Energy Consumption of Personal Computing Including Portable Communication Devices

Pavel Somavat[1] and Vinod Namboodiri[2]

[1]*CCS Haryana Agricultural University, Hisar, Haryana, India*
[2]*Department of Electrical Engineering and Computer Science, Wichita State University, Wichita, KS 26260, USA; e-mail: vinod.namboodiri@wichita.edu*

Received: 24 May 2011; Accepted: 19 July 2011

Abstract

In light of the increased awareness of global energy consumption, questions are being asked about the energy contribution of computing equipment. Although studies have documented the share of energy consumption by this type of equipment over the years, research has rarely characterized the increasing share contributed by the rapidly growing segment of portable, pervasive computing devices. Portable computing is widely predicted to be a dominant mode of computing and communication in the future, and accounting for its energy consumption is necessary to develop efficient practices. This work takes a fresh and updated look at energy consumption as the result of computing devices with regard to global consumption, and pays special attention to the contribution of portable computing devices. We further quantify the impact of energy consumed by the computing sector on the environment, and the cost of electricity for an average residential consumer. Finally, based on the results of this study, we provide recommendations for the computer networking community for sustainable portable/mobile computing.

Keywords: energy, electricity, computing, portable devices, environment, networking.

Journal of Green Engineering, 447–475.

1 Introduction

The increasing role of the Internet in our lives has ushered in a tremendous growth in computing devices governed by patterns such as the famous *Moore's Law*, which describes a long-term trend in the history of computing hardware that has continued for more than half a century, whereby the number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years. Computing devices are playing different roles in server farms, data centers, and office equipment, among others. There is increased awareness, however, in how the world consumes energy and its impact on the planet. Thus, it is natural to think about the impact of computing on the global energy consumption as well. There have been many studies that document this impact [1–3].

The world, however, is changing the way it accesses the Internet, and computing in general. The relevance of portable, battery-operated devices to handle computing and communication tasks is increasing. The first phone call over a GSM cellular phone occurred in 1991. By the end of 2007, half the world's population possessed such phones. This phenomenon is similar to the growth of computing devices in general, where central processing unit (CPU) processing power and capacity of mass storage devices doubles every 18 months. Such growth in both processing and storage capabilities fuels the production of ever more powerful portable devices. Devices with greater capabilities work with more data and subsequently have greater capability to communicate data. This has resulted in a similar exponential growth of wireless communication data rates as well the need to provide adequate quality of service.

There have been no studies to date that fully document the impact of the rapidly growing segment of portable computing devices on global energy consumption and what we can expect in the future. Such a study requires a detailed analysis of energy consumption by these devices as compared to computing devices in general, as well as an understanding of the magnitude of these numbers in terms of global energy consumption. This accounting also needs to include the impact not only in terms of energy, but also on the environment.

In this work, we profile the energy consumption of portable computing devices and account for their impact on global energy consumption. Our contributions in this work are the following:

1. We account for global energy consumption due to all computing devices that include server farms/datacenters, office equipment, and desktops.

Our statistics indicate that computing consumes more than 6% of the global electricity consumption.

2. We characterize the power consumption of portable computing devices like laptops and mobile phones, and account for their share of global energy consumption. We find that the share of energy consumed due to portable devices is 14% of the overall personal computing segment.[1]
3. We put the energy consumption due to computing devices in perspective of global electricity consumption and consider their broader impact. Our accounting indicates that emissions due to computing annually are equivalent to that produced by 10 million vehicles on the road. From the perspective of residential electricity consumption of an average consumer, the share due to computing is 3% in the US. However, when a populous, developing country like India is considered, computing consumes about 8% of the total share, due to the lower electricity consumption per household compared to the US.
4. We make recommendations to deal with the issue of energy consumption by portable devices based on the results of this paper that portable devices consume non-negligible energy.

These contributions are significant and novel due to the fact that we provide adequate detail about how our energy numbers are calculated for various computing sectors, including the fast-growing portable device segment. We expect that our paper will encourage researchers to identify the impact of individual computing sectors in terms of energy and to work towards more energy-efficient pervasive computing in the future. Without such detailed accounting, the notion that computing is a significant consumer of energy will never emerge from the shadows of other energy-consumer segments like transportation, appliances, and lighting. A preliminary version of this work appeared in [60] that presented results of our accounting study; based on subsequent feedback, updated data available, and additional data analysis, most of the key results and their insights have been updated and presented in this work including the addition of energy consumed due to the Internet infrastructure.

This paper is organized as follows: In Section 2, we account for the energy consumption from various sectors. In Section 3, we profile the energy con-

[1] We define the "personal computing segment" to include devices used on the front-end by consumers like laptops, mobile phones, and desktops, and devices used on the back-end like server farms/data centers, the Internet, and mobile infrastructure. We do not include office equipment like printers, copiers, etc., and consumer electronics like TVs, DVDs, etc.

sumption of individual portable computing devices. In Section 4, we estimate the total number of portable devices used globally. Subsequently, using numbers from Sections 3 and 4, we calculate the total energy consumption due to portable computing in Section 5. Also in Section 5, we present energy consumption statistics for the personal computing segment in the context of overall global electricity consumption. In Section 6, we examine the environmental impact in terms of emissions due to the personal computing sector, and the cost to consumers from a residential consumer perspective. Based on the results of our analysis of energy consumption from multiple perspectives, in Section 7, we make specific recommendations for keeping portable device energy consumption in check and preparing for a future in which the energy consumption due to computing cannot be ignored. Finally, in Section 8, concluding remarks are made.

2 General ICT Accounting

In this section, we account for the energy consumed by devices that fall into the general class of information and computing technology (ICT). This section is intended to familiarize the reader with trends in energy consumption, significant events happening in the area, projected growth, and environmental impact. We will narrow our focus to specific energy consumption numbers in Section 4.

2.1 Data Center/Server Farm Energy Consumption and CO_2 Emissions

Data centers or server farms are fast becoming a considerable source of energy consumption. Some of the factors driving this increase include the increasing popularity of web-based applications, an ever increasing number of information-hungry Internet users, streaming video and audio, the popularity of Internet-based social networking, and a need to store considerable data to satisfy user demand. Many large companies like Google, Microsoft, Yahoo, Ebay, Amazon, etc., are investing very heavily in establishing newer server farms to provide support to their respective customer queries. The emerging concept of cloud computing is fueling this development even further. However, the rapid increase in data centers implies drawing more and more power from the grid in order for them to function. This not only includes power to run the servers but also the energy involved in heating, ventilating, air conditioning (HVAC), and lighting. A large data center may require many

megawatts of electricity, enough to power thousands of homes. Although not all data center servers are power intensive, those like search engines consume a considerable amount of power. According to Google, every query consumes about 1 kilojoules (KJ) [4]. Because of these data farms, estimates put Google's annual electricity consumption figures at approximately 0.63 million megawatt hours (MWh) costing more than US $38 million [5].

With the increase in global computation needs, these farms are set to multiply, thus becoming a real cause of environmental concern. In 2006, servers and data centers accounted for an estimated 61 million MWh, or 1.5% of US electricity consumption, costing about $4.5 billion. It is projected that the power consumption by US server farms in 2011 will reach 100 million MWh, an increase of 12.7% that will require about ten new nuclear or coal-powered generation plants [6]. Therefore, these farms are becoming electricity guzzlers and a considerable source of carbon dioxide (CO_2) emissions. The total CO_2 emissions globally is close to about 30 billion tons [7, 48], where the server farms alone contribute 200 million tons of CO_2. According to the Environmental Protection Agency (EPA), data centers in the US alone produced 44.4 million tons of CO_2 in 2007, and continuing trends mean that these centers will release 80–100 million tons of CO_2 in 2011 [6].

Extensive studies by Koomey in 2008 [9] were carried out to calculate the overall energy consumption by data centers and to predict future trends. The approximate energy consumption in 2005 was 153 million MWh, and building on this study, Pickavet et al. [10] estimated this figure to be 254 million MWh in 2008. Based on these studies and projections based on growth trends, we can estimate the overall energy consumption due to data centers in 2010 to be 350 million MWh. However, if we deduct the amount of energy consumed indirectly for HVAC and others, which is about the same as energy consumed directly for computation operations according to [9], we can estimate the direct energy consumption to be 175 million MWh.

2.2 Office Equipment Energy Consumption and CO_2 Emissions

According to Department of Energy projections ranging from 2005 to 2015 and published in 2005, office equipment will be the fastest-growing commercial end use between 2003 and 2025 [11]. The potential for energy savings in offices through devices employing various energy efficient designs was identified in the early 90s. The Energy Star Program was initiated in 1992 by the US EPA as an effort to reduce the energy consumption and greenhouse gas emissions from power plants. In 1993, EPA extended that program to include

computers, monitors, and printers. The initial motivation was to extend the energy saving features of laptops to desktops and printers. These measures became popular partly due to governmental regulation that all the microcomputers, monitors, and printers purchased by federal agencies be Energy Star compliant [12]. Begun as a voluntary labeling program designed to promote energy efficient design in computer related products, this movement has been extended to more than 40,000 components ranging from homes and buildings to lighting. Since its inception in 1992, Energy Star has grown from a program focusing on personal computers to a multinational program promoting over 30 products across commercial and residential markets, with thousands of program partners [13]. According to the annual savings report published in March 2009, it is estimated that the program resulted in more than $19 billion in total energy bill savings, and at the same time reduced green house gas emissions by more than 43 million tons [14].

Motivated by the success of this program, various studies have documented the energy consumed by office equipment, with recommendations given to bring this number down; this has resulted in new start-ups with green technologies in mind [15]. A detailed study done in 2006 found that although power management modes of office computing devices are saving energy, there is still a considerable amount of energy being wasted when these devices are inactive. This study recommended that PCs be connected to networks for more savings potential [2]. Taking this approach even further, a Japanese study explored potential savings by shortening the power management delay time for office devices like PCs, displays, copiers, and laser printers. Results showed that such device management can save as much as 3.5 million MWh per year, which is nearly equal to 2% of commercial electricity consumption in Japan [3]. Therefore, even though a considerable amount of work has been done in the area of energy savings for office devices, much more can still be achieved.

2.3 Growth in Personal Computing Devices

Personal computing devices globally, like server farms and office equipment, have increased rapidly over the years becoming another major consumer of electricity. Data provided by the Computer Industry Almanac, through its annual briefings since 1993, give very detailed information for the total number of computers in use around the globe. Beginning in 1975, the approximate number of computers in use in the world was 0.3 million, of which 0.2 million were in the US. In the next five years, this number rose to 4 million, showing

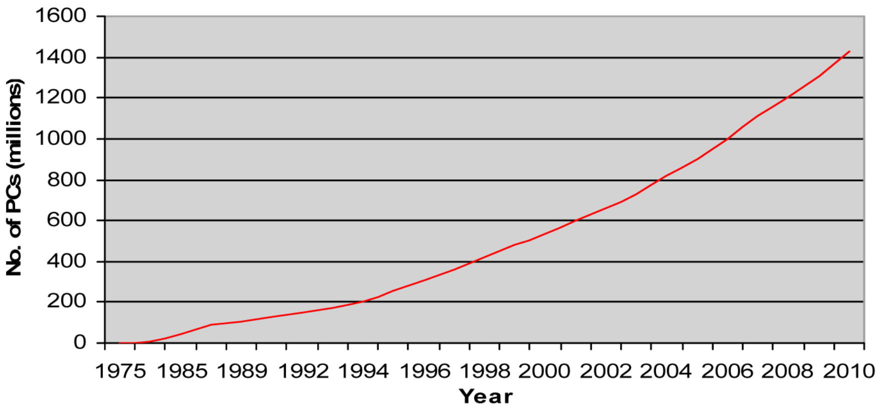

Figure 1 Our projected statistics for number of computers in use worldwide.

a 1233% increase. From 1980 to 1990, this increase was from 4 million to 116 million with a 2800% increase over the decade. The computer industry continued to grow at a remarkable pace in the 1990s, and the number of computers in use increased from 116 million in 1990 to 530 million in 2000, implying a 357% increase [16].

In the new millennium, this growth continued unabated, although the industry reached a relative state of maturity. Estimates by Forrester Research Institute forecast the total number of computers in 2015 to hit 2 billion, with countries like India, China, Brazil, and Russia accounting for more than 775 million new computers [17]. Similar estimates by Gartner expect this number to reach the 2 billion mark by 2014, forecasting the annual growth to be 12% per year [18].

Thus, from the above-mentioned statistics, the number of total computers in use can be estimated to be 1,300 million at the end of 2009 [16]. The increase in number of computers in use since 1975 and growth projections until 2010 are illustrated in Figure 1, based on [16, 17] which gives an estimate of 12% growth per year. Of the total number of computers in 2010 of 1,460 million, there are 1,000 million desktops and 460 million laptops, with the contribution of laptops increasing rapidly.

2.4 Other Related Work

Significant power is consumed by the mobile telecommunication infrastructure, including base stations. According to a study done by mobile communications giant Ericsson in 2007, communication infrastructure contributed

to approximately 0.12% of global energy consumption and about 0.14% of global CO_2 emissions [19]. As an ever increasing number of people are becoming subscribers, this will further fuel the demand for extensive coverage networks, which in turn will draw more power from the grid. This will be especially significant in developing economies where current infrastructure is not enough to satisfy the increasing demand.

Rising awareness about the detrimental environmental effects of the increase in greenhouse gas emissions and increasing costs of energy has compelled a large number of companies and industrial segments to reconsider their priorities. Therefore, motivated by ethical or economical reasons, a large number of companies have started considering green practices. Huge savings attained by the Energy Star Program have also provided positive momentum in this direction, motivating companies like Nokia, Ericsson, Intel, Google, Microsoft, and others to go for innovation-ensuring energy-saving practices in their products. The concern for one industry has proved to be the bounty for others; in the UK alone, there are approximately 7,000 companies operating with environmental technologies, as the sector is set to grow to $34 billion by the end of the decade [15]. Increasing data-center energy costs and related emissions have put the entire industry in a spot of anxiety, and considerable effort is being made to ensure the most efficient practices. Countries like Iceland have started investing tremendously in data-center infrastructure to attract data centers, as most of the electricity is generated from clean sources, and also the cold weather in that part of the globe can be utilized for efficient cooling [20]. In addition to companies, academia is also playing its part by bringing these issues to the fore. Earlier in this section, we discussed a number of such studies concerning the documentation of results from the Energy Star implementation and similar other initiatives discussing various efficiency scenarios.

3 Portable Device Energy Profile

In this section we take a detailed look at the power consumption profile of the two common classes of portable devices: laptops and mobile phones. We believe these two classes to be representative of the spectrum of portable computing and communication devices. We obtain the power consumption profile of these devices through a combination of our own measurements and prior work by researchers. Our measurement was based on using the Kill-A-Watt meter [21]. This meter provides the instantaneous power consumption of any device plugged into it.

Table 1 Laptop power study.

Mode	Specification	Power consumptio when WNIC (W	Power consumption Idling with WNIC on	Power consumption when video streaming through WNIC (W)
HP pavilion dv4t	4GB RAM, 2GHz processor	30	31	32
Dell Inspiron	3GB RAM, 2GHz processor	21	24	36
Compaq Presario C30	2GB RAM, 2GHz processor	28	30	34
Dell Inspiron	4GB RAM, 2.2GHz processor	18	19	24
Aspire 4730Z	2GB RAM, 2GHz processor	27	29	31
Dell Inspiron XPS M1310	2GB RAM, 1.6GHz processor	36	39	48
Hp pavilion dv 200	2GB RAM, 2GHz processor	34	41	42
Fujitsu Siemens AMILO M7440	512 MB RAM, 1.73GHz processor	29	31	35
Lenovo ThinkPad X60	512 MB RAM, 1.6 GHz processor	21	25	28

3.1 Laptops

We looked at nine different laptop models belonging to various manufacturers and measured their power consumption. Since communication is an integral part of portable computing devices, we paid special attention to the state of the wireless network interface card (WNIC). We kept the laptops in three different states: Idle with WNIC off, Idle with WNIC on (but no traffic sent or received), and receiving streaming video through WNIC. All laptops were running Windows XP or Vista, and were measured when idling with no applications running. By averaging the "Idle with WNIC on" column in Table 1, factoring in some additional power for traffic, we arrive at an average consumption of a laptop around 35 W, with some approximation.

Similar numbers have been reported by prior studies with laptops [22, 23]. These studies also provided the power breakdown across different components of a laptop. We show this breakdown in Figure 2 for the sake of completeness of this paper. It can be seen that, for an active laptop, about

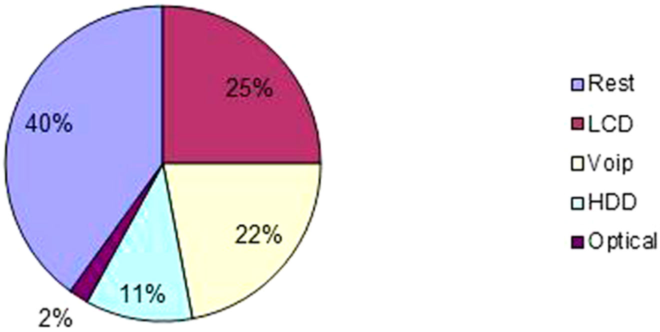

Figure 2 Power consumption breakdown of a laptop making VoIP calls.

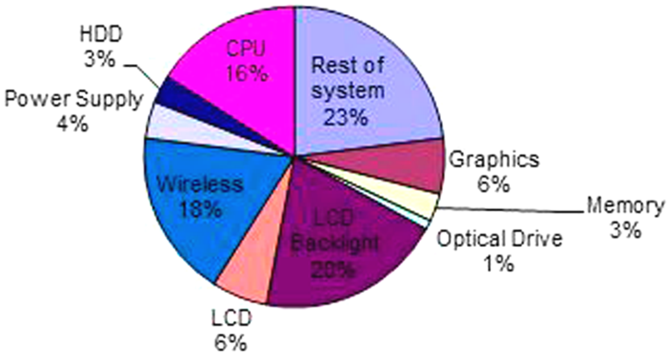

Figure 3 Power consumption breakdown of a laptop actively transmitting FTP traffic [22].

20% of the power consumption is due to the WNIC and rivals power consumption due to the display and CPU. As the work and results by Mahesri and Vardhan [22] (shown in Figure 3) is based on currently outdated hardware, we did our own study of the energy consumed by different components of a Lenovo SL400 laptop during a Voice over IP (VoIP) call which is a popular application. Our results (Figure 2) show that the network interface is still a significant consumer of energy compared to the LCD, CPU, memory, and other components.

3.2 Mobile Phones

Our study of mobile phone power consumption was based on only one smartphone, the Samsung BlackJack, which does not have a Wi-Fi WNIC. The Bluetooth interface was kept off. The idle phone consumed about 1 W

while during a call it consumed 3 W. Thus, during active communication, the communication interface consumes about two-thirds the power of the device. This is confirmed by other studies done on devices with Wi-Fi interfaces like PDA's [24]. Studies by Nokia also confirm that mobile phones typically take little more than 1 W of power on average (1.2 W to be precise).

Since all emerging smartphones like the Apple iPhone and RIM Blackberry have a Wi-Fi interface in addition to the cellular interface, we believe our estimate of power consumption of mobile phones is a conservative one.

4 Accounting for Number of Portable Devices

In this section we account for the number of portable computing devices used in the world. As before, we focus on only two classes: laptops and mobile phones. Based on the cumulative numbers determined in this section, coupled with the power consumed for each of these devices as presented in the previous section, we will account for global energy consumed due to portable devices annually in the following section.

4.1 Laptops

Based on the total computing numbers reported in Section 2, our challenge here is to identify the number of laptops from this overall projected number of computers in the world. Recent trends have shown that mobile computing is the most rapidly expanding segment in the computer industry. Historically laptops always have cost more than their desk counterparts. With advancements in microelectronics and continuing validity of Moore's Law, laptops are becoming cheap and affordable. Advancements in Wi-Fi technology are making mobile connectivity more and more ubiquitous, and one of the biggest factors driving the popularity of laptop computers. With ever increasing processing speed and lower costs, more and more people prefer laptops. One of the watershed events in the history of computers was achieved in 2008 when the number of laptops sold exceeded those of desktops for the first time [25]. According to an International Data Corporation (IDC) survey, the third quarter of 2008 saw notebook shipments into the US market surpass 50% of the share of the computer market. The figure for laptops stood at 55.2% as per IDC's US Quarterly PC Tracker [26]. It becomes abundantly clear from the above studies that laptops (and devices like tablets of similar form factor) are increasingly preferred and their ratio is set to increase in the future as people becomes more mobile. For our study we can estimate the number of

laptops currently in use to be around 460 million based on numbers presented in Section 2 and current market share and projected trends.

4.2 Mobile Phones

Mobile communication is one of the most rapidly expanding technologies has influenced every facet of human life since its inception. Thanks to the economic viability and decreasing prices of micro-electronic components, more people are able to own a mobile phone than ever before. When it comes to electricity consumption, we have reached a stage where mobile phones and related telecommunication infrastructure can no longer be ignored anymore because of their sheer volume. At the end of 2008, an important milestone in the ICT development race was achieved with over 4 billion mobile cellular subscriptions worldwide [27, 28].

Similarly the number of more sophisticated and processing oriented mobile phones is on rise. It is estimated that the number of smart-phones sold in five years will triple reaching 60 million [29]. Among the top 25 growth markets ranking list (2006–2011) there are a few surprises. India wins the top spot, just ahead of China, and almost equally in third place are Brazil, Indonesia, and Nigeria, but the real surprises start in the sixth place with the US mobile market tipped to grow by almost 66 million net additions from the start of 2006 to the end of 2011 [30]. The latest figures suggest that 5 billion mobile phones are in circulation [31] so we can estimate the total number of mobile phones globally to be 5 billion.

5 Energy Consumed by Personal Computing in Global Perspective

In this section we account for global energy consumption and focus specifically on the overall electricity consumed. By calculating the energy used for various segments of computing devices, we subsequently show the energy consumed by computing devices as a percentage of global electricity consumption. Furthermore, we specifically characterize what percentage of the computing segment is consumed by portable devices alone.

5.1 Global Figures

According to the World Energy Outlook-2008 Executive Summary published by International Energy Agency, global primary energy demand will increase

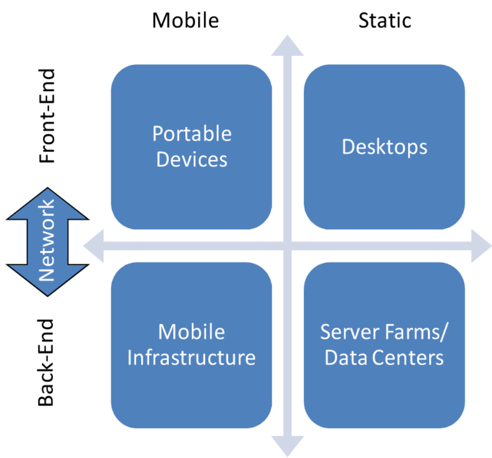

Figure 4 Elements considered in our definition of personal computing.

at an average of 1.6% per annum from 2006 to 2030. In 2006 the total energy consumption was estimated to be 11,730 million tones of oil equivalent (Mtoe) which is projected to increase to 17,010 Mtoe by 2030 [32]. Using above estimates, the approximate energy consumption in 2010 translates to 145 trillion KWh. Now the next step will be to approximate the total amount of electricity consumed globally. According to Central Intelligence Agency (CIA) World Factbook estimates, the amount of electricity consumed worldwide in 2008 was around 16.88 trillion KWh [33]. Using this amount, and assuming a modest 3% increase in global electricity consumption, the overall number for 2010 can be estimated as 17.8 trillion KWh indicating that electricity is about 12% of global energy consumption.

5.2 Computing Figures Including Portable Devices

Next, we will try to account for the approximate energy consumption by various front-end and back-end elements of the personal computing segment as defined in Figure 4, including those of the network infrastructure that connects them.

5.2.1 Energy Consumption by Portable Devices

According to our earlier estimates 5 billion mobile phones are currently used world-wide. Annual electricity consumption for a mobile phone as cited by the Nokia study is around 11 KWh per year [34], or around 1.2 W per unit at a

given time. This figure is confirmed by our calculations with smart-phones in Section 3. The annual energy consumption of all mobile devices in the world can thus be estimated at 55 million MWh.

Based on our earlier discussion, we estimate the number of laptops in the world to be approximately around 460 million. Average power consumed by a single laptop is about 35 W [23]. We assume that a laptop is used about ten hours a day, therefore the energy consumption of a single laptop for a year is around 127.7 KWh. Hence overall energy consumption in the world due to usage of all the laptops would be around 58 Million MWh.

5.2.2 Energy Consumption by Desktop Computers

From our assumptions in Section 2.3, there are about 1000 million desktop computers. The average power consumption of a 'typical' desktop is about 150 W based on a study by Intel [23], which includes the power consumed by a 17-inch LCD monitor. That study notes that without the LCD monitor, the system power consumption would be about 65 W.

We assume that an average desktop PC is used for about eight hours a day so that the energy consumption of one desktop computer with LCD display used for a year with an average power 150 W is about 438 KWh. Hence, 1000 million desktop computers consume about 438 million MWh annually. This is a conservative estimate, which does not take into account those desktops that are active or left idle for 24 hours a day.

5.2.3 Energy Consumption by Data Centers

From our earlier discussion in Section 2, electricity consumed globally by data centers during operation is 175 million MWh. This figure is the energy consumed during the operation of the computing equipment in datacenters. This does not include the energy needed for cooling and power distribution which was estimated to be roughly equivalent to the energy cost of computation in [9]. Since this article's focus is on the computation aspects and how more efficient computing techniques can reduce energy consumption, we do not show the cooling and power distribution energy consumption except in Section 7 where we compare energy consumed for the personal computing segment from a lifecycle perspective, including all energy costs during the period of usage. A discussion on achieving efficiency in cooling and power distribution is out of scope of this article.

5.2.4 Energy Consumption for Mobile Infrastructure

According to the Ericsson study [19], mobile communications infrastructure (including lifecycle costs and mobile handsets) consumed about 0.12% of energy globally in 2007. We can budgeting for a 15–20% increase over this share for the year 2010 to avoid an underestimate resulting in a share of 0.14%.[2]

Taking into account that only 53% of the above figure is consumed as electricity during actual operation [19] and global energy consumption is 145 trillion KWh, the electricity consumed for mobile communications infrastructure (including mobile handset operation) can be estimated as 107 million MWh. Subtracting the electricity consumed by mobile handsets as found above of 55 million MWh, we can estimate the mobile infrastructure consumes 52 million MWh. The study in [19] was mainly for GSM base stations and not 3G and 4G base-stations that are being rolled out. However, the presentation in [57] points out that these new base stations consume comparable power, allowing us to use the above estimate.

5.2.5 Internet/Computer Networks

With a large number of people in developing countries joining the IT revolution, the energy required keep networks, including routers, switches, and firewalls running is becoming quite considerable. The above mentioned study [10] estimated this amount to be 219 million MWh in 2008. Since the Internet is greatly expanding fueled by the ever increasing demand of more and more data, multimedia, online gaming and new applications, and extrapolating the growth patterns from [10] we can estimate the overall energy consumption in 2010 to be around 300 million MWh. We introduce this number along with other elements of personal computing to provide a complete perspective.

Figure 5 shows how the energy consumed by portable devices compares with that of other elements of personal computing. Traditionally, data centers and mobile infrastructures have been considered as the power hogs within the ICT area, and most prior work in energy efficiency has specifically targeted only these two areas [35–41]. However, the results above show that personal computing devices consume comparable if not more energy and it is worthwhile to research ways to achieve energy-efficient operation for these as well.

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[2] We prefer to overestimate energy consumption for the mobile infrastructure when there is some uncertainty as this prevents the overall share due to personal computing from being an overestimate as well.

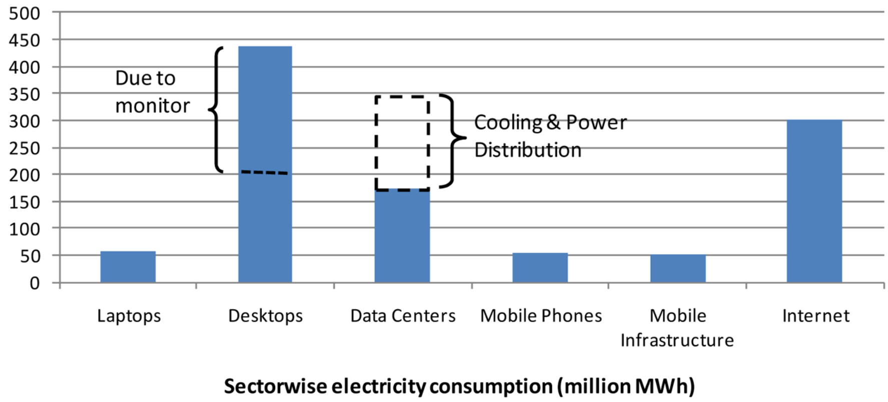

Figure 5 Comparison of energy consumed by portable devices with other elements of personal computing.

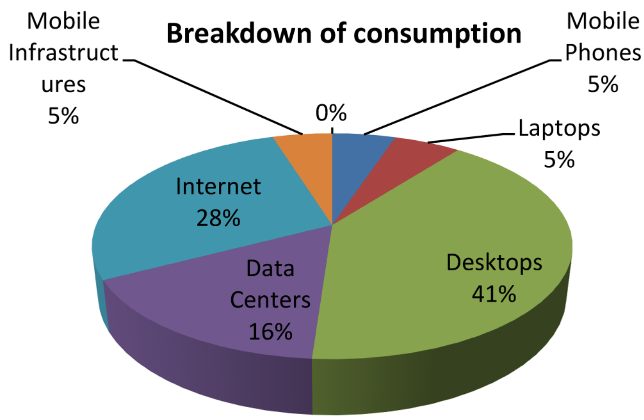

Figure 6 Personal computing related electricity vs. global electricity use.

5.3 Personal Computing in Global Perspective

From the above calculations, we can obtain an estimate for total electricity consumed by personal computing devices. The combined electricity consumed by the entire computation sector for 2010 was 1078 million MWh. Hence, electricity consumed by computational devices is 6% of the global electricity consumption. Figure 6 shows the segment-wise percentage contribution while Figure 7 illustrates the ICT electricity consumption vs. global electricity consumption.

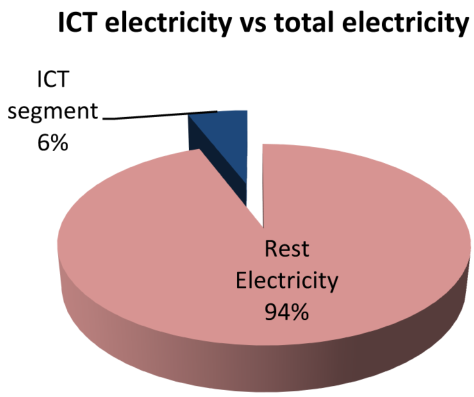

Figure 7 Global electricity consumption vs. total ICT sector electricity consumption.

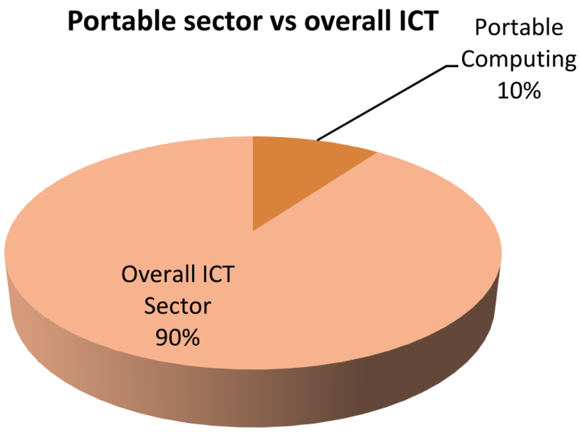

Figure 8 Total personal computing sector electricity use vs. portable sector.

From the above-mentioned numbers, we can also calculate the individual contribution of portable devices versus the whole computation segment. Overall consumption is 1078 million MWh whereas the contribution of the portable segment (including only laptops and mobile phones) is 107 million MWh. Hence, portable devices contribute close to 10% of the energy consumed by computational devices. This contribution is further elaborated in Figure 8. As we deduced, the contribution of electricity to the overall global energy sector is about 12%. From our numbers, we can also ascertain the con-

tribution of the computation sector to the overall global energy consumption as a modest 0.71%.

5.4 Limitations

The readers should make note that some of the numbers presented are estimates based on available data. There is expected to be some variability based on source of data and assumptions made by that source. For example, we used a value of 2 for Power Usage Effectiveness (PUE) from [9] for data centers that represents the ratio of energy costs for running the data center to the energy cost for just computing operations. It could be the case that some data centers operate with a lower PUE than this. Other examples include assumptions on average usage durations for various computing devices. As all our accounting numbers and methodology is described fully in this article, we expect the readers to be able to modify our calculations as needed when more accurate data is available for an particular segment. It should also be easy to extend our results for additional years as new data becomes available. We expect that in future tablet computers and smart phones and their impact would need to be incorporated.

6 Broader Impact

In this section we look at other dimensions of the numbers obtained in Section 5 and earlier. We begin by presenting the energy consumption by computing devices in terms of carbon di-oxide (CO_2) emissions to demonstrate environmental impact. Subsequently, we will look at the amount of residential electricity consumption by computing devices to get a consumer perspective as well.

6.1 Environmental Impact

One of the major points that often remain unnoticed is that, although electrical energy consumption represents only 12% of the global energy requirements, its contribution to the global CO_2 emissions is a whopping 40%. A study by International Energy Agency entitled CO_2 emissions by sectors released in 2005 puts the CO_2 emissions worldwide due to public electricity and heating to 37.2% [42]. Similar studies by European Commission's Directorate-General for Energy and Transport released in 2009 for the year 2006 puts the CO_2 emissions in the European Union (EU) zone because of energy industries

and household to be around 48% [43]. Surprisingly, coal is still one of the major fuels employed to generate electricity worldwide. For example according to American Coal Foundation about 56% of electricity generated in the US is done through coal [44]. Based on report on CO_2 emissions by different power plants in the US by Energy Information Administration, for every kWh of electricity generation, 2.117 pounds of CO_2 is produced by burning coal, 1.915 pounds from petroleum and 1.314 pounds from gas [45, 46]. Hence on average electricity sources emit 1.297 lbs CO_2 per kWh (0.0005883 metric tons CO_2 per kWh). Thus, given that 1078 million MWh is contributed by the personal computing segment, it responsible for about 0.63 billion tons of CO_2 annually. One way to interpret this is that it is equivalent to the emissions of 10.35 million vehicles on the road when driving 10,000 miles per year considering an average car giving 21 miles per gallon (mpg). Another way to interpret this is that these emissions are equivalent to 0.5 KWh per day per capita, or every person on the planet running a 1 KW electric heater, 30 minutes a day throughout the year. The consideration of source of energy is interesting as well. 73% of emissions in the electricity generation sector come solely from coal which explains why this sector has disproportionately high level of CO_2 emissions as compared to other segments; even though the computing sector electricity consumption is only 0.71% of the global energy consumption, this fragment contributes to 2% of global CO_2 emissions as illustrated in Figure 9 [7, 48]. *Therefore the computing sector presents a very attractive opportunity in the global race to control greenhouse emissions.*[3]

6.2 Individual Consumer Perspective

As per the US Department of Energy [49], energy consumption per household in the US for a year is about 11000 KWh. The average number of people per household is about 2.59 as per the US Census Bureau [50]. Assuming that there will soon be (if not already) two mobile phones, one desktop and one laptop in a typical home, the total energy cost due to computing would be around 580 KWh using our calculations in Section 5. The corresponding energy consumption due to only portable devices (one laptop and two mobile phones) would be around 150 KWh. Hence, energy consumption due to computing in an average residential home in the US would be around 5.25% while energy consumption due to portable devices would be about 1.36%.

[3] Of course, cleaning up electricity generation itself is an useful goal that has broad consensus among the research community with various efforts underway, but is outside the scope of this paper.

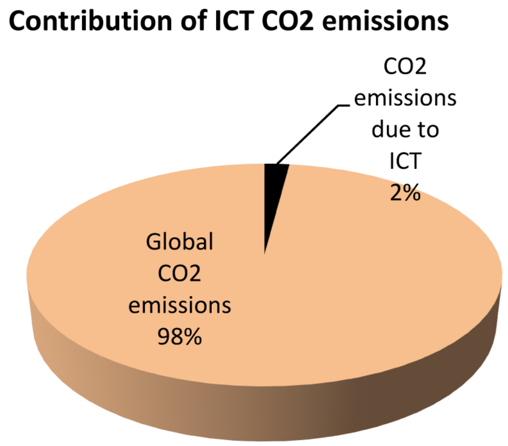

Figure 9 Global CO_2 emissions due to ICT sector vs. global CO_2 emissions.

To get another viewpoint we also consider the statistics of one of the rapidly growing economies in the world: India. The domestic energy consumption in India was 20.8 Mtoe in 1990 and about 56.5 Mtoe in 2001. Based on projected rate of growth, we estimate that the domestic energy consumption in 2009 would be around 82.46 Mtoe that is roughly equivalent to 0.959 trillion KWh. The population of India as per World Statesmen [51] is about 1.14 billion. Considering there are 4.8 people per household [51], the average household energy consumption would be 4038 KWh. With 2 mobile phones, 1 laptop, and 1 desktop per household as above,[4] the share of energy consumption due to computing would be 14.36%, while that of portable devices would be 3.71%. These numbers are presented in Figure 10.

Hence it can be observed that in developing economies like India, the computing device energy consumption share is much higher due to general household energy consumption being lower compared to the US.

[4] This assumption holds typically in urban areas in India, but in rural areas only the assumption of 2 mobile phones is justified with far fewer laptops and desktops [52, 53]. Nevertheless, these numbers are projected to be true in the very near future as most of India's middle-class already had at least one desktop or laptop by 2006 [17, 54]. Thus, for ease of comparison, we keep the number of household computing devices to be the same both in India and the US. Note that there are more people per household on average in India than the US, and thus, the former could be considered to have a greater potential to utilize more computing devices per household in the future.

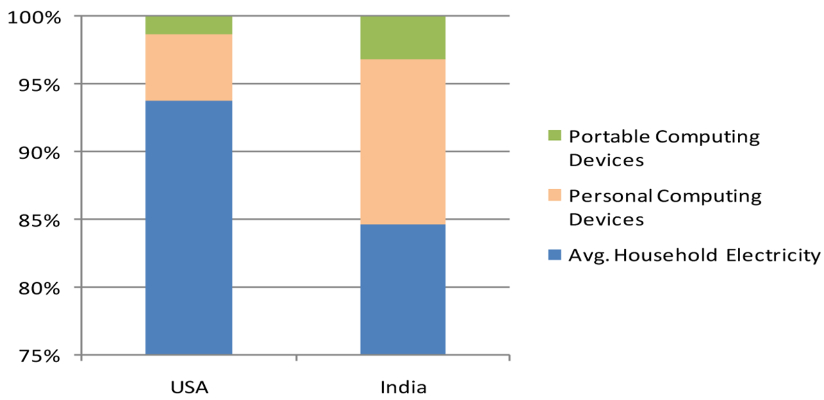

Figure 10 Comparison of household electricity consumption due to personal computing devices in the US and India. Note that the Y-axis starts at 75% to clearly show relative percentage differences.

7 Recommendations for Energy-Efficient, Sustainable Portable Computing

The issue of energy consumption of computing devices can best be alleviated by all members of the computing community that include researchers working on different aspects like displays, CPUs, network interfaces, memory, to talk of a few. Individual optimizations to each hardware component would help, and could be improved by joint hardware optimizations. Similarly, software optimizations focusing on operating systems, data caching, data compression, to name a few, would be helpful as studied, and even put into practice over the last decade or so. In this section, we pay particular attention on how to reduce energy consumed by portable devices.

We believe that computer networking researchers can contribute the most in reducing portable device energy consumption due to the fact that an active network interface is likely to be the task that consumes the most power among all components, as seen in Section 3. Our following recommendations are thus aimed directly at the networking community, including possible cross-component approaches.

We classify our recommendations into two categories: energy-efficient operation, and increasing lifespan. The first category deals with how to design and/or operate a device more efficiently. The second category deals with how to decrease the energy costs based on a lifecycle approach, primarily focusing on reducing the impact of manufacturing by increasing lifespan.

7.1 Energy-Efficient Operation

7.1.1 Power Management

Power management has been an active area of research over the years for computing devices as well as appliances [13]. Device components have been optimized to lower power consumption. There are at least two areas where further work can be done apart from continued optimizations of components individually.

The *first area* is to make users utilize power management more often. An informal survey of 50 students at our university showed that most were unaware of power management modes of the network card, and used the default settings. A simple check of the default settings of laptops studied in Section 3 earlier showed that power management was disabled by default.

The *second area*, once users are aware of power management options, is to enable tunable software based trade-offs between energy and performance. For example, wireless cards can be kept in sleep mode longer at the expense of higher delay of received packets, for say, a VoIP application [58]. Or, the resolution of a video being streamed could be reduced for reduced energy consumption [59]. The creation of a general framework across different computing platforms to allow such tunable tradeoffs is sorely required. If the hardware equivalent of a 'knob' could be developed that allows each users to tune it to their own tolerable performance levels, it would make power management more acceptable.

7.1.2 Battery Management

When batteries are necessary, as is the case when a user is mobile, better usage of batteries can get better efficiencies. Protocols and algorithms should be designed to provide time for battery charge recovery, and use less current draw when possible. For example, medium access control (or even upper layer) protocols could be designed that send and receive packets in short bursts, that allows nodes enough time in sleep mode in between bursts [55]. Greater utilization of battery capacity can reduce power consumed of the electricity grid.

7.1.3 Adjust Optimization Metrics

Protocols and algorithms should be designed keeping total energy consumption as a metric, as opposed to individual node lifetimes when considering a collaborative network in specific scenarios. For example, consider the case of a static wireless mesh network. It may be possible to replace the batteries in

such nodes periodically. In such an instance, protocols must be designed to minimize total energy consumption of the network as opposed to each node trying to minimize its energy consumption [56]. Another example is that of an ad hoc network in a conference room where a power outlet for each node is easily available and all nodes are plugged in. Again, in this scenario, the total power consumption by all nodes should be minimized as opposed to the common metric of individual node consumption.

7.1.4 Utilize Energy Harvesting

Recently, there are many products on the market which allow the use of energy harvesting techniques to power portable devices. For example, the Solaris product (cost about $360) from Brunton can charge laptops, while the SolarPort product (cost $120) from the same manufacturer can charge smaller devices like phones. These devices can become more main-stream with time as prices drop due to scale, or through government subsidies to encourage more renewable energy use. Of course, one must also weigh the energy benefits of solar panels against the actual energy needed to manufacture them.

From a networking researcher's perspective, there is a need to understand how to design protocols to utilize such sources of energy effectively. For example, during periods when plenty of energy is available, portable devices could do more of delay-tolerant tasks. Once the energy harvest is unavailable, the device can ramp down to minimal operating modes similar to the power management paradigm.

7.2 Increasing Lifespan

There are two approaches which could result in consumers using their devices longer: economic incentives, and reliance on thin-client paradigms.

The first approach could be to provide economic incentives for consumers, or at least remove the current incentives to stop using phones after a period of time. For example, typical cellular phone carrier contracts in the US last for two years after which customers typically upgrade to newer devices that are heavily subsidized conditional on the signing of a two-year contract. If consumers would instead buy hardware without contracts and subsidies, they might be inclined to keep their devices longer. As reducing energy consumed for manufacturing devices and decreasing environmental waste provides environmental benefits, governments could provide incentives for consumers to keep their devices. For example, the government could pay

a part of carrier costs after a device has been used over a period of time. Note that, typically governments and manufacturers would prefer consumers to keep buying and replacing their phones. Thus, in this case the services and software aspect of maintaining or improving user satisfaction would need to be encouraged more than replacing hardware, apart from the incentives mentioned above.

The second approach could be to rely more on a thin-client paradigm where individual consumer devices would have reduced capabilities acting as 'dumb' terminals with most of the processing done at remote servers. This would allow most upgrades to be done at the servers, with little incentive for consumers to upgrade their devices. This approach would require greater reliance on software upgrades than hardware upgrades. There is likely to be an increased burden on communication within the thin-client paradigm which would then need the design of energy-efficient communication techniques.

Additional approaches could include greater modularity in the way portable communication devices are manufactured so that, with the replacement of only a few parts, desired functionality can be maintained. Currently available devices, especially mobile phones, are rarely modular with the whole device needing replacement with the malfunction of one of the major components. This should be an additional area of research towards the quest for sustainability in portable computing and communication devices.

8 Conclusions

We presented a revised and updated study over [60] that accounted for energy consumed by various computing devices, including the growing portable device segment. In [60] our key results were that ICT accounted for only 3% of global electricity consumption with portable devices responsible for 17% of this share. In this updated study including electricity consumption due to the Internet infrastructure, our accounting shows that computing consumes about 6% of the global electricity consumption. Of this, about 10% is contributed by portable devices, still a significantly high share. This statistic should serve as a reminder to researchers that energy should also be treated as a resource consumption issue in portable computing devices, as opposed to the traditional operating lifetime metric. Our study also shows that the CO_2 emissions due to the computing sector are much higher due to the fuel source used for power, and efficiencies in the computing sector can make a bigger impact on global CO_2 emissions than efficient practices in

other sectors. From an individual consumer perspective, we also demonstrate that the cost of electricity for computing rivals that of many other common household appliances, and requires careful thought on usage behavior. This is especially true in developing countries like India where average household energy consumption is lower than the US, and results in the share of computing devices being higher. We made specific recommendations for greater energy-efficiency and sustainability in the portable computing area through a combination of reduction of energy consumption during the use phase, and increase in lifespan through economic incentives and reliance on thin-client paradigms.

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Biographies

Pavel Somavat is currently working as Assistant Professor in Electrical Engineering at CCS Haryana Agricultural University, India. He obtained his M.S. in Information & Communications Engineering from University of Applied Sciences Giessen Friedberg, Friedberg, Germany. He has worked as a researcher in fiber optics industry working in the field of dynamic attenuation testing on fibers. His research interests are diverse ranging from energy efficiency issues in ICT sector to optical fiber based sensors. He has published work in estimating the environmental effects of rapid proliferation of ICT technologies and the probable directions for ensuring sustainable development.

Vinod Namboodiri is currently Assistant Professor at the Department of Electrical Engineering and Computer Science at Wichita State University, USA. He graduated with a Ph.D. in Electrical and Computer engineering from the University of Massachusetts Amherst in 2008. He has served or is currently serving on the technical program committees of IEEE GLOBECOM, IEEE ICC, IEEE IPCCC, and IEEE GREENCOM, and is an active reviewer for numerous journals and conferences in the wireless networking and mobile computing areas. His research interests include designing algorithms and protocols for energy-intelligent and sustainable computing, and

designing an effective communication architecture for smart electric grids. In the past he has worked on designed MAC and routing protocols, and developing energy-efficient protocols and algorithms for different wireless technologies like Wireless LANs, RFID Systems, Wireless Sensor Networks, and Wireless Mesh Networks.