing is needed.

Policy Recommendations

Introduction

60% (laptop) to 90% (desktop) of a computer's energy is consumed while a computer system is operating in its *on* modes.[59] Our various measurements of laptop components in *on* mode reveal that *on* mode efficiencies vary widely among laptops. Although detailed *on* mode analysis of desktop computers is outside the scope of this report, there is reason to expect a larger absolute and percentage difference in energy consumption in desktops than in laptops. Desktop processors have faster and more powerful CPUs, video cards, and hard drives, less efficient power supplies, and widely varying internal configurations. We demonstrated that it is possible to create a meaningful comparison of laptop *on* mode efficiencies either by examining laptop components or by utilizing benchmarking software and a watt-hour meter to create a performance/watt metric. With little or no modification, the laptop *on* mode efficiency metrics and approaches could be applied to desktops to discern the *on* mode energy savings potential of these machines.

Because there is potential to meaningfully quantify the *on* mode efficiency of computers, and the energy savings seems to be significant in laptops and at least an order of magnitude larger in desktops, we propose that ENERGY STAR® and other concerned organizations consider modifying their computer energy specifications to include an *on* mode efficiency requirement.

Current ENERGY STAR® Specification

Currently, in order for a computer system to qualify as ENERGY STAR®, the system must be under a certain power level in various modes. The draft ENERGY STAR® specification for monitors indicates that a monitor must draw less than 4 Watts in sleep mode and less than 2 W in off mode. In addition, ENERGY STAR® monitors are only allowed to draw a certain amount of power in on mode; higher power levels are allowed for monitors with a larger number of pixels. There is one ENERGY STAR® specification that applies to both laptop and desktop computers. In this case, the computer must be able to enter a hardware sleep mode after 30 minutes of inactivity and must have the capability to sleep while connected to a network, responding to wake-up events. In addition, the consumption of power in sleep mode is based on the maximum rating of the power supply of the computer. (These details are in Table 16.)

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[59] See Figure 3.

Table 16- Energy Star Computer Specification[60]

Max Power Supply Rating (in Watts)	Sleep Mode Requirement (in Watts)
<200W	<15W
<300W	<20W
<350 W	<25W
<400W	<30W

If none of these apply, the sleep mode requirement must be <10% of the power supply's maximum continuous output rating.

Under this current specification, computers (desktops and laptops) can consume any amount of energy while they are in *on* mode or *max on* mode and still be considered ENERGY STAR® compliant.

Possible on Mode Approach

Because desktops and laptops differ greatly in the amount of energy that they consume in the *on* mode,[61] an *on* mode energy specification that would apply to both laptop computers and desktop computers could be conceived in one of the three following ways:

1) The specification is calibrated to typical desktop computer power consumption. A reasonable number of desktops qualify and all laptops easily qualify, allowing for no differentiation among laptop models.
2) The specification is calibrated to typical laptop power consumption, and few, if any, desktops qualify, while most or all of laptops qualify.
3) Two separate specs are created for the desktop and the laptop, using the same measurement methodology, but with different thresholds for the laptop and the desktop. These thresholds would be based on each technology's *on* mode power consumption.

Considering the purpose of ENERGY STAR®, there are a number of reasons why scenario one and two are unattractive. Scenario one, which would generate energy savings with the desktop computer, would leave the laptop energy consumption in the *on* mode unchecked exactly at a time when the laptop market is growing: the dollar value of laptop sales moved past desktop computer sales in the middle of this year.[62] In addition, recent trends indicate an increase in the production of power consuming desktop replacement models, such as Apple's PowerBook and the Toshiba's Satellite P25-S507. These types of laptops have 17-inch displays, desktop processors, and more substantial speakers, all of which contribute to the increased energy consumption.

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[60] Details of the computer spec can be found at http://208.254.22.7/index.cfm?c=computers.pr_crit_computers

[61] See Figure 3.

[62] "Laptops Take Center Stage, Buyers Face More Decisions." Mike Musgrove. Washington Post 9/3/03, p. F1.

Scenario two would allow consumers to differentiate between power consumption in laptop computers, but would neglect the large energy savings opportunity presented by desktops. Because the desktop computer consumes more energy relative to the laptop, any percentage improvement in efficiency of the desktop will be greater in magnitude than the same percentage improvement in the efficiency of a laptop. In addition, as CPUs increase their clock speed, more powerful video cards are developed,[63] and other more complicated features come to market, the power consumption of desktops is likely to increase.

We recommend that the third scenario be pursued, as it has the potential to generate large energy savings with the currently popular desktop and at the same time innovatively address the increasing presence of laptops in the marketplace. Desktops most definitely represent the largest savings opportunity in the short term. Even though there are currently far more desktops than laptops in use, savings from an ENERGY STAR® laptop computer specification will steadily increase as the laptop market continues to grow. This approach also recognizes the efficiency leaders in both sectors, encouraging energy efficiency innovation in both technologies. Finally, it responds to a desire expressed by manufacturers themselves for a separate laptop specification.

A component-based specification could be pursued in the near term, with a focus on the handful of components that have the greatest impact on overall energy use. For desktops, this list would likely include the power supply, CPU, video card, and power management software. For laptops, this list would likely include the power supply, CPU, display, and power management software.

Ecos Consulting, EPRI-PEAC, and Intel have already completed measurements on more than 25 multi-voltage desktop PC power supplies and 15 single voltage laptop PC power supplies. These organizations, with input from others, could recommend efficiency specifications across a range of loads and power supply sizes.

CPU efficiency could either be specified quantitatively or qualitatively. A quantitative approach would compare the number of instructions a CPU could execute or its benchmark performance score per unit of energy consumed by the CPU and its associated cooling fan across a range of “loads” or levels of computing demand. Alternately, a qualitative approach could simply require that any qualifying CPU be able to operate at a number of frequency and voltage combinations below maximum in response to varying loads. By including the power consumption associated with any dedicated CPU cooling systems, such a specification would reward designs that can be passively cooled or otherwise easily cooled with innovative heat sink designs.

Video card efficiency (in desktops) could be judged either very simply by a maximum absolute full-load and part-load power specification, or by a more sophisticated metric that would account for a video card’s performance and rendering capabilities relative to its power or energy use. Display efficiency (as an embedded component in laptops)

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[63] See the previous section, ‘Recommendations for Further Research.’

would likely be judged by pixels/watt, according to the same methodology and test procedures currently under consideration in the process to revise the ENERGY STAR® monitor specification.

Power management software could be qualitatively assessed for efficiency by the extent to which the operating system that ships with the computer enables reductions in CPU clock frequency and voltage, screen dimming, monitor sleep, video card sleep, peripheral sleep, and overall system sleep. Such options should be provided as the default condition in labeled laptop and desktop computers as shipped, rather than requiring a configuration change by the user (which is unlikely to occur in many cases).

The second possibility for an *on* mode computer ENERGY STAR® spec would be to develop a system energy efficiency metric that places value on the computer's performance and on the computer's energy consumption to achieve that performance. Under such a metric, neither a computer's raw processing capability nor its absolute power consumption would predict its efficiency, but rather the relationship between the two would become the means to compare systems to one another. Benchmarking software that combines the best aspects of PC Mark, MobileMark 2002, and PCWorldbench4 would be used to rate the performance of the computer in *AC state* and, when applicable, *battery state.* While the computer runs the benchmarking software for a set amount of time, a measurement of the energy that it consumes can be taken with a watt-hour meter. The combination of these measurements yields an efficiency metric.

$$\text{System Efficiency} = \frac{\text{Benchmark Performance Score}}{\text{Average Power (watts)}}$$

We suggest the following steps in order to achieve a revised ENERGY STAR ® specification that includes a separate a system efficiency *on* mode specification for both laptops and desktops.

- Work with benchmark developers such as BAPCO, PCWorld, and Futuremark to develop benchmarking software that is fully compatible with system efficiency benchmarking. Ideally an energy efficiency benchmark would be easy to use and to run, would subject the system to tests that mimic a 'normal' user workload, and would be capable of running in *AC state* and *battery state.* Additionally, the benchmark should be developed with the input from other interested members in industry.

- Develop a test method that details the how the values of performance and energy consumed are measured to yield a final efficiency metric. Measure a small set of laptops and a larger set of desktops under this method to see how system efficiencies compared to one another, in magnitude and in spread. Analyze data to determine potential efficiency thresholds for desktops and laptops.

- Working with manufacturers, benchmark a wide range of laptops and desktops to more closely determine values for *on* mode system efficiency. Develop final efficiency thresholds for desktops and laptops, based on the value and spread of the data collected.

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Appendix A: Configuration of Systems Tested with MobileMark 2002

	IBM ThinkPad T23	Toshiba Tecra 8100	MiTAC	IBM Think Pad T40	Fujitsu S-Series Lifebook	Sharp MM-10
CPU						
Manufacturer	Intel	Intel	AMD	Intel	AMD	Transmeta
Family	Mobile Pentium III-M	Pentium® III	Mobile AMD Athlon 4	Centrino	Mobile AMD Athlon 4	Crusoe
Internal Clock (MHz)	1132	697	1000	996	1461	995
External Clock (MHz)	133	100	100	400	266	66
Capabilities	MMX, CMov, RDTSC, SSE	MMX, CMov, RDTSC, SSE	MMX, CMov, RDTSC, 3DNow! Extended 3DNow!, SSE	MMX, CMov, RDTSC, SSE, SSE2	MMX, CMov, RDTSC, 3DNow!, Extended 3DNow!, SSE	MMX, RDTSC
L1 Cache Size	32 KB	32 KB	128 KB	NA	128 KB	NA
L2 Cache Size	512 KB	256 KB	256 KB	NA	256 KB	NA
Memory						
Total Physical Memory	254 MB	512 MB	368 MB	510 MB	480 MB	232 MB
Total Pagefile Memory	617.52 MB	1.22 GB	695.34 MB	1.22 GB	1.10 GB	567.45 MB
Motherboard						
Manufacturer	IBM	TOSHIBA	MiTAC	IBM	NA	SHARP
Model	26474MU	Portable PC	NA	237382U	NA	PC-MM10 Series
Display Device						
Name	S3 Graphics SuperSavage/IXC 1014	S3 Inc. Savage/MX Display Driver	S3 Graphics Twister K + S3Hotkey	MOBILITY RADEON 7500	RADEON IGP 320M	Silicon Motion Lynx3DM
Local Video Memory	16 MB	8 MB	16 MB	32 MB	32 MB	8 MB
Local Texture Memory	16 MB	3.98 GB	16 MB	32 MB	32 MB	8 MB
Total AGP Memory	32 MB	32 MB	32 MB	56 MB	NA	NA
Display Hardware						
Width	1024	1024	1024	1024	1024	1024
Height	768	768	768	768	768	768
BPP	16	16	16	32	32	16
Software						
OS Name	Microsoft Windows 2000	Microsoft Windows 2000	Microsoft Windows 2000	Microsoft Windows XP	Microsoft Windows XP	Microsoft Windows XP
OS Version	5.0.2195	5.0.2195	5.0.2195	5.1.2600	5.1.2600	5.1.2600
DirectX Version	8.1	8.1	8.1	8.1	8	8.1
DirectDraw Version	5.1.2600.881	5.1.2600.881	5.1.2600.881	5.1.2600.1106	5.3.0000000.900	5.1.2600.1106
Battery System						
Battery 1 Capacity	43200 mWh	48600 mWh	53280 mWh	47520 mWh	41040 mWh	19980 mWh
Battery 1 Voltage	11152 mV	11300 mV	13491 mV	11551 mV	11098 mV	11748 mV

Appendix B: Computer Stock Calculations

PC (Desktop and Laptop) Stock estimates[1]

Year	Units Sold (millions)	98 in use	99 in use	00 in use	01 in use	02 in use	03 in use	Total in Use	% growth
1998[2]	**36.70**	36.70						36.70	
1999[3]	**73.10**	31.20	73.10					104.30	
2000[3]	**79.30**	26.52	62.14	79.30				167.95	
2001[4]	**44.51**	22.54	52.81	67.41	44.51			187.27	
2002[4]	**46.47**	19.16	44.89	57.29	37.84	46.47		205.65	
2003	**50.38**	16.28	38.16	48.70	32.16	39.50	50.38	225.18	8%[5]

Laptop Stock Estimates[6]

Year	Units Sold (millions)	98 in use	99 in use	00 in use	01 in use	02 in use	03 in use	Total in Use	% growth
1998[2]	**6.40**	6.40						6.40	
1999[3]	**13.32**	4.86	13.32					18.18	
2000[3]	**15.93**	3.70	10.12	15.93				29.75	
2001[7]	**8.69**	2.81	7.69	12.11	8.69			31.30	
2002[7]	**10.11**	2.13	5.85	9.20	6.60	10.11		33.90	
2003	**11.06**	1.62	4.44	6.99	5.02	7.68	11.06	36.82	9%[5]

Desktop Stock Estimates[1]

Year	Units Sold (millions)	98 in use	99 in use	00 in use	01 in use	02 in use	03 in use	Total in Use	% growth
1998[2]	**29.03**	29.03						29.03	
1999[3]	**59.84**	24.68	59.84					84.52	
2000[3]	**63.31**	20.98	50.87	63.31				135.16	
2001[7]	**34.32**	17.83	43.24	53.82	34.32			149.21	
2002[7]	**34.42**	15.16	36.75	45.74	29.17	34.42		161.24	
2003	**34.76**	12.88	31.24	38.88	24.80	29.25	34.76	171.82	1%[5]

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[1] Decay Factor = 0.85 (mean life of 4 years)

[2] Akatsu, M., Anderson, D. Brown, J.,Bui, A., Bulat,G. Ernst-Jones, T. Griffith, G. Olhava, s., Paoli, K., and Stephen, B., 1999, "Worldwide PC Forecast Update, 1999-2003," IDC Report #20599.

[3] Data from EPA courtesy of Carrie Webber, LBNL, March 2003.

[4] Gartner Group "Gartner Dataquest Says PC Market Experienced Slight Upturn in 2002, but Industry Still Shows Market's Strong Rebound" 2003 press release from http://www4.gartner.com/5_about/press_releases/pr17jan2003a.jsp

[5] "PC Forecast Lowered, Laptop Sales Up" by boston.internet.com staff. Accessed via the net on 3/13/03 http://cyberatlas.internet.com/

[6] Decay Factor = 0.76 (mean life of 2.5 years)

[7] Gartner Group: "Gartner Marginally increases U.S. PC Forecase for 2002" accessed via the net on 3/13/03 http://www.gartner.com

Appendix C: Details of CPU Power Consumption

Generally speaking, the power consumption (P) for a processor can be described by the following equation:

$$P = C * V^2 * F * A + L$$

where C is the capacitance of the transistors in the processor, V is the voltage, F is the frequency at which the processor is clocked, A is the activity factor, and L is the leakage factor.

The capacitance of each transistor is shrinking as miniaturization technology improves. However, because the total number of transistors is rising dramatically (42 million in the latest generation Pentiums), the C term is increasing with new technology developments.

V, or the voltage, is by far the most important term because it is squared and therefore dramatically influences the value of the power consumed by the processor. Voltage also influences frequency (F). Average CPU voltages for Intel have dropped from 5 volts in the old 486 designs to about 1.2 volts today.

The clock frequency of the CPU (F) has been rising dramatically. Intel's 486 chips ran at clock frequencies of 33 to 100 Mhz. Today's Pentium 4 chips run at clock frequencies up to 3 Ghz and higher, or 30 to 100 times greater than the older designs. The power dissipation at these levels can be remarkably high, however, with up to 60 watts of peak power being dissipated in some desktop computer CPUs from a very small chip area. This presents a significant cooling challenge, akin to imbedding a 60 watt light bulb inside the confined space of a laptop chassis.

The activity factor of the chip (A) measures how intensively clock cycles are utilized. An A value of 100% is quite rare. Today's chips are so fast that they rarely need to operate at a high activity factor, so power use can be substantially lower than what is indicated by peak power consumption calculations.

The last term is L, or leakage. Manufacturers have endeavored to reduce voltage and operating frequency by continuing to shrink average transistor size and spacing on CPUs, but are approaching fundamental limits in some respects. According to Intel engineers, up to 40% of the peak power (or about 10 to 20 watts) consumed by its latest generation of Pentium 4 processors is lost as leakage when electrons jump from one conductive pathway to another across areas of resistive material that have become too narrow to contain them fully.

Appendix D: Details of Laptop Battery Design

Two battery types are found in laptop computers: lithium ion (Li-Ion) and nickel metal hydride (NiMH). Introduced for commercial use in the 1970s and 1980s, respectively, these technologies have made major leaps in energy density and service life since their conception. Both technologies do not contain the toxic metals found in the familiar Nickel Cadmium (NiCd) battery technology. However, Li-Ion has many advantages over NiMH, and it is the clear choice of laptop manufacturers as of the end of 2002. Li-Ion has:

- approximately twice the energy density of NiMH (energy stored per unit of volume)
- relatively low internal resistance (making it less sensitive to the manner in which it is discharged)
- nearly twice the cycle life (number of times it can be charged and discharged)
- 1/3 the self-discharge rate (pace of energy loss when not in use).

Another reason why Li-Ion batteries are preferred over NiMH for laptop battery use is that they show minimal deterioration with the widely varying loads typical of computers. Li-Ion has been more costly in the past, but is now only about 40% higher than NiMH, making the technology within reach of virtually all laptops.

All laptop computer batteries that were surveyed are “smart batteries.” Smart batteries, as they have been labeled by the industry, take all the control away from the charger and instead, dictate to the charger how and when they want to be charged. In this way, the battery automatically accounts for factors like age and subtle changes in chemistry. The end user sees an increased battery life because the battery is better able to maintain its health. In addition, smart battery technology makes it easier for the consumer to buy replacement batteries for laptops when there may be changes in chemical technology and capacity in newer models. Smart batteries cost about 25% more than standard designs, and require a more expensive charger to be installed in the laptop. The advantage is that the battery always contains information concerning the state of health and the state of charge of the battery, and the battery life performance and safety for the consumer is improved.

Appendix E: Battery Charger Efficiency Procedure

The sample included three laptop computers: an IBM T23, a Micron Transport GX, and a Toshiba Tecra 8100. The IBM laptop was purchased in November of 2002, and had a battery with a capacity (measured vs. nominal) of approximately 90%. The Tecra 8100, purchased in 2000, was measured with a new battery that was purchased in December of 2002 that had a capacity of 82%, and an older battery that had a capacity of approximately 18%. The Micron Transport GX, purchased in 2001, had a battery with a 76% capacity.

First, the batteries completed one full discharge/ recharge cycle. This was done to condition the battery, priming it to its full condition and eliminating inefficiencies that would result from the cycle history of the battery. The laptop computer determined the full status of the battery and then the battery was disconnected from the computer and discharged on an external battery analyzer. The battery was discharged at a rate of 0.33 C to mimic the approximate run-time of the computer (3 hours).[8] The voltage, current and time were recorded at intervals of 10 to 15 minutes and the total energy that was derived from the battery was calculated via summation. The total energy contained in the battery is equal to the sum of the energy discharged during each interval. One energy interval is equal to the product of the voltage of the battery during that interval, the current during that interval, and the time elapsed during that interval:

$$E_{Battery} = \sum_{n=1}^{m} E_n = \sum_{n=1}^{m} V_n I_n t_n$$

where E_n is the energy allotted to one time interval n, V_n is the voltage during that interval, I_n is the current during that interval, and t_n is the time associated with that interval.

All batteries were discharged to a level of 3.00 V/cell, or 9.00 Volts for the battery. The newest batteries (IBM and Toshiba) performed well compared to the other batteries, as would be expected. These batteries discharged at the rated electric potential for a longer period of time; the voltage dropped quickly when they approached the edge of their capacity. The electric potential of the older batteries, on the other hand, dropped more linearly.

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[8] In order to rate batteries for the amount of energy they can store, the industry has created a standard that a battery will be rated at a discharge level of 1-C. This is the current level (in amps or milliamps) needed to completely deplete the battery in one hour. Discharging the battery more slowly will increase the measured storage capacity (measured in amp-hours or milliamp-hours). Discharging the battery more quickly will decrease the measured capacity.

Figure D1: Laptop Battery Discharge

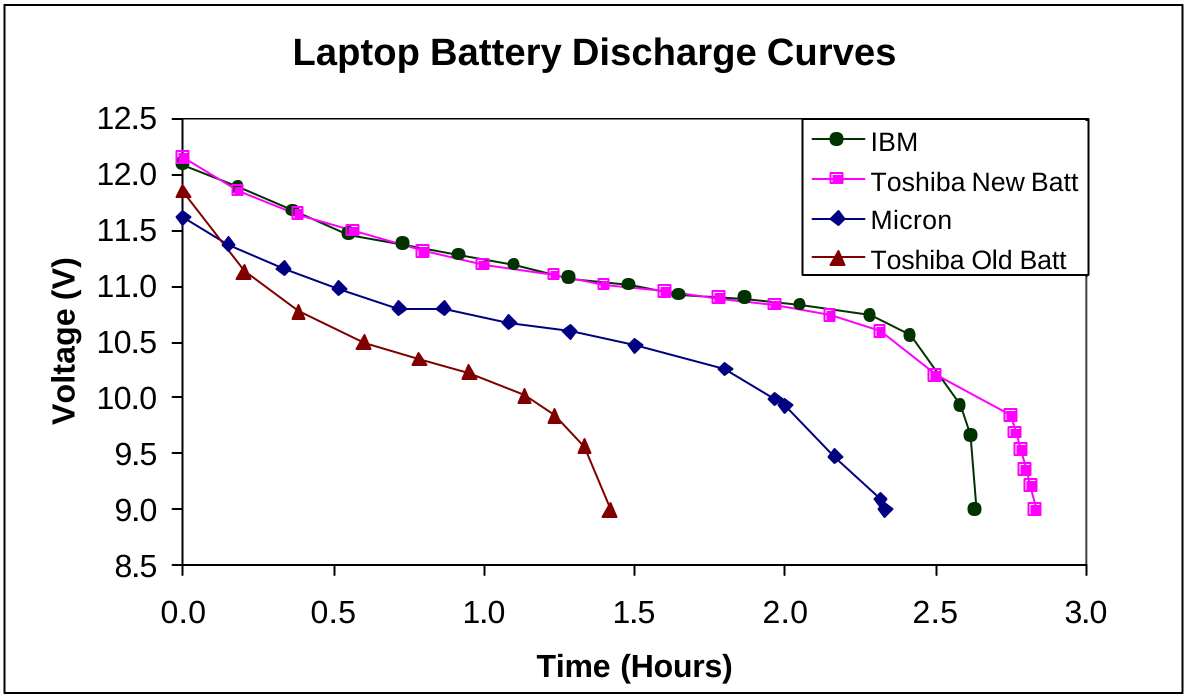

Figure D1: The area underneath the discharge curve times the current during discharge (which was constant) is equal to the energy obtained from the battery. This energy value, divided by the amount of energy used to charge the battery is equal to the efficiency of the battery charging system.

After the batteries were discharged, each battery was then re-inserted into the computer and the energy that the computer used to charge the battery back to full level was recorded. The computers were turned off so that the charger and the power supply were the only devices in active use. A PLM-1-PK meter was used to meter the watt-hours consumed during the charging process. The process was defined as finished when the computer defined the battery to be full, indicated by the appropriate glowing lights on the display panel. These lighting patterns differed from laptop to laptop and were familiar to the recorder.

The two stages of the Li-Ion charge sequence become evident when we consider the voltage of the battery as a function of time while the battery is being discharged as plotted in figure D2. The first and flat part of each curve is the constant current portion of the charging sequence where most of the energy is transferred to the battery. The semi-linear second portion of each curve is the constant voltage stage of the charge sequence. Note that the battery that is significantly older and has little useable life left has a very short constant current stage, as would be expected.

Figure D2: Laptop Battery Charge Sequence

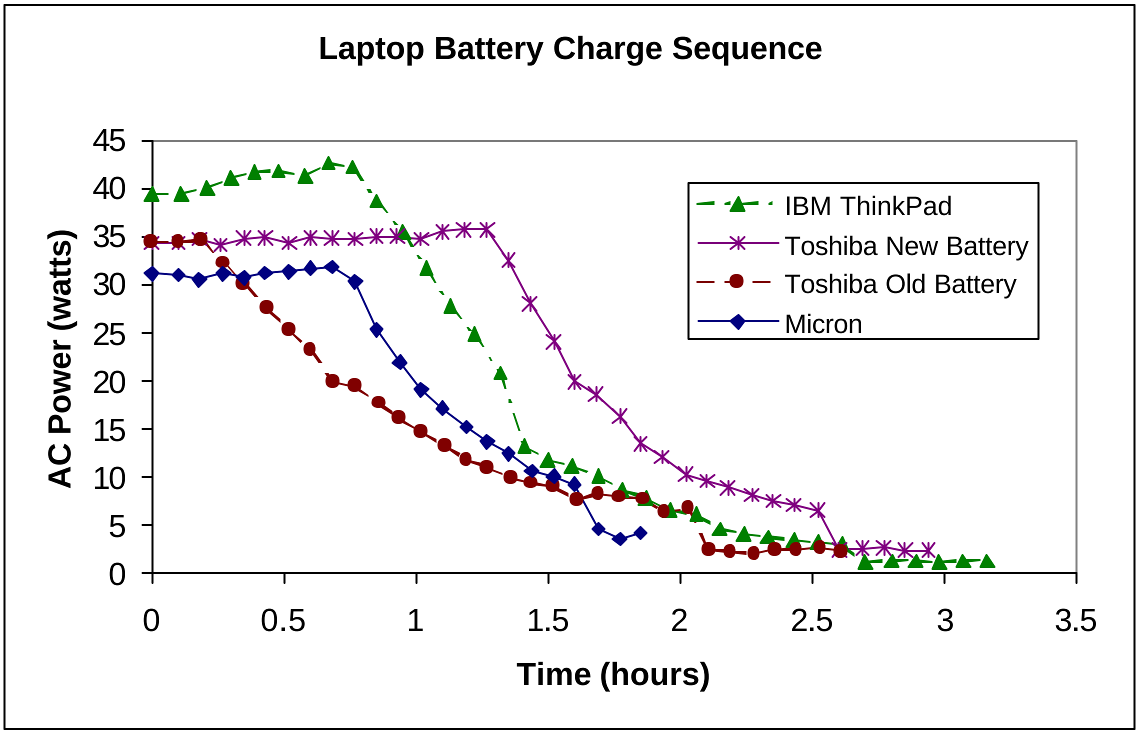

Figure D2: The battery charging sequence of the laptop computer is characterized by two stages. The frist stage, or the constant current phase, is where most of the energy is transferred to the battery. Some 'fast charger' technology only incorporates this phase of the charging sequence. In the second and longer phase, the battery is charged at constant voltage.

After the AC watt-hours drawn was recorded, the power supply losses were accounted for by extrapolating efficiency estimates from the power supply curves generated for those specific laptops. The efficiency of the power supply varies somewhat with the load that it powers, so the charging energy was divided into bins according to the load with which it was associated. The corresponding efficiency for that load was used to calculate the actual energy that went to the battery charger. For one load bin, the total energy drawn to charge the battery of that interval, times the efficiency of the power supply for that interval equals the total energy used to charge the battery during that interval. A summation of the intervals gives the total energy used to charge the battery.

$$E_{Charge} = \sum_{n=1}^{m} E_{LoadBin} = \sum_{n=1}^{m} E_n EFF_n$$

The efficiency of the charger is then energy of the battery over the energy used to charge the battery.

$$EFF = \frac{E_{Battery}}{E_{Charge}}$$

Appendix F: Charging Battery in *On* Mode

In addition to measuring the charging characteristics while the computer was in *off* mode, we also measured the battery charger energy efficiency of two laptops, the Micron Transport GX, and the Toshiba Tecra 8100, while the computer was in *on* mode and the battery was charging. In order to isolate the energy required to charge the battery in *on* mode, the total energy consumption of the computer while the battery was charging, corrected for power supply efficiencies, was tabulated. Also calculated was the energy consumption of the computer in *on* mode over the same length of time, corrected for power supply efficiencies. The difference between these two values is the amount of energy used during the time period to charge the battery.

Surprisingly, we found that if the laptop is *on* and charging the battery, the charger is more energy efficient (approximately 95% efficient) but less time-efficient than if the laptop is *off* and charging the battery. In both cases, charging the battery while the computer was in *on* mode added an extra hour to the charge time. This is compared to a baseline of 3 ½ and 2 ¾ hours required for charging the laptop battery while off, for the Micron, and Toshiba, respectively.

The most likely explanation for this difference in energy consumption is that less power is available for charging when the computer is running. The computer needs to charge the battery more slowly as a result, and less of that power is likely to be dissipated as heat, improving charging efficiency. In the *off* mode, the laptop charges the battery more quickly, potentially increasing thermal losses.