ENABLING ENERGY AWARENESS OF ICT USERS TO IMPROVE ENERGY EFFICIENCY DURING USE OF SYSTEMS

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Abstract

Data centres have been the primary focus of energy efficiency researches due to their expanding scales and increasing demands of energy. On the other hand, there are several orders of magnitude more end-users and personal computing devices worldwide. Even the modest energy savings from the users would scale up and yield significant impact. As a result, we take the approach towards energy-saving by working with the end-users.

We recognise that users of ICT systems are often unaware of their power usage, and are therefore unable to take effective actions even if they wanted to save energy. Apart from energy awareness, the majority of end-users often lack of sufficient knowledge or skills to reduce their energy consumption while using computing devices. Moreover, there is no incentive for them to save energy, especially in public environments where they do not have financial responsibilities for their energy use.

We propose a flexible energy monitor that gathers detailed energy usage across complex ICT systems, and provides end-users with accurate and timely feedback of their individual energy usage per workstation. We tailored our prototype energy monitor for a 2-year empirical study, with 83 student users of a university computer lab, and showed that end-users will change their use of computers to be more energy efficient, when sufficient feedback and incentives (rewards) are provided. In our measurements, weekly mean group power consumption as a whole reduced by up to 16%; and weekly individual user power usage reduced by up to 56% during active use.

Based on our observations and collected data, we see possibilities of energy saving from both hardware and software components of personal computers. It requires coordination and collaboration between both system administrators and end-users to maximise energy savings. Institutional 'green' policies are potentially helpful to enforce and regulate energy efficient use of ICT devices.

Relevant Publications

Some of the work presented in this thesis has been previously published:

- Yi Yu and Saleem N. Bhatti. Energy Measurement for the Cloud. In Proceedings of *the IEEE International Symposium on Parallel and Distributed Processing with Applications (ISPA'10)*. IEEE, Taipei, Taiwan.
  DOI=10.1109/ISPA.2010.29
  http://doi.ieeecomputersociety.org/10.1109/ISPA.2010.29

- Yi Yu and Saleem N. Bhatti. The cost of virtue: reward as well as feedback are required to reduce user ICT power consumption. In Proceedings of *the 5th ACM international conference on Future energy systems (e-Energy '14)*. Cambridge, UK.
  DOI=10.1145/2602044.2602063
  http://doi.acm.org/10.1145/2602044.2602063

Declarations

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I, Yi Yu, hereby certify that this thesis, which is approximately 33,200 words in length, has been written by me, and that it is the record of work carried out by me or principally by myself in collaboration with others as acknowledged, and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student and as a candidate for the degree of Doctor of Philosophy in January 2010; the higher study for which this is a record was carried out in the University of St Andrews between 2010 and 2014.

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Glossary

AC	Air Conditioning
ACPI	Advanced Configuration and Power Interface
AID	Agent Identifier
API	Application Programming Interface
Apple SMC	Apple System Management Control
CFD	Computational Fluid Dynamic
CIM	Common Information Model
CPU	Central Processing Unit
CSV	Comma Separated Values
DCE	Datacentre Efficiency
DSM	Demand Side Management
DVFS	Dynamic Voltage and Frequency Scaling
EEMBC	Embedded Microprocessor Benchmark Consortium
EMP	Energy Management Protocol
FEM	Flexible Energy Monitor
GPU	Graphics Processing Unit
HDD	Hard Disk Drive
ICT	Information Communication Technologies
IDE	Integrated Development Environment
IHD	In-Home Display
IP	Internet Protocol
IPMI	Intelligent Platform Management Interface
KPI	Key Performance Indicator
LCD	Liquid Crystal Display
LDAP	Lightweight Directory Access Protocol
OID	Object Identifier

OPEX	Operational Expenditure
OS	Operating System
PC	Personal Computer
PDU	Power Distribution Unit
PUE	Power Usage Effectiveness
QoE	Quality of Experience
QoS	Quality of Service
RAM	Random Access Memory
RID	Relay Identifier
RPC	Remote Procedure Call
RR	Real Resource
RRD	Round Robin Database
SLA	Service Layer Agreement
SNMP	Simple Network Management Protocol
SPEC	Standard Performance Evaluation Corporation
SSD	Solid State Drive
TCO	Total Cost of Ownership
UML	Unified Modeling Language
URN	Uniform Resource Name
USB	Universal Serial Bus
UUID	Universally Unique Identifier
vEC	Virtual Energy Counter
VM	Virtual Machine
WEBM	Web-Based Enterprise Management
WMI	Windows Management Instrumentation
WWW	Would Wide Web
XML	Extensible Markup Language

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Chapter 1

Introduction

1.1. Background

Modern Information and Communication Technologies (ICT) systems are built upon large number of computing, telecommunication devices, as well as crucial supporting equipments including lighting and cooling. These appliances require electricity to function.

ICT systems continue to grow rapidly all over the world, especially in developing countries. Forrester Research Institute forecasts that India, China, Brazil and Russia together will have over 775 million new computers installed between 2007 and 2015. The total number of computers in the world will exceed 2 billion by 2014, with an annual growth of 12% [112].

Meanwhile in developed countries where internet penetration rates are already high, demands of ICT services continue to increase. For example, in 2010, Finland made access to a 1Mbps broadband network connection a legal requirement, which would boost its internet penetration rate from 96% to 100% [15]. The UK government started to promote and provide digital services across multiple sectors including Governmental services, entertainment, education, information and communication industries from 2009 [8, 14, 21].

In 2010, data centres were estimated to account for between 1.1% and 1.5% of global electricity use [73]; personal computers were expected to consume twice as much as data centre consumption globally (272 tera watt hours) in the same period [90]; the estimated total energy consumption of all ICT equipments was over 3% of the global electricity consumption [112]. Overall, the combined energy usage as well as CO_2 emissions by the global ICT industry are expected to triple from 2008 to 2020 following the current trends, to approximately 3% of the world's [6, 49]. It is estimated that the global ICT industry is similar to the aviation industry in terms of CO_2 emissions [49].

The US Department of Energy projected that, from 2006 to 2030, the world's electricity consumption will rise by 76%, and that electricity generation will increase by 77% [13]. Although electricity is commonly considered a clean and relatively safe form of energy to use, the generations of electricity are mostly associated with negative impacts. Today, most power plants still burn fossil fuel, biomass, or waste. They produce not only carbon dioxide (CO_2), but also carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOX), particulate matter (PM), and heavy metals such as mercury [9]. These combustion by-products either cause environmental issues such as global warming [11], or harm human health. On a global basis, CO_2 emission itself outweighs all other gas emissions, contributes about 70% of the potential global warming effect of anthropogenic emissions of greenhouse gases [5]. Coal-fired power stations supplied 41% of world's electricity needs in 2006, and will account for 43% by 2030 [13]. This implies a huge future increase of carbon emissions by electricity generation itself. Electricity prices will continue to increase as both raw fuel costs and carbon taxation rise [12, 109]. As a result, the costs of computing services due to energy usage will also rise in the future. Microsoft has publicly predicted that by 2015, "*costs to operate servers will exceed the costs to purchase server hardware*" [2].

Therefore, for either environmental or economical considerations, it is important to improve energy efficiency in ICT systems.

1.2. General Energy Saving in ICT Systems

As both coverage and speed of Internet improve, ICT systems nowadays have become complex systems with inter-connected user-facing, low-end terminals (e.g. personal computers, portable devices) and remote, high-end servers in data centres that provide a variety of services (e.g. web search, email, entertainment).

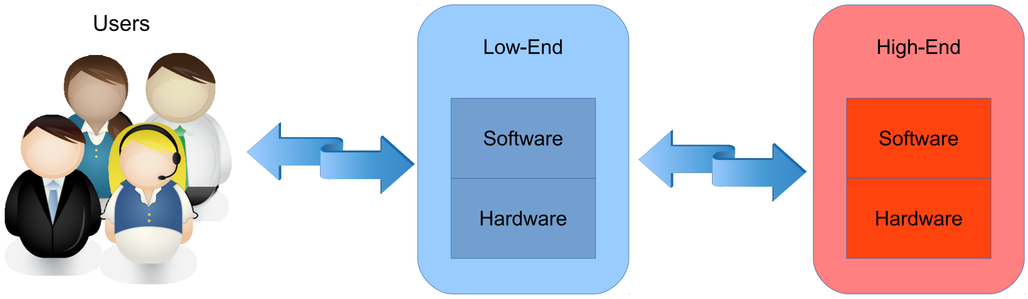

Figure 1.1. ICT system composition: users, low-end software, low-end hardware, high-end software and high-end hardware.

Since it is the hardware that requires electricity to operate, naturally, researchers and engineers primarily focus on energy reduction from the hardware, ranging from small scale individual computer components, to large scale data centre design that consists of thousands of high-end servers as well as supporting systems including lighting, cooling and backup power supplies. Among all the energy saving technologies, very few can be applied to both low-end and high-end ICT systems; the majority of them target specific type of hardware or part of the ICT systems by exploiting their unique characteristics.

For instance, Random Access Memory (RAM) generally has very little variations in power consumption despite different utilisation levels or capacity. Manufacture have achieved significant power savings applicable to memory chips in both high- and low-end systems. For instance, Kingston, the world's largest independent manufacturer of memory products, have developed low (1.35V) and ultra low (1.25V) voltage RAM that use up to 20% less power compared to equivalent memory chips working at 1.5V [70].

Excluding peripherals, the Central Processing Unit (CPU) is recognised as the most energy consuming component in a computer [66]. As one of the most successful energy saving technologies, Dynamic Voltage and Frequency Scaling (DVFS) technology has been widely applied in low-end computer systems. It controls CPU to provide *just enough* processing power by dynamically adjusting CPU voltage and frequency settings according to real-time system load [36, 48, 76, 96, 99]. Figure A.1 in Appendix A illustrates power profiles of 2 CPUs used in high-end servers and 2 CPUs used in low-end desktop computers based on real measurements. Overall, we observe that DVFS is in place for both desktop CPUs tested. In which case, DVFS offers satisfying fine-grained voltage- frequency control towards proportional power dynamics to CPU utilisation. On the other hand, DVFS is either not implemented or disabled by default for server CPUs due to the requirements of high performance, high availability and low latency. The power saving feature of high-end CPUs is limited to switch each core between either low or high power states. However, despite the lack of DVFS technology, newer high-end CPUs still have improved power dynamics and performance. Some of the latest generations of CPUs claim to half the power consumption while providing the same compute power compared to some older models [1, 120]. In some cases, low power CPUs with or without DVFS technology are no longer responsible for the majority of power consumed in servers during idle periods [115].

For persistent data storage, conventional hard disk drives (HDDs) are increasingly replaced by solid-state drives (SSDs) in data centres. Compared to typical 3.5-inch enterprise grade HDDs, SSDs are smaller in size, have up to to 100 times higher read/write performance and higher reliability, but consume up to 90% less energy [22]. Despite the high cost of SSDs (approximately 10 to 25 times per GB compared to HDDs), it makes sense for some data centres to adopt SSDs due to the high utilisation of disks (i.e. disk idle periods are used for improving reliability. e.g. scrubbing [118]. This conflicts with energy saving mechanisms that attempt to spin down or turn off traditional HDDs during such periods [61, 110]). In contrast, disk utilisation in low-end systems is too low to make economical sense to use SSDs. It is predicted that SSDs are unlikely to completely replace HDDs in the next 10 years [51, 117]. However, researchers have taken the situation into account and proposed an energy-efficient file system for a hybrid storage system that takes advantage of both HDDs and SSDs [108].

A survey in 2006 benchmarked 22 data centres, and concluded that computational hardware alone is accountable for 33% to 75% of the total data centre power [63]. Compared to conventional office buildings, data centres can be over 40 times more energy intensive. Some data centres consume so much energy that it makes sense economically to build on-site power plants to satisfy their own needs of electricity [64, 87, 102, 116]. What worsens the situation is that the more energy is consumed in data centres, the more heat is generated, which also consumes power to be extracted. In some cases, a server's internal fans can consume between 10-25% of total server power. And at the data centre level, cooling can account for as much as 50% of the total power consumption [4, 63, 95]. Over the recent years, there have been significant accomplishments in data centre design that minimise cooling costs. Some new data centres are strategically built in cold regions of the globe or close to rivers or the sea, so that free natural cooling resources such as cold air and water can be utilised. For existing data centres or those can not be built in optimal geographical locations, computational fluid dynamic (CFD) models are often used to simulate and analyse the allocations of server racks as well as the cold air flow from air conditioning (AC) units, aiming to achieve the optimal cooling effects, and hence reduce cooling costs [94, 95]. In contrast, low-end ICT systems deployed in offices, schools, and hospitals for example, have much lower power consumptions compared to data centres, hence the need of dedicated cooling system. Ordinary AC systems for office buildings are sufficient to keep them from overheating.

On top of energy saving from hardware, computer software has also been improved to better coordinate hardware devices for higher power efficiency. For low-end ICT systems that are expected to be underutilised with small and bursty workloads, more aggressive power management policies are used to reduce waste of energy. For example, computer peripherals including displays and printers are configured to automatically enter low-power stand-by mode after short periods of idling; workstations are automatically turned off during non-working hours (e.g. 6pm - 8am).

In data centres, due to high power consumptions of idle servers, different software and system management policies are used aiming at maximising individual server utilisation while minimising the total number of servers that are powered on, to approximate energy-proportional computing [30] at the ensemble level, where an ensemble is defined as a logical collection of servers and could range from an enclosure of blades, a single rack, groups of racks, to even an entire data centre [115]. Some system management policies do consider the influence of the uneven server room temperature distribution, and deploy the workload in a temperature-aware manner [31, 88, 93].

As virtualisation technology quickly matures, it is now widely used in data centres to improve server utilisation, hence less waste energy. In short, it allows one physical server to host a number of virtual machines by allocating available system resources to them. Each virtual machine works and appears same as a physical server to the users, but with either fixed or on-demand system resources. e.g. CPU cores, network interfaces, RAM and disk capacity. With virtualisation technology, in theory, it is possible to consolidate 8 servers each with 10% utilisation ratio to 1 that is 80% utilised, and power off the rest 7 servers to conserve power. In practice, effective workload consolidation is not as trivial as packing the maximum workload in the smallest number of servers; and workload resource usage, performance, and energy usages are not additive [113]. Extensive researches have been done to improve both energy efficiency and performance of data centres with virtualisation technology [33, 34, 44, 55, 92, 97, 107, 113]. Some low-end systems, e.g. public computers in libraries, are able to reduce power consumption from virtualisation technology by replacing traditional desktop computers with low-power thin-clients [1] for access to remote services including data/document processing software, data

[1]Computer terminals that only provide basic input/output functionalities and network connectivities with minimal computing and storage capabilities.

storage, multimedia and virtual desktop computers hosted in data centres. However, due to concerns including security, single point of failure, network reliability and speed, slow or degraded graphics performance, most end-systems are yet to benefit from virtualisation technology in terms of saving power.

1.3. Research Motivation and Approach

This thesis attempts to improve energy efficiency in ICT systems from the following two approaches:

(1) Power monitoring and feedback can potentially improve system management policies. Software and hardware can potentially be better coordinated to reduce energy wastage and improve system energy efficiency.

(2) Apart from relying on existing systems-level energy saving interventions, there is the potential to reduce users' energy wastage by raising their energy-awareness and encouraging change in user behaviour.

1.3.1. Need for Measurement-Based Power Monitoring. Clearly, if the energy usage of an ICT system can be monitored, there is the potential to introduce system management policies that will allow energy usage to be used in management practices. However, this is not the general practice today: no common energy measurement infrastructure exists [111].

In today's ICT environment, the incentives are wrong for wide-scale implementation of energy-saving policies, and useful information is not available from deployed systems to help business policy makers and system managers move towards energy efficiency.

Firstly, energy-saving equipment and energy-saving tools often add additional cost to basic ICT purchases for end users, e.g. lower power CPUs in server equipment are optional 'upgrades'. Where total cost of ownership (TCO) considerations are made for purchases, these usually do not include energy-usage estimates, and operational and/or functional requirements to the business objectives are key. Furthermore, the installed base of (legacy) equipment may not have suitable hardware for energy monitoring, let alone permit energy control. Even when money can be found for purchase and installation of energy-usage monitoring hardware (e.g. for legacy systems), there is lack of an *information model* that permits appropriate collection of energy-usage and resource-usage data for devices within an administrative domain.

Secondly, for new equipment, established vendors currently use proprietary energy-saving features to compete for sales and maintain their customer base. So, there is little incentive for the established vendors to co-operate and agree cross-platform, vendor-independent, energy-aware information models. As very few ICT environments are single-vendor provisioned, this means that there are a disparate set of devices and components, which may be energy-aware, but whose energy usage is not easily visible to systems managers in an easily accessible or consistent manner. This prevents rationalisation of systems management for greater energy efficiency.

Commercial providers such as *Elster EnergyICT*[2] offer proprietary services for energy management using their own hardware (power meters) and software, which could be costly to deploy comparing to utilising exiting and/or off-the-shelf power meters. In addition, proprietary management software is often not as flexible as open source applications in terms of integration with existing systems management infrastructure.

What are the correct data and incentives for business policy makers and managers? For the UK, an NCC survey report [7] makes clear some key issues:

- Only 13.4% of organisations monitor power consumption, and there is little knowledge or experience about being green.

[2]EnergyICT `http://www.energyict.com/`

- Legislation, current and proposed, is *not* a major incentive to be green: cost savings are the *overwhelming* incentives.

We take the position that providing a detailed energy-usage measurement infrastructure can benefit ICT systems in the following ways, to propose and prove the concept of a scalable measurement-based energy monitor.

- Direct costs savings: in complex ICT systems with heterogeneous devices, e.g. data centres, system management policies can become adaptive to accurate and timely energy usage information to maximise system energy efficiency.
- Incentivising users: in user facing ICT systems, accurate and timely power usage feedback is more convincing and appealing to end-users in terms of raising energy- awareness and promoting energy saving behaviours.

1.3.2. Getting Users Involved. Some advanced 'green' data centres with cutting edge technologies have already achieved near-optimal power usage effectiveness (PUE, see Equation 1). For example, *Facebook*'s data centre in Prineville, US, claimed a PUE of between 1.06 and 1.1 at full load [18] in 2011, and *PEER 1 Hosting*[3] has also built data centre of PUE 1.1 in Portsmouth, UK, in the same year [20]. As data centre PUE scores approach the optimal level, i.e. 1.0, additional energy efficiency and possible gain of further power saving in data centres becomes marginal and harder to achieve.

$$PUE = \frac{TotalFacilityPower}{ITEquipmentPower} \tag{1}$$

What makes it more difficult to achieve more energy saving in data centres is that since the economic crisis of 2008, US companies have closed thousands of distributed, small, server rooms, and initiated the trend towards data centre consolidation. Globally, small- and mid-sized data centres continue to reduce in number, merging into fewer mega-sized data centres for economical and technical benefits. By 2015, 2% of all

[3] `http://www.peer1hosting.co.uk/`

data centres will occupy 60% of the total data centre floorspace, and account for 71% of all data centre hardware spending [56]. IDC [3] reported that the number of data centres in the US will decrease by over 1 million from 2012 to 2016.

On the other hand, consumer ICT systems continue to grow rapidly all over the world, especially in developing countries with large populations but small Internet penetration rates at the moment. For instance, there were over 1 billion and close to 4 billion population in Africa and Asia by 2012 respectively. The total is more than half of the world's population. However, only 15.6% and 27.5% of which respectively are connected to the internet so far, but already representing 51.8% of the global internet users [24].

Forrester Research [122] and Gartner [57] reported that there were over 1 billion PCs in use worldwide by the end of 2008, and the total will surpass 2 billion by 2010. Gartner predicted [58] that consumer ICT devices, including PCs, tablets and mobile phones, will increase by a total of 2.4 billion units in 2013, reaching over 2.9 billion by 2017. Although most office and domestic ICT devices nowadays are compliant with *Energy Star* standards[4], which consume very little power in standby mode, the aggregated energy waste due to *inefficient usage* is still high. For instance, it is estimated that 2.8 billion USD was wasted in 2009 in the US by ~108 million office PCs left on when not in use [10]. While technical solutions for managing such desktop systems continue to mature, *even modest energy savings from the user would scale up and yield significant impact.*

We make the following assumptions, such that:

- Most users do not naturally attempt to save energy unless direct incentives are given. Therefore there is the potential to reduce users' energy wastage.
- It is possible to motivate users to improve energy efficiency, both through encouraging change in user behaviour, and not just relying on systems-level (hardware and software) interventions.

[4] http://www.energystar.gov/

The objective of the work in this thesis was to find out, without changing users' activities or their physical tools (lab computers in this case):

- If ICT users can change their behaviour in using computers and improve energy efficiency.
- What changes in their use of ICT systems are they willing to make to improve energy efficiency;
- How feedback on energy usage and incentives (rewards) would help them to improve their energy efficiency.

1.4. Thesis structure

The rest of this thesis is organised to 5 chapters, outlined as follows:

Chapter 2 (Literature Review) – discusses existing research and technologies that are relevant to this thesis, including a review of ICT system monitoring technologies that can be used to collect device power usage, a comparison between software-modelling and measurement-based power monitoring techniques, and a discussion on how raw power information could be made meaningful to end-users and help them improve energy efficiency.

Similar studies have been carried out in household and office environments. This thesis attempts to discover if energy feedback can make end-users of public computers more energy efficient.

Chapter 3 (A Flexible Energy Monitoring Infrastructure for ICT Systems) – describes an agent-based flexible system monitoring infrastructure with a focus on collecting power information from heterogeneous devices. Prototypes are presented as proof-of-concept, and were extended to monitor a university computer teaching lab and serve the purpose of the experiment. Design decisions, implementation and performance analysis of the extended power monitor are included in this chapter.

Chapter 4 (Power Reduction During Use of Computers) – presents findings observed from the lab computer users over a two-year experiment. Based on both quantitative and qualitative data, this chapter concludes that real-time on-screen power feedback together with small rewards can change student users' behaviours while using lab computers. Up to 56% individual weekly power reduction and up to 16% weekly group power saving were observed.

Chapter 5 (System-Level Energy Usage and Interventions) – presents system level insights gained from the two-year experiment that are useful to system level interventions and actions. Energy wastage was observed primarily from users' misconfiguration of operating systems, and energy-demanding applications. Without replacing any existing devices in the lab, system administrators could better educate users as well as collaborate with academic staff, therefore help improve energy efficiency inside computer labs.

Chapter 6 (Conclusions and Future Work) – summarises the work done and highlights its novel contributions. Possible improvements to both the scalable energy monitoring infrastructure and the end-user power saving experiment are discussed as future work.

Chapter 2

Literature Review

2.1. Introduction

This chapter reviews existing systems and technologies that are related to this study, and discusses their practicabilities for the research scope. We begin with system monitoring technologies that are required to collect various information from a number of devices over the ICT systems, then move onto solutions of obtaining system power usage, and finally talk about how the collected data could be used to raise users' energy awareness and reduce user-end energy wastage via feedback.

2.2. System Monitoring

In order to effectively improve energy efficiency of either a single device or complex ICT systems, users/policy makers need to be aware of the relationship between detailed system resource usage and power consumption [103], in order to make more informed decisions to improve energy efficiency. Such awareness is achieved via comprehensive system monitoring.

System monitoring tools can be broadly classified as agent- based or agent-less. There is no definitive answer of which one is better. Each type has its own weaknesses and strengths. Use of agent-based or non-agent based systems shall be decided on the requirements and system constraints.

Agent-based monitoring requires running a software service/daemon on each target host. The daemon periodically collects information and sends (pushes) it to a collector, often through computer networks. With appropriate configuration, agent-based monitoring can easily penetrate the entire ICT system across complex network set ups (e.g. different sub-networks) and configurations (e.g. firewalls). In addition, the agents may also listen to pull requests from the collector, and provide on-demand information. It enables users to collect a broad and extensible range of system information, from hardware resource utilisation (e.g. disk utilisation) to software service status (e.g. printing queue). On the other hand, agent-based monitoring has two obvious weaknesses.

Firstly, although the implementation of agent software is normally lightweight in terms of system resource utilisation, it inevitably has operational overheads that may affect the host system, especially machines used for production and critical services. It is risky to deploy an agent-based monitoring system without a careful evaluation process. On the plus side, agent-based monitoring software is mostly open source and free of charge. Some popular options are *Nagios*[1], *Ganglia*[2], *Cacti*[3] and *Munin*[4]. These are the most widely used, reputable tools with long development history and comprehensive features. They can be configured to operate utilising agents or as stand-alone monitoring tools.

Secondly, the cost of deployment is proportional to the scale of the target system and number of devices. i.e. each target host needs at least a copy of the agent software installed and configured, plus the deployment of at least one data collector and/or a central controller. Although this process can be mostly automated in ICT systems that consist of large number of identical (hardware and software set up) target hosts, in reality, the amount of manual work is still considerable given that most ICT systems contain heterogeneous and multiple generations of hardware devices and software

[1] `http://www.nagios.org/`

[2] `http://ganglia.sourceforge.net/`

[3] `http://www.cacti.net/`

[4] `http://munin-monitoring.org/`

platforms. In addition, the work of maintenance must also be taken into account. As upgrades and bug/security fixes are released from time to time, every instance of the agent software needs to be updated to ensure its reliability and capability.

In contrast to agent-based monitoring, agent-less monitoring does not need to deploy any additional software on the target host. Instead, it relies on standard or proprietary APIs of software that are already embedded in the systems to gather information.

As more high-end servers and network devices have remote management capabilities built in, much low level system information, including network throughput statistics, device processor temperature, hardware failure alerts, can be remotely collected via the Simple Network Management Protocol (SNMP) [65] [5] and/or the Intelligent Platform Management Interface (IPMI) [6].

Since Windows 2000, all Windows servers have Windows Management Instrumentation (WMI)[7] built-in by default. It is a proprietary implementation of the Web-Based Enterprise Management (WBEM)[8] and Common Information Model (CIM)[9] standards, which provides an even larger set of metrics than SNMP can offer. Some software service and network status can also be probed in an agent-less manner, for example, web server availability, device connectivity and network latency.

[5] Strictly speaking, SNMP is a server-client system. SNMP manager polls information from SNMP agents via SNMP commands over the network. It is classified as agent-less monitoring for the fact that SNMP agents are already implemented and embedded in various devices. There is no need to deploy additional agent software on the target device as part of the monitoring system, but to utilise existing APIs for data collection. http://tools.ietf.org/html/rfc1157

[6] An autonomous system embedded in the baseboard (motherboard) of high-end servers. It operates independently of the host computer system (CPU, memory or operating system), provides remote management and monitoring capabilities through the network interface of the host computer. http://www.intel.com/design/servers/ipmi/

[7] http://msdn.microsoft.com/en-us/library/aa394582(v=vs.85).aspx

[8] http://www.dmtf.org/standards/wbem

[9] http://www.dmtf.org/standards/cim

Agent-less monitoring does not add overhead to individual target devices, and can be quickly deployed with little administrative overhead. Using APIs provided by hardware management modules also means agent-less monitoring will continue to function even the Operating System fails or the host is powered down to standby mode. Its centralised deployment makes the configuration and maintenance relatively fast and easy.

In terms of general capability, agent-less monitoring is rather limited because it relies on what API or service is already available. At the moment, hardware vendors decide what information and metrics are made accessible via their implementation of remote management APIs. Older generations of hardware or software may not even have built-in remote management APIs. Therefore both breadth and depth of monitoring of complex ICT systems is limited via the agent-less approach.

Nowadays, agent-based monitoring systems tend to include agent-less monitoring mechanisms as well, to support broader range of devices and system configurations. For example, *Nagios* has been primarily implemented to collect data via its agents, but it is now also capable of remotely polling some basic information such as host liveness, SSH server availability, web service status, as well as some advanced information via SNMP. In addition, Nagios and many other monitoring systems also support third party plugins to add support of more varieties of devices. As a result, the main concern is no longer making the choice of a type of monitoring system, but its software architecture, overhead and scalability. In 2003, authors of [54] evaluated the performance and scalability of three monitoring and information services used for large scale production or near-production grid testbeds. Despite minor performance/overhead differences of these three systems, they all have good scalability as a result of similar hierarchical architecture that consists of the following four functional components:

Directory Server: data storage that provides local and remote access to the collected data.

Information Collector: receives data from (Aggregate) Information Server and stores or processes them.

Information Server: the agent that directly gathers information from target devices, then pushes it back to the Information Collector either periodically, and/or upon Information Collector's 'pull' requests are received. Normally the agent runs as a daemon on the target host. In case the agent can not be deployed on the target host due to computational constraints (e.g. a switch with SNMP) or system privilege restrictions (e.g. a public computer), it can also be run on any suitable host to communicate and gather information via remote access APIs of the target host.

Aggregate Information Server: an intermediate Information Collector that collects and reduces the amount of data using pre-defined functions. e.g. summing up or taking the mean value of collected data from a number of underlying data sources (agents) to reduce the volume of data to upload. This is where trade off between information fidelity and transmission costs are made in order to improve monitoring system scalability [37].

In addition to ensuring scalability of monitoring systems, the overhead of data collection and transmission should be kept minimal and not to compromise the performance of target devices. This is particularly important when monitoring low-end, user-facing devices such as laptops. In contrast to data centre and cloud systems, high computing power or high speed network connections can not be assumed in end-user systems. As a result, even though the primary goal of a monitoring system is to effectively collect useful information, trade off between the information fidelity and computational costs must be considered when system resources are limited [85].

To overcome potential data loss due to intermittent network connections of portable computers, additional local buffer mechanism should be implemented to preserve data before they are correctly received by the collector, even it contributes to the overhead by disk I/O.

2.3. Software-Based Power Modelling and Estimation

In the absence of widely deployed power sensors that can report the power usage of any device-of-interest (typically computers), software-based power modelling and profiling tools become the cost-effective alternative solutions. Instead of directly collecting device power usage, a number of utilisation and performance metrics are monitored and used to estimate the actual device power usage.

Rivoire et al. [103] show that power models of computer systems can be built based on collections of hardware resource utilisation metrics, CPU performance counters and real-time system power measurements, where power measurements are obtained from temporarily installed power meters. Once a power model for a device is built, it can then be widely applied to other devices of the same model without the need of physical power meters.

Real-time power modelling is generally accomplished in two ways: detailed analytical power modelling, and high-level black-box modelling. Analytical power models of hardware components can be built based on performance counters, and are highly accurate. For instance, Kadayif et al. [69] successfully built Virtual Energy Counters (vEC), a power model to estimate the energy consumption of user applications on the Sun UltraSPARC hardware platform. It accurately determines application power consumption of CPU and memory with as low as 2.4% error rate. However, analytical modelling relies on detailed knowledge of the hardware components, therefore has limited generality and portability [67, 68]. In reality, ICT systems consist of mixtures of hardware from different manufacture. From single hardware components (e.g. CPU, memory) to whole devices (e.g. workstation) are constantly upgraded and replaced with newer models. Although it is possible to port performance-power models generated on one machine to another in the same family and keep error rate within 5% [100], it is still impractical to effectively build accurate analytical power models for all devices of interest in large ICT systems.

In contrast, the high-level black-box models do not require detailed information of the hardware components, but are less accurate. For example, Contreras and Martonosi built a power estimation model using hardware performance metrics and events as inputs for Intel PXA255 processor and memory; this achieved up to 4% average error rate [38]. In general, the black-box models have been developed for a wide range of processors, workstations, and more complex ICT systems [32, 38]. Rivoire et al. [103] evaluated 6 high-level linear power models and concluded that system resource utilisation metrics do correlate to power consumption. All 4 tested utilisation- based models were superior than the other 2 constant (utilisation-independent) power models. Even simple CPU utilisation-based power models could achieve accuracy of less than 10% error on average. However, these models are CPU dominated and only model partial system power to approximate the whole system power consumption. As power consumption of future computer systems is expected to become less CPU dominated with more effective and aggressive CPU power saving technologies [30], these power models will become less accurate. In addition, if a large component is not directly included in the power model, then the relative accuracy becomes unpredictable. To maintain the accuracy would require more insights and metrics of other system components (e.g. disks) that have dynamic power consumption, which increases the difficulties in building such power models.

At full-system level, Li and John [78] managed to build a performance-counter-based power model for SGI IRIX 5.3[10] in 2003. Together with a few metrics reported by the OS, this model was capable of estimating run-time energy consumption of OS activities and workloads with less than 6% error. However, it was unclear how well this power model could be generalised or ported to other more popular platforms with different performance-counters.

[10]IRIX is a UNIX-based operating system developed by Silicon Graphics, Inc. (SGI) to natively operate on their MIPS workstations and servers. Its development ceased by August 2006 with a final release version 6.5.30.

In 2006, Economou et al. [45] proposed *Mantis* - *"a non-intrusive method for modelling full-system power consumption that can be easily and flexibly used in power research"*. Mantis produces a power model based on one-time power monitoring while a certain set of calibration workloads are run on the target workstation. The calibration workloads stresses each major components (CPU, memory and disk) in the computer to different levels of utilisation, and correlates utilisation metrics to the measured power. Network I/O was excluded as the authors believed the network subsystems do not consume noticeable amount of power. As tested, the resulting full- system power models achieved up to 15% error in predicting average system power. However, this was considered not accurate enough for timely dynamic power management.

Two years later, Lewis et al. [77] took this approach further and demonstrated a comprehensive statistical power model that takes processor, memory, disk, as well as motherboard, internal fans and system ambient temperature into account, thereby produces more accurate real-time prediction of power consumption of long-lasting workloads. Its error rate was less than 4%. On the flip side, this approach requires one mathematical model per server architecture, as well as further calibrations and linear regression analysis. These requirements greatly limit the portability of such model. In addition, this model still did not take networking power into account. This could lead to increased errors in today's new network I/O intensive ICT systems.

To sum up, software-based power modelling and estimation tools can be useful and cost-effective for the specific devices they are built for. It is impractical to build software-based power models for complex ICT systems. Moreover, power models of different subsystems have inconsistent accuracy, which makes it extremely hard to predict the collective reliability when using them to model a larger complex system, e.g. a data-centre consists of different devices. In the next section, we will review and discuss the practicability of direct measurement-based energy monitoring in ICT systems.

2.4. Measurement-Based Energy Monitoring

In contrast to software modelling-based energy estimation that is closely tied up with specific hardware architectures/models, measurement-based energy monitoring uses physical power meters to directly obtain timely and more accurate power measurements. The advantages and disadvantages of this approach are justified as the follows.

For devices that do not have built-in power meters, it will be costly to invest in and deploy power meter for each individual device, especially in large-scale complex systems. At least for now, there is no way to estimate how much saving from reduced energy usage can be made by enabling energy monitoring at such costs. Therefore, it does not seem sensible either financially or practically to adopt measurement-based energy monitoring in ICT systems.

Having said that, this situation will soon be over. Energy awareness and efficiency have become an important consideration globally not only to hardware manufacture, but also to end-users and system administrators; and the cost of manufacturing integrated power sensors continues to decrease. A general trend we could foresee is that more and more devices will have built-in power meters by default. This is the key enabler for energy-aware computing. The increased use of power sensors is similar to the process of how thermometers became standard components integrated in various ICT devices. Temperatures of wide range of components including CPU, GPU, memory, motherboard, hard disk drive (HDD), power supply, battery, etc. are continuously monitored to better coordinate workloads and cooling demands in an automatic manner, in order to prevent overheating while maximising the hardware and software performance [59, 72, 82, 89, 121].

Regarding the power meter – device power is either measured internally using integrated power sensors, or externally through separate power meters ranging from high-end smart power distribution units (PDUs) in data centres, to low-end off-the-shelf meters for domestic use. In most cases, measured power is more accurate than mathematically derived 'measurements' using power models, and the accuracy is not affected by hardware changes. The standard off-the-shelf plug-in power meters offer ±3% error with 0.1 Watt precision [11], while high-end PDUs normally offer ±1% error with 0.1 Watt precision (e.g. *Raritan Dominion PX-5367*[12]).

Ideally, all devices-of-interest in ICT systems will have capable power sensors integrated, so that no external power metre is needed. For now, external power meters are still required to cover those non-energy-aware equipments, e.g. printers, cooling and lighting systems, in order to help users or administrators gain a detailed view of system energy consumption. Depending on the capabilities of power meters, measurements are retrieved in different ways:

- For typical low-end power meters such as *CurrentCost Envi CC128* (see Appendix B) that was used in this thesis as a proof-of-concept, there is no computational capability but a Serial-USB interface that outputs real-time power and temperature measurements as plain texts. The collector of the power monitoring system either has to be physically connected to CC128 to read in measurements, or a power monitoring agent is required to collect the data from a computer that is connected to CC128, and then push them to the collector through the network. Although having a dedicated computer just to host the power monitoring agent for data collection seems complicated and troublesome, it actually can be achieved with little spending and effort with cheap and low power 'mini computers' such as Raspberry Pi[13] and Linksys NSLU2[14]. They are capable of hosting Linux OS and therefore power monitoring agents. Each mini computer only consumes a few Watts of power, and can communicate with a number of power meters nearby via USB interface (hub). The amortised cost per power meter and monitored device becomes relatively small.

[11] http://www.electricity-monitor.com/plug-power-meter-p-36.html

[12] http://web1.raritan.adxstudio.com/px-5000/px-5367/tech-specs/

[13] http://www.raspberrypi.org

[14] http://www.nslu2-linux.org/

- High-end power meters such as PDUs as mentioned before, normally have a built-in network interface for remote management. For instance, the PDU we used in this thesis as a proof-of-concept was Raritan Dominion PX-5367. It provides an Ethernet port as well as a serial port for communications. Power measurements of individual outlets can be directly collected through the network using SNMP.

- Computers' built-in power sensors are normally accessible locally via standard APIs. The Advanced Configuration & Power Interface (ACPI) [15] created by Hewlett-Packard, Intel, Microsoft, Phoenix, and Toshiba, is widely supported by user-facing computing systems, e.g. laptops and desktops. It provides power usage reporting and some power management functions. IPMI, as mentioned before, is commonly available in high-end computing systems. It provides similar power reporting to ACPI, but with more advanced management capabilities. An existing issue is that although computer manufacture expose power information through standard interfaces, they only partially implement these power management capabilities. Portable devices are constrained by battery power, therefore have more sensor coverage of its power usage, including current and voltage measurements. Stationary devices tend to have limited built-in power sensors since they draw unlimited power from the mains. It is expected that in the near future, a minimal collection of power reporting and management capabilities can be assumed in any modern computers to support energy-aware computing. Compared to the majority of computer manufacture, Apple has been the pioneer in integrating an extensive range of power sensors into all of its Macintosh computers since 2007[16], if not earlier. Real-time power measurements of a number of core components including CPU, GPU, north bridge, data bus and total machine power are

[15] http://www.acpi.info/

[16] Assumption based on an Apple's internal software tool version number 0.01 that was leaked to the public which allows access to all Macintosh computers' built-in sensors. e.g. fan speed, components temperatures, currents, voltages. More on this tool in Chapter 5

accessible via Apple's proprietary API (more on Apple's built-in power measurements in Chapter 5).

2.5. Improving Energy Efficiency with Feedback

"*If you can not measure it, you can not improve it*" – Lord Kelvin

We have discussed techniques and technologies that can help measure and collect power usage per device or subcomponent in ICT systems. In this section, a number of ways of how energy measurements could help raise ICT users' energy awareness and improve energy efficiency are reviews.

Overall, people are increasingly willing to be conscious of their energy usage. Some may wish to consider their energy usage as part of their overall carbon footprint for environmental reasons; others may wish to understand about the costs incurred by their energy usage, especially if they could save money by using less energy. However, studies [71] have shown that people do not always translate their good intentions into actions. There are social, cognitive and behavioural factors explaining why many people have not yet introduced changes to help reduce energy consumption. For instance, there are some cost effective techniques available to improve energy efficiency, but people are yet to adapt them. As a result, there is the demand for an understanding of what people already know/understand and why they do not act.

In 2011, the UK Cabinet Office Behavioural Insights Team [17] presented three of the most significant insights from behavioural economics and psychology grounded by academic evidence:

Discounting the future: People may prefer a small discount or reward today rather than a larger reward in the future [84] – this is the reason why people do not always pay now to get more saving in the future.

Social norms: Behavioural studies have shown that people are heavily influenced by what others around them are doing.

Defaults: Behavioural economics tells us that individuals tend to go with the default options/settings, often regardless of whether it maximises individual or collective well-being.

Fogg's human behaviour model [52] suggests three crucial factors that are required to change human behaviours: *sufficient motivation*, *sufficient ability* and an *effective trigger*. In domestic environments, reducing energy costs naturally becomes a strong motivation; and people have sufficient control over household electric appliances. Some form of *feedback* is the key trigger that helps realise energy saving behaviours.

Use of *indirect energy feedback* in household environments, e.g. frequent billing showing historical usage and a detailed listing of energy consumption, has been proven effective in promoting energy awareness and energy saving behaviours by a Norwegian power supplier in 1999 [119]. A similar technique is Demand Side Reduction, or Demand Side Management (DSM). It is primarily used in the electric power industry to reduce consumers' demand for energy during peak hours [29]. By offering financial incentives (i.e. reduced prices) and educating consumers to shift the power demanding jobs to off-peak periods such as night time, domestic energy usage during peak hours is effectively reduced as desired. This has demonstrated that reduction in energy usage can be achieved by *changing user behaviours*, rather than solely focusing on improving the energy efficiency of electric appliances.

On the other hand, psychologists, power providers and the UK government have conducted experiments and determined *direct power feedback* via small desktop displays was useful for energy savings in household environments [28, 41]. In-home displays show real-time and/or historical energy usage, as well as the estimated costs, enabling consumers to monitor and control their energy usage. The results showed that by making consumers more conscious of their day to day energy consumption, such displays can help change behaviour and promote long term energy saving habits. National and international experience suggests that such feedback leads to between 5 and 15 per cent energy savings in households over the long term [39].

Faruqui et al. [50] reviewed 12 pilot programs on the effects of In-Home Displays (IHDs) and also concluded that direct feedback through IHDs encourages people to reduce energy waste and improve efficiency. An average of about 7% energy saving can be achieved by those who actively make use of IHDs and get billed for their electricity usage afterwards; and the average saving was doubled when IHDs were combined with prepayments of electricity. It indicated that people tend to forget about long term savings or costs which is not normally visible in daily lives. On the other hand, financial incentives do work well in terms of promoting energy saving behaviours if they are easily accessible. e.g. a display of decreasing balance.

According to Darby's research [40], 21 out of 38 feedback studies that took place over 25 years indicated direct feedback lead to energy savings. 11 out of the 21 studies observed 10-20% energy savings; and the average energy saving across all studies was 6.5%. Darby considered direct feedback the single most effective information in promoting energy saving behaviours and increased awareness. She recommended that each household should have its own metre display that is accessible, attractive and clear. On the other hand, she also pointed out that "*feedback is a necessary but not always a sufficient condition for savings and awareness*".

It has been observed in both domestic and office environments, that users have strong impact on energy demand and usage [80,114]. Through surveys, people expressed that real-time and historical data of their energy use helped them to reflect on the impacts of their activities on energy consumption and possible wastage [114]. However, raw data without annotations provide little useful information to non-expert users; and finely annotated data may pose privacy concerns [114] or even threats to security, which lead to resistance towards energy saving by feedback. It is therefore important to balance between detailed usage monitoring and protection of user privacy.

Previous studies have generally focussed on domestic energy consumption and savings. The use of ICT devices, especially in institutions (e.g. offices) poses more challenges than in a domestic context. Energy wastage is common when people are using non-personal devices and equipments. Most users in offices, computer labs and other public environments do not pay directly for their use of energy; hence there is lack of financial incentive for them to conserve energy. Some may think of energy saving, but lack of feedback on individuals' energy usage and little information on the impacts of different user actions could make almost eliminates possibilities of saving energy.

Indeed, there are existing software tools for hardware manufacture and software developers with expertise knowledge, to inspect and improve the energy efficiency of their products. Two commonly known utilities are *PowerTop*[17] and *PowerCfg* [16].

PowerTop is implemented for the Unix/Linux OS family. It monitors CPU time/interrupts, hardware components status and system level raw power measurements via ACPI. Estimated per application power profiles are then produced, together with a number of system level power saving 'tunables', for example, OS power management policies and peripheral power saving settings. Unfortunately, PowerTop only produces power profiles on devices that are capable of reporting sufficient power measurements (e.g. most laptops). It offers limited information on desktops.

PowerCfg is a utility for evaluating system energy efficiency for the Windows operating systems and works in similar ways to PowerTop. It detects potential energy efficiency problems with both hardware and software configurations, and diagnoses application level performance issues. On laptops, it also incorporates battery charge/discharge/capacity information via ACPI, but no power information on desktops otherwise.

In 2013, after this study was completed, Apple shipped *Mac OS Mavericks* (version 10.9) with its proprietary *Energy Impact* [26] metric available in the system *Activity Monitor* application (see Figure 2.1 for a screenshot). Up to now, it is still unclear how Energy Impact ratings are produced. People have seen ratings ranging from 0.0

[17] https://01.org/powertop

up to nearly 1000. All interpretation is limited to Apple's one-line explanation: "*The lower the Energy Impact number, the less power the process is currently using*" [26]. However, this is a good indication that there is increasing interest in giving energy feedback to users, and users are interested in these ratings.

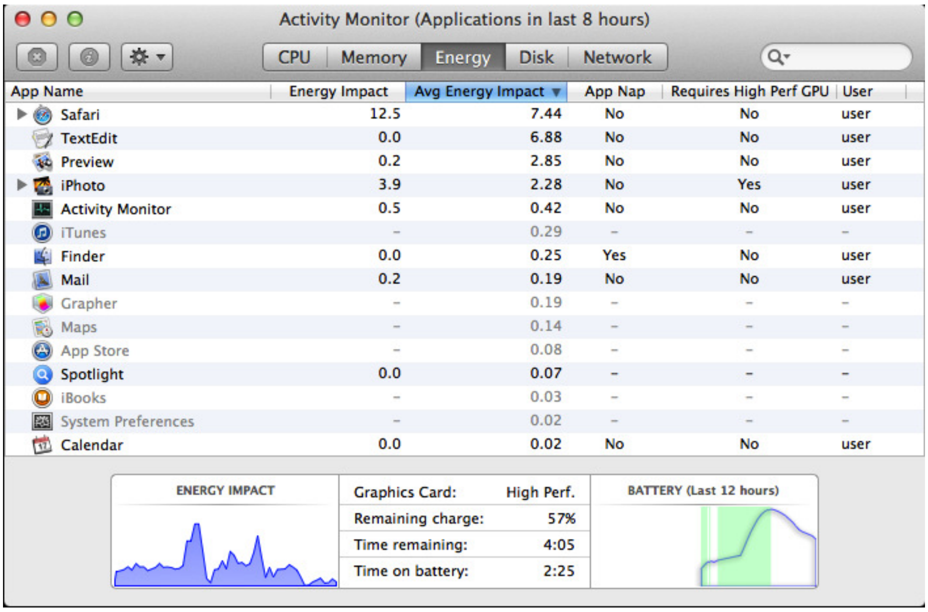

Figure 2.1. Screenshot of *Energy Impact* metric in *Activity Monitor* application of *Mac OS Mavericks*. (Image taken from Apple knowledge base [26])

Although these tools have limited capabilities and user group, they have demonstrated promising potential for improving system and application level energy efficiency with system level power measurements alone. In more recent years, researchers have successfully developed general techniques for energy efficient software implementation and usage, verified with system level power measurements. For instance, Sabharwal et al. [106] pointed out that 8-threaded applications use approximately 25% less energy than single-threaded applications for the same tasks. Ejembi et al. [46] discovered that up to a factor of 3 in energy saving for video playback could be achieved by using more energy efficient codecs with the same resolution and bit rate settings.

2.6. User-End System Usage and Power Metrics

Users are familiar with the use of benchmarks in order to assess the performance of equipment. Suitable power benchmarks or metrics are required to determine and compare energy efficiency between different system hardware or configurations. Depending on the capability of the power meters in use and controls over the workload, energy efficiency benchmarks can be created from component level, workstation level, up to complex data centre level. For instance, to specifically power-benchmark a network interface card if its power can be accurately measured, and some controlled workload (i.e. network traffic) can be transmitted or received through this component.

Rivoire et al. [105] and Poess et al. [98] have reviewed a wide range of recognised power benchmarks used in the ICT industry, but the majority of them target at enterprise level ICT systems and are used by hardware manufacture. Out of limited few benchmarks targeting component and workstation level energy-efficiency, none of them is appropriate for the scope of this study (i.e. end-user workstations) as described below:

Energy Star[18]: an international standard for energy efficient consumer products ranging from personal computers to household appliances such as lighting and air conditioning systems. For personal computing devices including desktops, laptops and game consoles, power consumption of their sleep, idle and standby *modes* are evaluated. An Energy Star certificate is issued if the whole device's power consumption are below specified thresholds in different modes. For instance, an Energy Star certified device should consumes no more than 0.5 Watt power in standby mode and its power supply efficiency is expected to exceed 80%. Overall, Energy Star is not a fine-grained standard, designed to be understandable to average users with minimal knowledge of power efficiency. A device is either Energy Star certified or not, regardless how is it used by the user. While it does not provide computer utilisation related energy usage as required for this study;

it may even mislead users to carelessly overuse the devices because they are 'green enough', therefore wasting energy.

EnergyBench[19]: one of Embedded Microprocessor Benchmark Consortium (EEMBC)[20] benchmarks that works with other benchmarks. It provides additional information on the amount of energy an embedded processor consumes for executing an EEMBC performance benchmarks, i.e. *performance per Joule*. While it does provide insights of processor level utilisation and power consumption, the metrics used are not understandable to average computer users, and can not be easily linked to common computer operations. After all, its primary use is to help hardware designer make performance-energy trade-off at component level to meet system level power budgets, e.g. under clocking mobile phone CPU to a low power state just sufficient for common tasks.

SPECpower_ssj2008[21]: one of the benchmarks developed by the Standard Performance Evaluation Corporation (SPEC)[22]. It assesses system level power usage using approved power metering hardware while generates controlled workload with a suite of Java programmes on the target system [19]. SPECpower_ssj2008 is primarily developed for benchmarking small number of sampled servers, that are expected to have high CPU utilisation and strict ambient environment requirements, including temperature, humidity, altitude and air flow. Its controlled workloads are CPU-intensive, and the range of approved power/temperature meters are strictly limited to high-end options that are usually used for scientific research and development. As a result, SPECpower_ssj2008 can not be easily ported to user-end workstations, that have significantly different use cases, environmental conditions and limited power metering capabilities.

[20]EEMBC is a non-profit organisation. It develops performance benchmarks targeting wide range of hardware and software used in embedded systems, including automotive, digital media, Java, multicore processors, networking, signal processing, portable devices and browsers. http://www.eembc.org/

[22]http://www.spec.org/

JouleSort: a simple and balanced benchmark originally prosed in 2007 by Rivoire ec al. [104]. Its workloads (normally 10G, 100G or 1T records to sort) utilise all core system components, therefore evaluates full-system energy efficiency trade-off of computing nodes ranging from portable smart phones to high-end servers. JouleSort uses three metrics: (1) number of records sorted within a fixed energy budget; (2) number of records sorted and energy consumed within a fixed time budget; (3) amount of energy consumed for sorting a fixed workload size. Results from all three metrics can be expressed in JouleSort scores, i.e. records sorted per Joule (records/J). Although JouleSort is simple enough to be applied to user-end devices and understood by average users without expertise knowledge, its workload or scores do not have direct connection to users' common daily activities such as browsing web pages. It is helpful in terms of helping users find out which devices of theirs are more energy efficient given the same workload, rather than what behaviours/operations are more energy efficient given the same device.

It is not surprising that we could not find a suitable power metric for user-facing devices and end-users – the existing energy benchmarks and power metrics are designed by and for professionals in the industry and academia. The benchmarking scores and metrics are expected to be used by people with expertise knowledge or directly by automated computer programmes. What we need in this study are simple and measurable indicators, applicable to individual user's daily computer operations. Based on experiences from other studies and existing computer power models, we chose to test the following user-friendly metrics as part of the determining factors of their system power usage. Changes of user behaviours were observed using these simple metrics as measures, described in Section 4.3.5 and 4.4.1.

- Screen brightness – measured in level 0 to 100 on the iMacs used for this study. Screen brightness to power conversions used in this study are described in Section 3.7.3.

- Applications – use of applications for the same tasks, identified by application names. Comparisons of application power usage are presented in Section 5.2.6 to 5.2.10.

- User processes – given the ethical constraints on data collection, only total user process counts were obtained instead of the intended actual *unused background* user process counts. The relationship between total user process counts and system power usage were discussed in Section 5.2.4.

These metrics are deliberately chosen to be *coarse* and *indicative* to allow *self-comparison*, because: (1) human users are not machines; personal needs and preferences should be respected and not to be judged. e.g. it is not bad or wrong to prefer a brighter screen over a dimmed one. (2) users do not normally have precisely controlled, identical workloads. Therefore measured power efficiencies of users are not expected to be directly comparable across the user group.

2.7. Summary

This chapter takes a bottom-up approach, starting with a discussion of low level system monitoring techniques for data collection in Section 2.2, as the foundation of the power monitoring infrastructure described in Chapter 3. We then discussed the practicabilities of power monitoring using software- modelling and measurement-based technologies, in favour of the latter for its accuracy and promising availability in the near future. Section 3.3 presents a number of prototypes as proof-of-concept, utilising power measurement technologies and techniques mentioned in Section 2.4. Lastly, we reviewed successful cases of how energy feedback could be used to help reduce energy consumption in households, that justifies the attempt in this thesis to test similar methodology described in Chapters 4 and 5.

Chapter 3

A Flexible Energy Monitoring Infrastructure for ICT Systems

3.1. Requirements

We propose that it is beneficial to enable detailed energy measurement within ICT systems. We chose to pose the following questions in order to help us in determining and justifying our requirements:

(1) How can we gather sufficient energy information on a system-wide basis, at scale, including heterogeneous devices and infrastructure within an ICT systems such as a datacentre?

(2) What metrics and Key Performance Indicators (KPIs) are suitable for use in system management policies and Service Layer Agreements (SLAs)?

(3) What effects are there on system operations and performance when energy information is included into system management policies?

(4) How can we provide feedback to system administrators and end-users in order that they can have confidence in the operations of management polices and SLAs that incorporate energy-usage measurements?

This chapter addresses the first issue, and provides some discussions of the other issues. Rather than take a top-down approach (e.g. as in [111]) or a tightly-coupled approach (e.g. as in [62]), we choose to take a very practical, loosely-coupled, bottom-up approach to our provision of energy usage measurement. This will allow maximal flexibility for enabling energy measurement in existing heterogeneous systems, as well as new systems. We are developing an architecture through an iterative refinement process, informed by the development of a prototype in parallel. For this prototype, we concentrated on six issues in two groups, which would be important for a widely applicable monitoring and management system. Firstly, as a simple set of guiding principles:

- *Legacy*: some legacy equipment may not have native power monitoring capability so we need to be able to integrate external devices and sensors for energy measurement, e.g. adopting off-the-shelf consumer power meters and/or high-end intelligent power distribution units (PDUs) with some from of communication capabilities.

- *Vendor-independence*: for new equipment, established vendors currently use proprietary energy-saving features, so we need a generic, vendor-independent information model as well as standardised API for centralised energy management.

- *Scale*: as there may be potentially many different systems, sub-systems and components to manage, including support infrastructure (such as cooling systems), we need to have an energy measurement system that can scale to large numbers of monitored units. Not only keeping the performance of data collection up, but also keeping the aggregated overhead in terms of processing power, network traffic and energy usage down.

From a technical and pragmatic view-point, our work so far has considered the following issues:

- *Identity*: we need to identify resources in a systematic manner, so that energy usage can be linked to specific systems, sub-systems or components. There are several possible systems that could be used for naming in this context, e.g. SNMP/ASN.1[1] object identifiers (OIDs) or Universally Unique Identifiers (UUIDs) [75].

- *Heterogeneity*: different sensors already exist and need to be incorporated into the measurement system. Local installations may have local communication constraints that must be overcome to permit energy measurements to be made visible beyond a device or sensor.

- *Integration*: rather than insist that existing systems management practices be completely re-oriented towards energy usage, we require that energy information should be integrated into existing management and monitoring systems (e.g. Ganglia, Nagios and SNMP systems). Creating completely new and separate architecture for energy management would raise barriers to integration of energy information into existing systems management capability, and so inhibit systems energy awareness.

With these issues in mind, we describe the functionality and design of our current architecture and prototype for energy measurement for ICT systems.

3.2. Architecture

The design of our *Flexible Energy Monitor (FEM)* was refined with direct experience from our prototype (Section 3.3). We present them separately in order to describe the main philosophy of our intent, especially with respect to the principles of Legacy, Heterogeneity and Scale described in Section 3.1.

We define FEM with three functional components: the *Agent*, the *Collector*, and the *Relay*. The Agent and Collector process and/or transform energy-related information; the Relay assists with communication functions. Figure 3.1 describes an example instance of the architecture. The *Agent* hides the current heterogeneity of the raw energy information measured from the *real resource (RR)* (i.e. device, computer, etc).

[1] http://www.asn1.org/

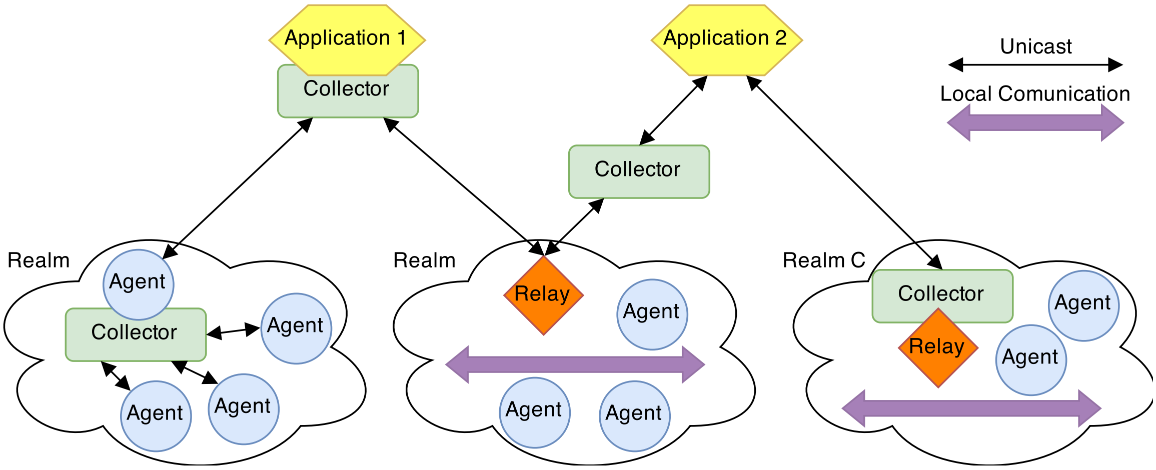

Figure 3.1. An example of the architecture showing different scenarios and also the use of co-located functions to form hybrid units (shown as overlapping units). Agents communicate with predefined Collectors via unicast. Collectors store collected data and (optionally) make it accessible by Applications via unicast. In case unicast is unavailable between Agents and Collectors, Relays are deployed to hide the heterogeneity in communication. Agent/Collector, Relay/Collector and Application/Collector are hybrid units of two components deployed on the same host, i.e. no network required for data exchange between them.

An Agent provides the energy usage information from the RR, and allows energy-related control actions from the Collector (ultimately from an Application) to be applied to the RR. The Agent could be embedded into the RR, but could also be loosely-coupled, e.g. a daemon on a computer which connects to the RR device or energy sensor via a serial line. Agents are organised in *Realms*, which are conveniently-defined (administrative or technical) domains that are organised within the context of the system being monitored.

The *Agent* identifies the RRs for which it provides energy information. Note that the energy usage information presented could be a single value for a single device, but could also be aggregated or summarised. For example, in Figure 3.1, for Realm A, there are three single Agents, and a hybrid *Agent/Collector*. The single Agents could be embedded each onto a blade or line-card in a chassis, and the Agent in the hybrid unit represents the energy usage of the whole chassis. Agents may poll the RR and cache energy information (with a local time-stamp), or may fetch the information on demand, as queries arrive from a Controller. An Agent cache is recommended in case a Collector is not present or inactive, but is not required.

The *Collector* function has three roles: (i) to collect energy usage information from Agents; (ii) to control and configure Agents; and (iii) to pass on to the Agent energy-related actions to invoke upon the RR. A Collector will cache information received from Agents. Control and configuration actions on Agents include: start/stop polling the RR; change polling intervals; and send power management *actions* to the RR, e.g. go to standby, sleep, power down, etc.

The *Relay* hides the heterogeneity in communication and offers scaling benefits for communication. It is used to provide a gateway facility for communications because, for example; the Agent(s) are in a Realm such as a private network, where direct communication to the Collector is not permitted; or, the Agent(s) are in a Realm which uses an underlying technology that does not support the Internet Protocol. The Relay is expected to be deployed on a node that is able to communicate with both Agents and the Collector directly. (We expect Agents and Relays will be defined by end users or developers as required for different equipment and infrastructure.)

These functional components may be combined to form hybrid components, permitting scaling for the information model and for communication. For example, an *Agent/Collector* hybrid in Figure 3.1, Realm A, collects energy information from several Agents, aggregates or summarises the collected data, and provides access to a higher level Collector via a single Agent: this Agent would have a higher level abstraction, e.g. energy usage for a whole room or a whole department. In Figure 3.1 Realm C, a *Collector/Relay* hybrid collects energy information from a number of Agents using a local communication mechanism, e.g. a collection of serial links.

3.3. Prototype

For our prototype instantiation of the architecture (see Figure 3.2), our goal was to show a proof-of-concept. We have chosen to use UUIDs [75] for identification, e.g.

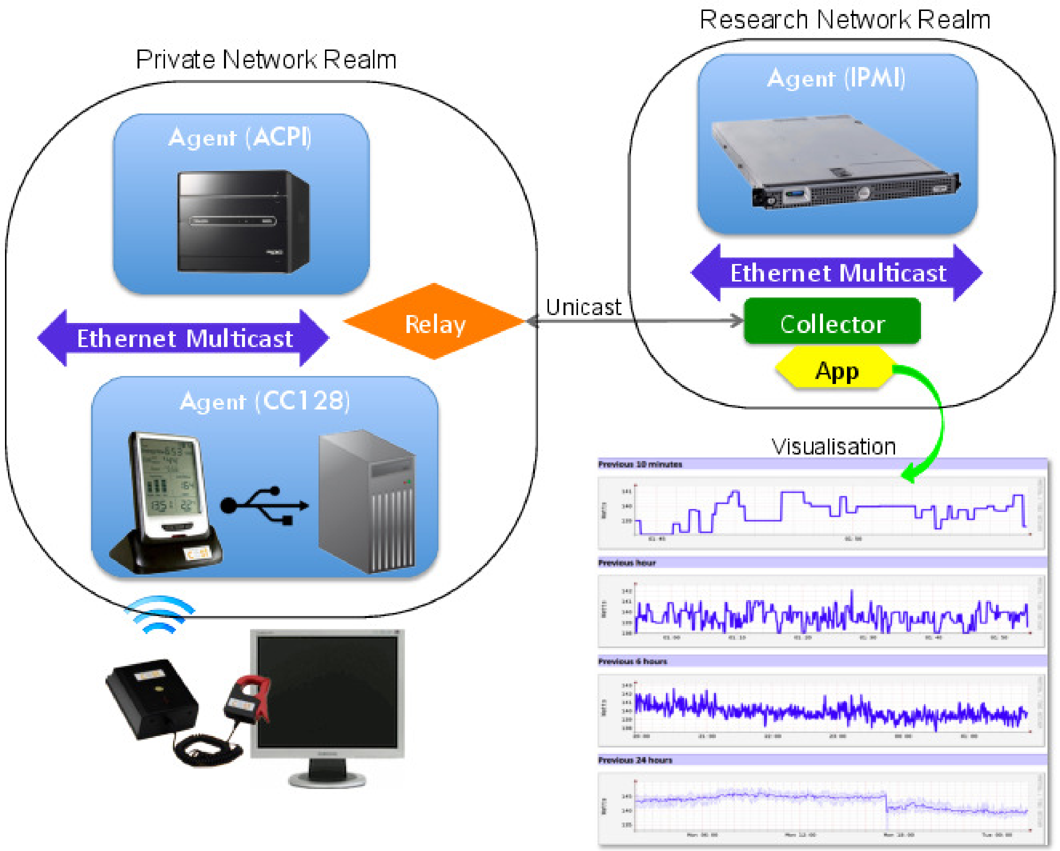

Figure 3.2. Prototype Agents implemented to work with Envi CC128 power meter, IPMI, and ACPI; monitoring three different devices (desktop PC, monitor and rack-mount server) in two networks.

Agent ID (AID) and Relay ID (RID), as they are unique, platform-independent, and can be mapped to both OIDs and Uniform Resource Names (URNs)[2]. The UUIDs are currently used in a simple message forwarding system through their inclusion in data and control messages. We have implemented three different types of Agents. Each Agent has a cache, and prefetches and caches information from the RR using a controllable polling interval. Our Agents run on separate computers and gather energy information from different hardware interfaces:

- *Envi CC128*: This consumer device provides access to readings from multiple power sensors (passive monitoring only), which it can identify individually[3].

[2]We choose specifically *not* to overload IP addresses, so that we can integrate non-IP environments.

[3]http://www.currentcost.com/product-cc128.html

It uses a proprietary radio protocol to communicate with the power sensors and connects to a computer using USB.

- *ACPI*: The Advanced Configuration & Power Interface (ACPI), created by Hewlett-Packard, Intel, Microsoft, Phoenix, and Toshiba, is widely supported by user-facing computing systems, e.g. laptops, and desktops. It allows power usage reporting and some power management functions.
- *IPMI*: With similar but more advanced functionality than ACPI, the Intelligent Platform Management Interface (IPMI) is widely supported by high-end computing systems, e.g. servers.

Since our Agent instances are in an experimental private LAN and do not have direct access to an external network, a Relay is deployed as a gateway. As it forwards messages between the Agents and the Collector, a Relay has its RID added to or removed from the ID list within relevant messages automatically (see Section 3.3.2). The RID(s) within a message are (i) used by the Collector to group Agents; and (ii) used by the Relay to filter control messages sent to the Agents for which it acts, i.e. to discard irrelevant control messages. In our prototype case, IP multicast is used to allow efficient, lightweight, local communication with the Agents.

The Collector receives energy-usage information from all Agents and caches them in a local database. The user is able to (re-)configure the polling interval of a chosen Agent by specifying the AID, through the Collector.

We chose for our Application a simple graphing tool for easy web access. Sample screenshots are shown in Figure 3.3 to 3.5. The Application simply accesses the Collector's database and plots the numerical information using an openly available graphing utility, *RRDtool*[4]. Indeed, the information could be used in many ways, e.g. it could be an application that uploads energy information to *Pachube*[5] or *Google PowerMeter*[6], or a back-end to an SNMP system, or an information feed to a cloud

[4] `http://oss.oetiker.ch/rrdtool`

[5] `http://www.pachube.com`

[6] `http://www.google.org/powermeter`

platform management system such as Eucalyptus [91], or some proprietary decision management function.

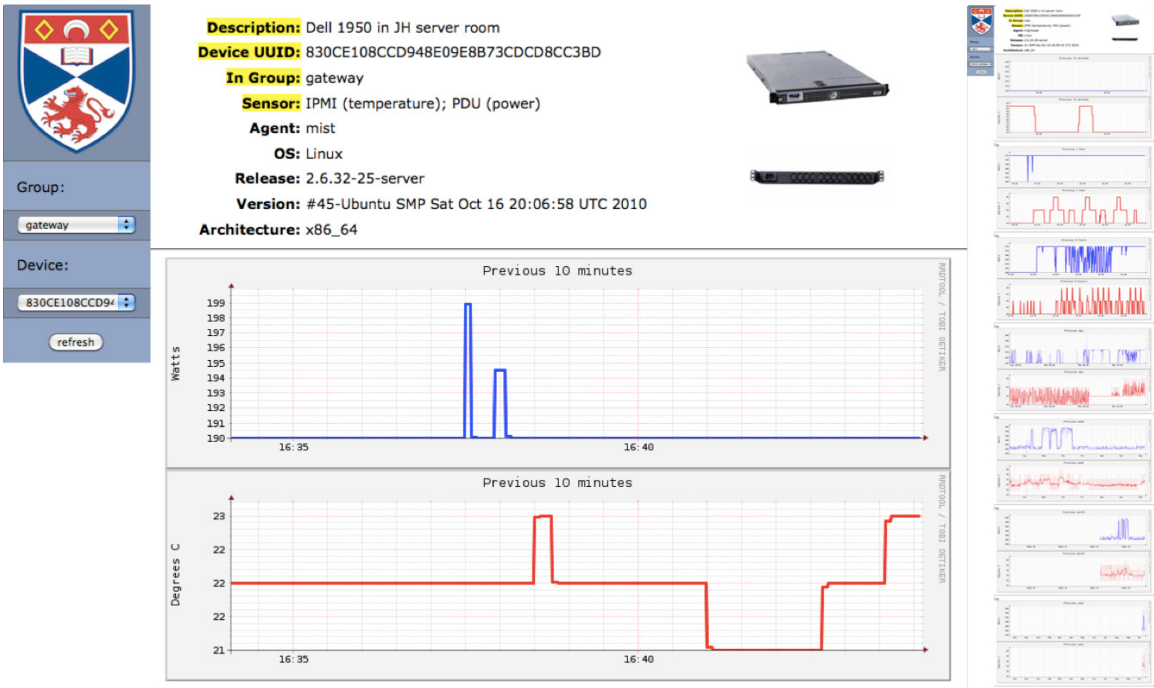

Figure 3.3. Sample web access to power (blue line) and ambient temperature (red line) measurements of Dell 1950 rack-mount server in server room. Aggregated data for different periods from previous 10 minutes, hour up to previous month are plotted as the thumbnail image of the complete web page on the right shows.

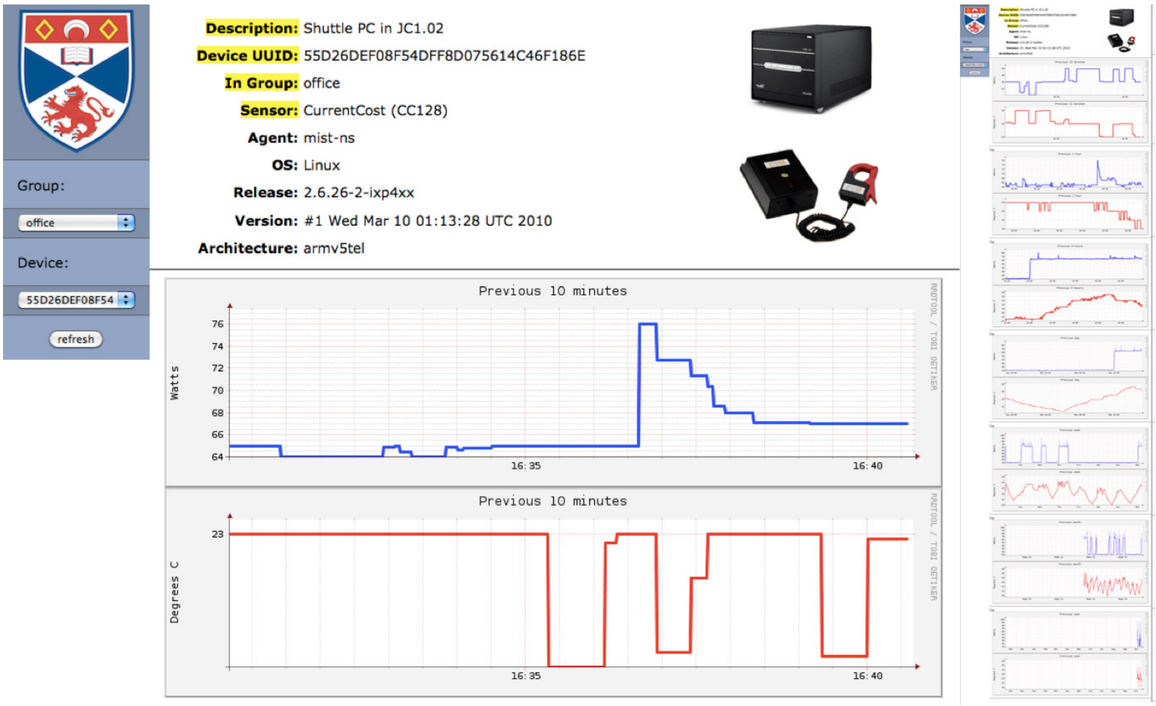

Figure 3.4. Sample web access to power (blue line) and ambient temperature (red line) measurements of a Shuttle PC in the office. Aggregated data for different periods from previous 10 minutes, hour up to previous month are plotted as the thumbnail image of the complete web page on the right shows.

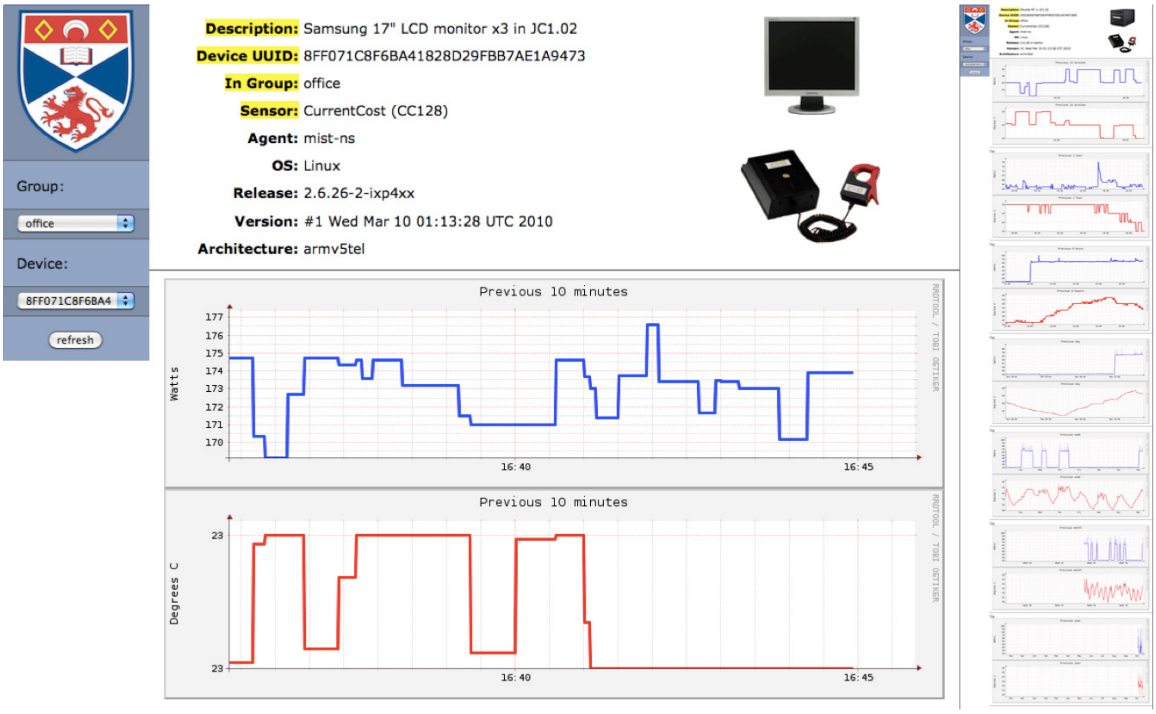

Figure 3.5. Sample web access to power (blue line) and ambient temperature (red line) measurements of a Samsung LCD monitor in the office. Aggregated data for different periods from previous 10 minutes, hour up to previous month are plotted as the thumbnail image of the complete web page on the right shows.

3.3.1. Energy Management Protocol. We define an *Energy Management Protocol (EMP)*, which allows the querying and retrieval of energy-usage information, as well as remote power management. Currently, for ease, the EMP is defined as a set of XML messages, lending itself to easy integration and interpretation within other applications (WWW applications as well as existing management applications). We can, of course, easily transform the XML messages (e.g. using XML schema-based transforms or stylesheets), or replace XML messages with a more compact format when we consider the design and architecture to be reasonably mature.

We use the following pseudocode to define two types of EMP messages:

```
begin EMP_message
    Type = 'control'|'data'
    Source = <UUID>
    Destination = <UUID>
```

```
    if Type == 'control' then
        # expect 1..* RPC messages
        begin RPC message
            Method = <method name>
            Param = <parameter(s)>
        end RPC message
    elseif Type == 'data' then
        begin Metadata
            Device = <device type>
            Sensor = <sensor type>
            Description = <optional descriptions of software platform, etc.>
        end Metadata
        # expect 1..* energy records
        begin Energy Record
            Timestamp = <local timestamp>
            Power = <power reading>
            Frequency = <current polling frequency>
            Top = <optional information of local top energy consumers> # to be decided
        end Energy Record
    endif
end EMP_message
```

(i) *control* messages, sent from Collectors to Agents; (ii) *data* messages, sent from Agents to Collectors.

A *control* message could carry more than one remote procedure calls (RPCs) targeting (i) a specific Agent by AID; or (ii) all Agents by a universal broadcast ID; or (iii) a specific cluster of Agents, for example by RID.

A *data* message includes an AID, *Device Metadata*, and a number of energy records. *Device Metadata* is (i) the type of device – computer, lighting, air conditioner (or *cluster* – meaning the record is aggregated from a group of devices); (ii) sensor type – IPMI, ACPI, consumer power meter, etc; and (iii) some optional description of the device. The *Energy Record* includes (i) a local timestamp; (ii) the actual power reading; (iii) the current polling frequency/interval; and (iv) additional information such as top *N* energy consumers. Depending on the actual type of the Agent and its underlying RRs, this latter information could be: process IDs or names of interfaces of the highest power consuming processes/devices on a computer; AIDs of the highest power consuming devices within a cluster; or, for the example of a larger-scale system with a hierarchy of Agents (hybrid units), the highest power consuming departments within a university.

For hierarchical energy monitoring using Agent/Collector hybrids (A/C), we expect each A/C hides its underlying Agents' metadata from the Collector at the next level (i.e. 'above') by default, but is able to provide information about individual energy consumers (Agents) upon request.

3.3.2. Minimising Manual Configuration. Considering the possibilities of large-scale Agent deployments, we intend to minimise the required manual configuration. For our prototype, we have chosen to use separate multicast IP addresses for upstream communication (Agent to Collector, via zero or more Relays) and downstream communication (Collector to Agent, via zero or more Relays). We have arranged that the Agents, Relays and Collectors can easily discover the relevant communication configuration from a multicast signalling channel. Some manual configuration will be required with suitable information regarding Realms, and of course any device-, sensor- or RR-specific information. However, the intention is that the system is self-organised.

3.4. Applications and Discussion

3.4.1. Improving Datacentre Management and Energy-Efficiency. Conventional datacentre management consists of dynamic voltage and frequency scaling (DVFS), sleep (on/off) scheduling, virtual machine (VM) management, and cooling management, in order to maintain a stable, yet highly utilised system [83]. However, even with very little workload, such as 10% CPU utilisation, any of today's high-availability rack-mount servers would consume more than 50% of their peak power consumption [35]. We are working on a system model for individual devices that is summarised in Figure 3.6: in our view, the energy consumption and system workload have a relationship that is partly near-linear, partly near-exponential, and partly workload-independent. When a computer is carrying out its optimal workload (at the point marked $x\%$), any small addition of workload could lead to dramatic increase in power consumption, thus raising operational expenditure (OPEX) non-proportionally. We are currently investigating the efficacy of this model based on experiments using deterministic, synthetic workloads. We would like to integrate power-awareness (including energy-usage of infrastructure such as cooling) provided by FEM into current system management policies, and observe the performance of various policies. Ultimately, our aim is (i) to allow system administrators to find the most reliable, yet economical system management policies for their own specific ICT systems; and (ii) to integrate power usage into user SLAs and raise users' energy awareness.

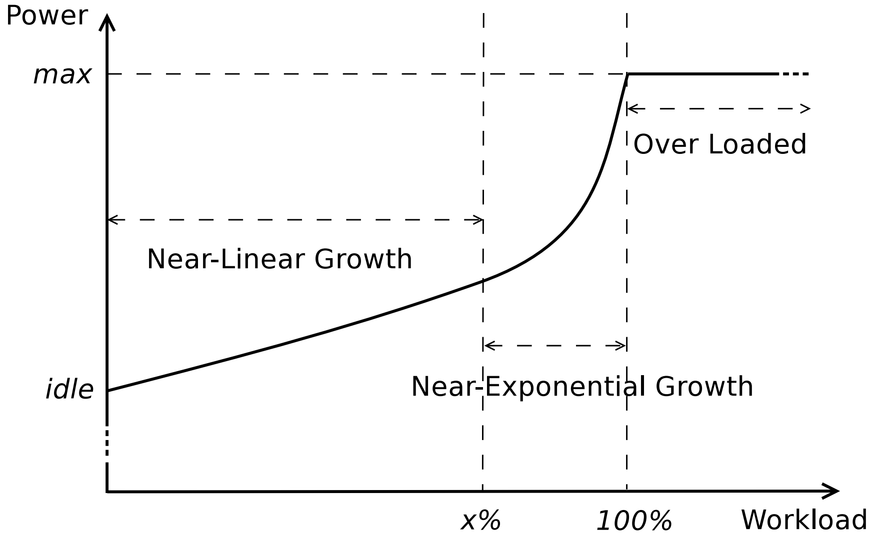

Figure 3.6. Power vs Workload Assumption

3.4.2. Extended Power-Saving for Shared ICT Infrastructures. Dynamically predicting users' demand and only providing necessary resources is a natural way to conserve power and increase resource utilisation with shared ICT infrastructures. However, for modern Internet applications and services, one user request may trigger hundreds or even thousands of servers of the service provider for short period, e.g. a large data-processing task using *map-reduce*. As a result, high bursts of resource demand, and hence energy consumption, are expected, and the magnitudes depend on the actual computational load [83]. To cope with such 'spikes', resource over-provisioning is a current solution: the service providers risk losing money with low utilisation, and also risk customer dissatisfaction (and perhaps loss of customers) if sudden increases in service requests cannot be satisfied.

On the other hand, online/remote services subscribers normally are not aware of the energy consumption and/or related costs and potential savings of the services they buy. In this case, service providers, who potentially "have a detailed knowledge of the overall and host-level energy consumption of their facilities" [62], could make their customers not only aware of their energy consumption, but also fully accountable for it by offering discounted service charges when aggressive energy-saving actions are likely to *temporarily* have a negative impact on user's perceived QoS by some pre-agreed and acceptable margin. This appears to be a win-win solution for both service providers and customers, with respect to costs.

One method to estimate how much discount to offer is for the service providers to accurately capture history of energy usage and resource usage (including SLA violations by the provider, for example), and estimate the amount of energy saved by ignoring or smoothing the demand spikes of service requests. A proposed solution of an accounting and billing architecture for federated cloud infrastructures [47] includes within its *Accounting Layer*, an *SLA Violation Assessment* component to pass any data regarding SLA violations to the billing layer. Such a component could be an important part of an energy-aware based SLA and charging scheme.

However, addressing SLA violations is not sufficient for enabling energy-aware SLAs and charging. Due to dynamic resource allocation, it is currently difficult to isolate resource usage for a single user [62]. We believe a comprehensive energy monitoring and power management integration as a contributor to meeting this challenge.

3.5. Energy-Aware Metrics and Policies

When detailed power measurements are made available, we then need to build system-wide metrics and KPIs of both system workload and energy consumption to (i) make power management decisions, and (ii) estimate savings by applying such power management decisions. The Green Grid consortium [2] define two related metrics – Power Usage Effectiveness (PUE) and Datacenter Efficiency (DCE).

$$PUE = TotalFacilityPower/ITEquipmentPower \quad (2)$$

$$DCE = ITEquipmentPower/TotalFacilityPower \quad (3)$$

where $ITEquipmentPower$ consists of power consumed by computing systems,including computers, network devices, monitors, and other supplemental equipments; $TotalFacilityPower$ covers the complete computing infrastructure, including the $ITEquipmentPower$, cooling systems, uninterruptible power supply (UPS), server room lighting, etc. The overall goal is to reduce PUE or increase DCE to as close to 1 as possible.

The advantage of adopting PUE and DCE is that, they provide a straightforward view of "(i) opportunities to improve datacenter operational efficiency; (ii) how a datacenter compares with competitive datacenters; (iii) if the datacenter operators are improving the designs and processes over time; (iv) opportunities to repurpose energy for additional IT equipment" [2].

However, these metrics rate data-centres as a whole, and are only applicable to our discussion of Section 3.4.1. To enable our energy-aware SLAs and charging scheme described in Section 3.4.2, we would eventually need *per user* metrics, that can be aggregated/accumulated over time, and used for accounting in terms of individual SLAs. This would allow us to apply energy-cost based savings to users. Currently, no such mechanism or metrics exist for this purpose, and the challenge is to design something that is practical and can be applied in useful time-scales, e.g. monthly bills by a service provider to a customer.

Previous work has already presented a comprehensive method to estimate the Total Cost of Ownership (TCO) for ICT service such as cloud computing [47]. Regarding the operation expenditure (OPEX) of ICT infrastructures, the authors pointed out that the power consumption of ICT equipment and their cooling costs have direct relationship [79, 101]. That is to say, as the energy consumption of computing systems reduces, less heat is generated, hence cooling cost also reduces. As a result, when we measure and estimate the total OPEX savings by applying advanced power management policies, cooling systems and the IT equipment shall be considered in our new metrics, as this would show correctly the overall benefit in energy-usage and cost savings.

3.6. Conclusion and Future Work

Scaleable, widely-deployed energy monitoring capability will enable energy-usage information to be integrated into existing system management policies and practises. In this chapter we presented an architecture for a Flexible Energy Monitor (FEM) that is capable of monitoring large-scale ICT infrastructure consisting of heterogeneous devices. We adopted agent-based design and added Relays in between Agents and Collectors when necessary, as a solution to hide heterogeneous communication media and standards. The FEM is implemented in Python, and the supporting utilities/libraries are all open source. Therefore the software suit can be easily improved to be compatible with different computer platforms, e.g. Windows OS. We have presented a prototype that will allow incorporation of legacy systems, many different types of devices and sensors, and also deal with local constraints in communications.

We have also proposed making SLAs energy-aware and enabling charging schemes that allow extended power-saving by temporary, yet controllable, perturbations of SLAs, which could financially benefit both service providers and customers.

In the future, it is desirable to refine the FEM by implementing more sophisticated prototypes and applications, as well as building a vendor-independent information model that enables energy efficiency analysis. Security and access control issues will be treated with high priority, as management policies may result in control actions that change the behaviour or configuration of systems. In addition, it is desirable to compile the FEM from Python scripts to binary codes for the target platforms, in order to further improve its execution efficiency and therefore reduces its energy overhead.

Instead of building a completely new and immature system for energy monitoring and management, it is possible to integrate tested FEM functionalities with existing monitoring systems such as Ganglia for quick deployment. Particularly, FEM shares similar hierarchical, agent-based data collection architecture with Ganglia. FEM's Agent and Collector directly map onto Ganglia's monitor daemon (`gmond`) and metadata daemon (`gmetad`). They both use RRDTool for data logging and graphing, through PHP-based web interface. The combination of FEM's energy usage monitoring and Ganglia's system metrics monitoring (i.e. various CPU utilisation, network I/O, disk I/O and memory utilisation) provide a comprehensive view of system activities, and insights of the correlations between system activities and the resulted energy consumption. FEM and Ganglia also have unique features that complement each other – FEM's capabilities over non-IP communication and IP network penetration; Ganglia's existing access control mechanism, metric aggregation functions and pluggable metric modules that can be extended to include energy or other information.

3.7. Modified FEM for Mac Lab Observations

To serve the rest of the study as well as evaluate FEM's data collection performance at a larger scale, the FEM prototype was extended to collect per-host energy as well as software usage from a total of 72 lab computers (Apple iMac 10.1 21.5" Late 2009), and a low power computer that polls data from Envi CC128 for ambient temperature[7].

We measured the use of energy and the activities of undergraduate users on the teaching lab workstations at the School of Computer Science, University of St

[7]The room temperature in the lab was monitored in case it changes significantly and affects computer cooling requirement therefore system power consumption.

Andrews. Over the teaching periods in academic years 2011/12 and 2012/13, we conducted the same experiment once in each year, with a few small modifications in the second year. In the rest of this paper, we use the labels shown in Table 3.1 to refer to different periods of the 2-year study.

Table 3.1. Labels used for periods of study and for the datasets collected from those periods.

Academic Year	Semester	Label
2011/12	1	Y1S1
	2	Y1S2
	1+2	Y1
2012/13	1	Y2S1
	2	Y2S2
	1+2	Y2

3.7.1. Design Decisions. A number of factors were taken into consideration when choosing the research scenario, including attempt to minimise experiment variables and stay within a low budget financially:

- Reasonable number of computers of the same or similar class – there were 72 iMacs of the same model deployed in the student lab. They share the same software set up, therefore can be considered identical machines. Participants of the study are free to use any computer in the lab and still generate comparable energy and software usage to previous records.
- Built-in power sensors – as inspired by *iStat Menus*[8], a commercial system monitoring tool that reports common systems metrics as well as detailed power usage on any Macintosh computers built since 2006. This eliminates the significant financial requirement of purchasing additional power metres for the scale of this study[9].

[8] http://bjango.com/mac/istatmenus/

[9] We previously purchased a 16-outlet, rack-mount PDU for over 600GBP that supports per outlet power metering to monitor a small cluster of machines as proof-of-concept. However, we had limited number of rack-mount servers that could potentially be used for this study, and it was impractical to deploy a few rack-mount PDUs in the lab to power and monitor 16 iMacs each.

- Stable software set up and local applications – except installations of on-going security updates, the lab computers' default software installation is kept unchanged from the beginning of each academic year till the end, although users may install their own applications in user space. All applications used in teaching and any tools that may be useful to students have been installed on each iMac. No cloud-based application was employed at the moment so that all computational tasks were completed locally utilising identical hardware resources on each host, which made application level energy profiling possible.

- Stable and Active User Group – the Mac lab was used by all first and second year undergraduate students. They are a large user group who guarantee to use lab computers almost on daily basis. They study similar modules at school and therefore use lab computers for similar tasks. See Section 4.2 for more descriptions of participating users.

This specific design may be ported to other scenarios with necessary alterations, provided similar technologies are available. For example, to conduct a comparable experiment in office environment where many employees carry out similar tasks using identical, company-provided laptops with standard ACPI power reporting capabilities built-in.

3.7.2. Computer and Component Power Collection. Utilising the open source Apple System Management Control (SMC) ToolC, we were able to acquire precise and frequent power measurements of many hardware components in a Mac computer from its built-in power sensors.

Apart from taking measurements of the system power as a whole (including screen power), we have chosen to include power measurements of CPU and North Bridge (data I/O controller) among the available readings by the Apple SMC Tool. Screen brightness level is also acquired from the OS, which can be translated to power consumption of the screen, although this measurement is not directly available from the internal sensors (see the next section). The reason why these components were chosen is because their power consumption is potentially highly variable depending on the *user's usage*. In other words, computer users could potentially save energy by adjusting the use of these components.

3.7.3. Screen Brightness and Power. Screen power was not available directly from the built-in power sensors, but its brightness setting was retrievable through an operating system API, ranging from level 0 (lowest brightness setting, but not off) to 100 (highest brightness setting) at step size of 1.

We repeatedly measured the total power of an idling iMac from the lowest screen brightness setting (level 0) to the highest (level 100) at step size of 1, subtracting the iMac's total idle power *when the screen is powered off* (22 Watts), and obtained a mapping graph from screen brightness level to its power consumption for our reference – see Figure 3.7. Overall, the screen power increases linearly as its brightness raises.

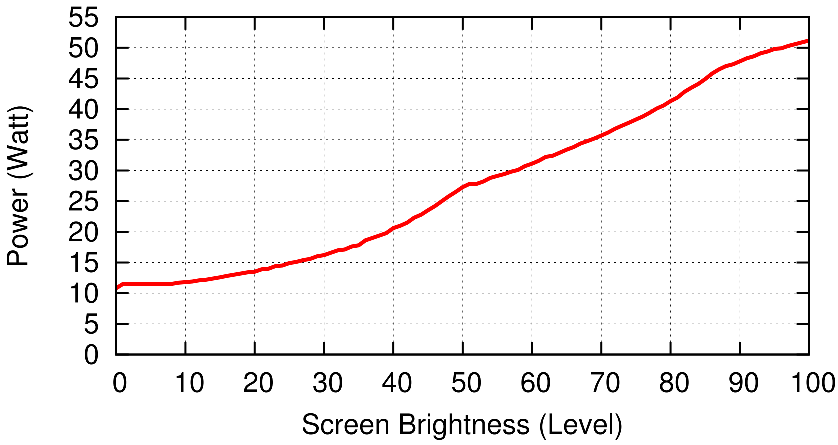

Figure 3.7. Screen brightness level to power consumption mapping.

3.7.4. Computer Usage and Anonymisation. Per-process level computer usage was collected using standard Unix process status utility (`ps`, see Appendix D for sample data). In line with our ethics approval, users' privacy is protected by stripping command-line arguments of applications and processes reported by `ps` utility. For example, `ssh user@host` will only appear as `ssh`; `wget http://URL/file` will only appear as `wget`.

To protect user's privacy and identity, any occurrence of user ID (UID) in the process status was anonymised with HMAC keyed-hashing [74] before the data left user's computer. The hashed UIDs are irreversible and prevent anyone from back tracing particular computer usage to a named individual, but allow us to build a unique computer usage/power profile of each user for research. See Appendix D for sample data.

3.7.5. Data Collection. Our data collection was performed by a Python-based daemon that incorporated the above mentioned information and then uploaded to a collection sink. All the information mentioned above was captured as a sample (a snapshot of system and power usage) every second during active use of a computer (i.e. at least a user is logged on and the screen is powered on). Otherwise samples were taken at reduced frequency of every 10 seconds to capture system idle activities.

Every 30 samples were compressed and cached locally in an archive. The power monitor daemon uploaded all cached samples at a random interval between 32 and 100 seconds to a collection sink to: (1) avoid network congestion; (2) avoid data loss due to corrupted file; (3) achieve near-real-time data collection with up to 100 seconds delay. The collector also served as data processor and storage at this occasion, although these functions could be deployed on different servers if necessary.

3.7.6. Web-Based Data Access. Two web-based graphing applications were made available. The first one generates a straightforward graphical overview of per computer power usage in the Mac lab as Figure 3.9 demonstrates. When the mouse cursor hovers over a host name, more details of the host are shown in a pop up window as Figure 3.10 shows. This was intended to give system administrators a quick host level power usage in the lab, and adjust system configurations as necessary. For example, by monitoring the entire lab and its ambient temperature could help find the optimal range of room temperature that is comfortable to users and does not add extra load on each iMac's cooling systems.

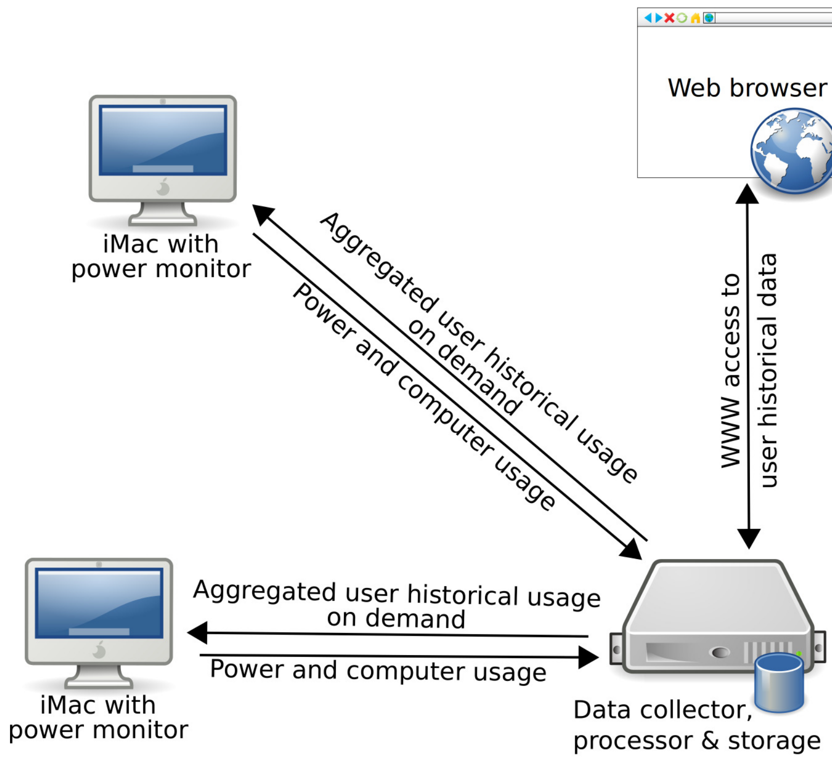

Figure 3.8. A sketch of the modified FEM and feedback model for our experiment. Note that aggregated user historical usage was sent back to the Agent (on iMacs) as a RPC parameter, and then passed to a local application for display. The server is a hybrid unit of Collector and Application, which stores and processes collected data for remote access. A Relay was not required in this set up.

Potentially, this overview could be shown on a big display in the Mac lab to all the users, and allow users compare computer usage to each other's, and possibly learn from peers what applications caused high or low energy consumption. Unfortunately, this was never shown to the Mac lab users because no suitable display could be deployed in a non-distracting way. The effectiveness of group feedback remains potential future work.

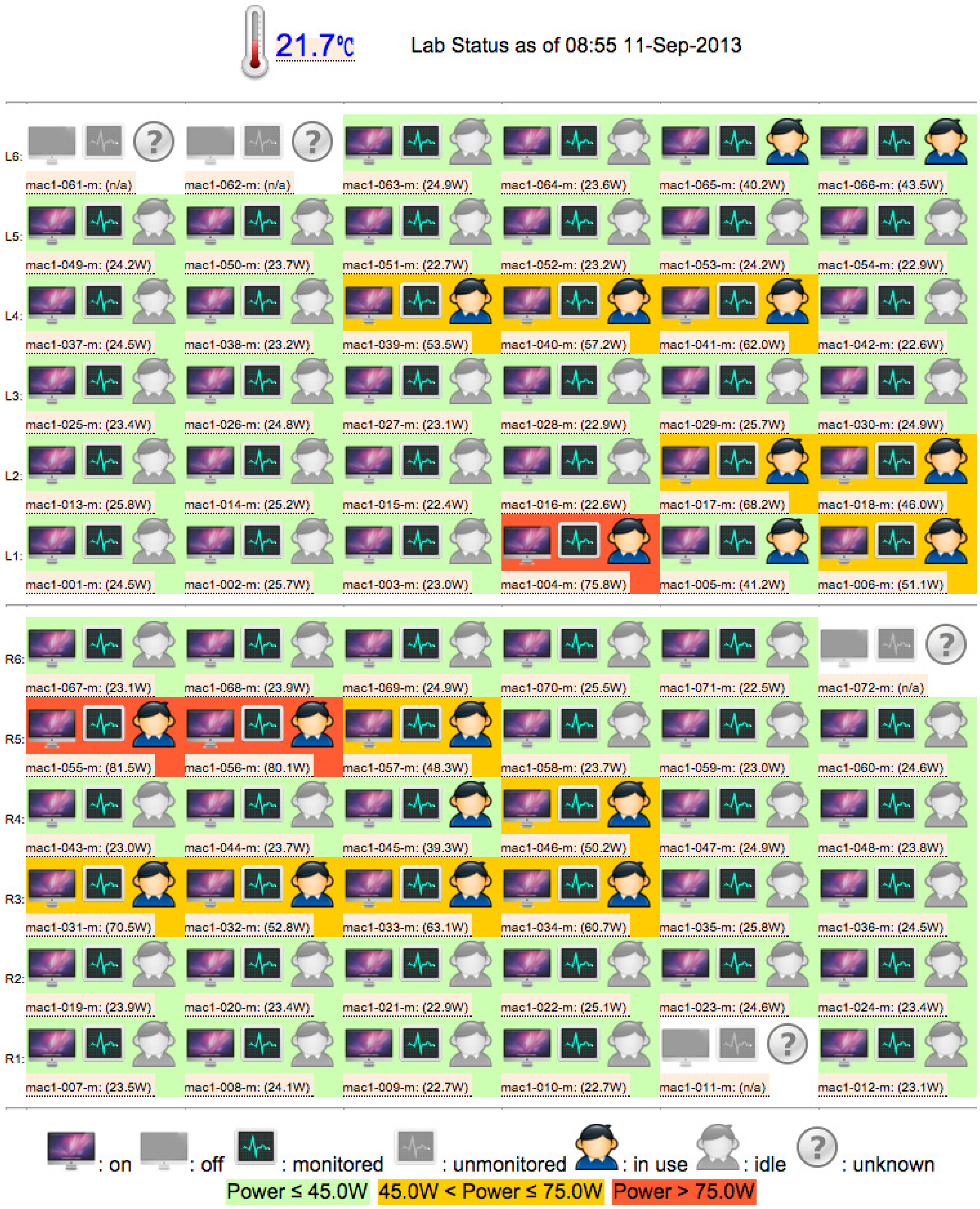

Figure 3.9. Real-time overview Mac lab power status. L1-6 and R1-6 represent six rows of computers on left- and right-hand side of the lab respectively. Each table cell represents an iMac, and shows if it was on or off, being monitored or not, and in use or idle. The colour-coded cell background indicates the level of power consumption based-on long term observations and group average power usage per iMac. Green indicates low power usage, amber indicates medium power usage, and red indicates abnormal high power usage. The lab ambient temperature is shown on the top of the page in blue, indicating the lab was in the regular temperature range as expected.

Figure 3.10. As the mouse cursor hovers over host mac1-039-m, its metadata, and detailed measurements are shown in a pop up.

The second one was implemented in Y2 to fulfil participants' requests of improvement. It offered each participant secure remote access to his/her own historical power usage tracing back up to 3 months (see Figure 3.12). As a security measure, users must authenticate themselves against the school directory service via Lightweight Directory Access Protocol (LDAP) before their user IDs are accepted as the key to retrieve data (see Figure 3.11). Users' historical power usage was displayed as plots generated with RRDtool[10] on the server side.

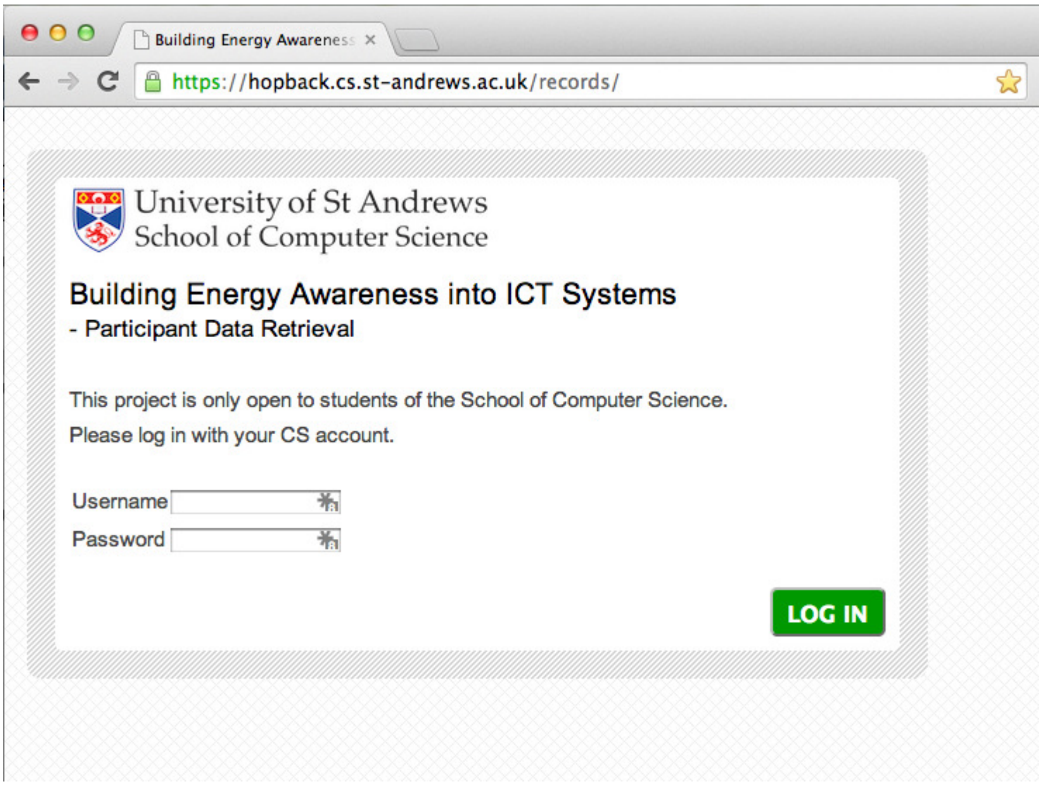

Figure 3.11. A screenshot of the web-based user authentication page.

[10]Round-Robin Database tool for high performance data logging and graphing system for time series data. http://oss.oetiker.ch/rrdtool/

Figure 3.12. A proof-of-concept view of a user's historical power usage in a web browser, covering different periods. Should we have more time, we would improve the user interface to better present historical usage.

3.7.7. Power Usage Feedback for Users. We implemented a simple application – a menu bar applet (power applet) – to provide information about power usage to the users. In Y1, our power applet showed very simple numerical screen brightness levels, real-time power reading and cumulative energy usage of the current session – see Figure 3.13. Users were able to change the display unit of cumulative energy usage to Watt-hour, mass of carbon footprint (grams), volume of CO_2 emission (litres) or the cost of electricity (pennies). Although many participants liked it and found it useful (27 out of 31 participants), we also received some suggestions and requests for improvements.

In Y2, the power feedback was improved to allow users to access their historical power usage either via the on-screen power applet (see Figure 3.14), or link to the web-based front-end in a browser from any computer (see Figure 3.11 and 3.12). We added green/amber/red 'smiley' faces as graphical indicators for low/moderate/high power consumption levels with predefined thresholds based on observations in Y1 (Table 3.2).

The power applet acquires the current computer user ID automatically, retrieves and displays user historical usage from data storage. When using the on-screen power applet, historical data view was optional but real-time power feedback was always displayed in the menu bar using local measurements taken from Apple SMC.

Table 3.2. Colour-coded smiley face indicators used in power applet in Y2.

Icon	Power
	$\leq$45W
	>45W and $\leq$75W
	>75W

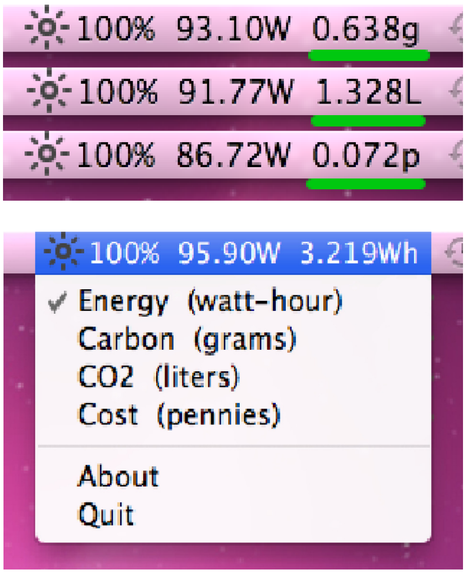

Figure 3.13. The menu bar power applet used in Y1. Users were able to select the display unit of total session energy consumption from 4 options.

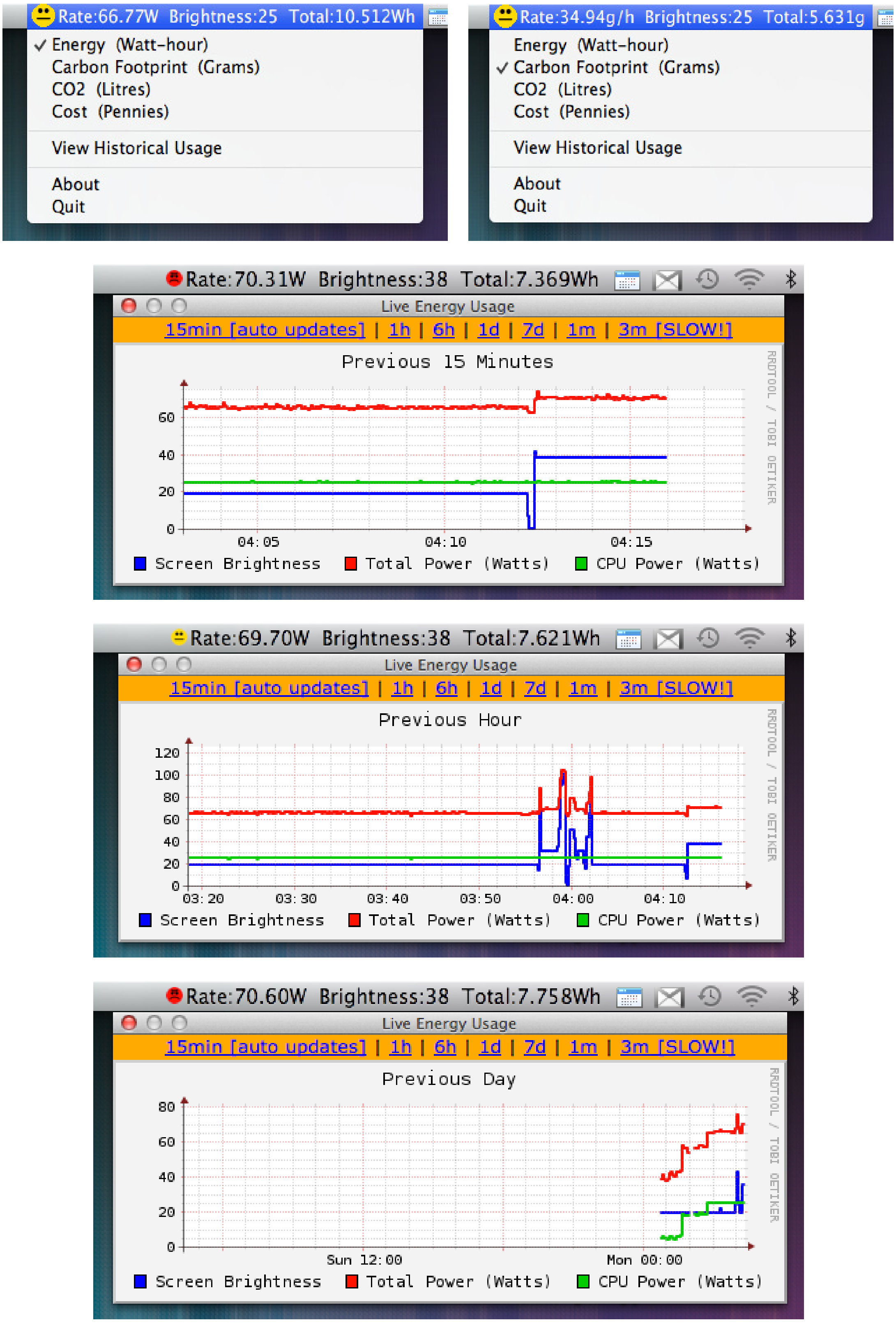

Figure 3.14. The improved power applet used in Y2, with a colour indicator, rate of power consumption in selected unit, and the option of viewing live plots of historical power usage.

3.8. Performance Analysis

The performance analysis of the power monitor was to demonstrate its usability and overhead as a tool used experimental purposes. There is indeed room for improvements, but it was not our priority when this study was conducted. Possible improvements are discussed below for future reference for any continuation work based on this study.

3.8.1. Data Generation and Potential Issues. When a host is in use, one log file that contains 30 samples is generated every 32 to 33 seconds (30 seconds waiting time and 2-3 seconds execution time to retrieve and save data), yields 112 log files every hour. The sizes of the log files vary depending on what system services are running, and more importantly, what user processes are running. As we have observed, the smallest size of a single log file from Mac OS 10.7 is 262 bytes, while there is technically no upper limit for a single log file. Individual samples become larger when more processes and longer paths/binary names are reported by `ps` utility. Table 3.3 shows some statistics of log files collected from all hosts in each semester over the 2-year study.

Table 3.3. Log file size statistics per semester.

Period	Min	Max	Mean	Files
Y1S1	262 B	653.4 KB	58.0 KB	434,841
Y1S2	262 B	547.3 KB	59.8 KB	583,573
Y2S1	262 B	1066.3 KB	43.8 KB	1,016,437
Y2S2	262 B	252.2 KB	21.3 KB	2,665,500

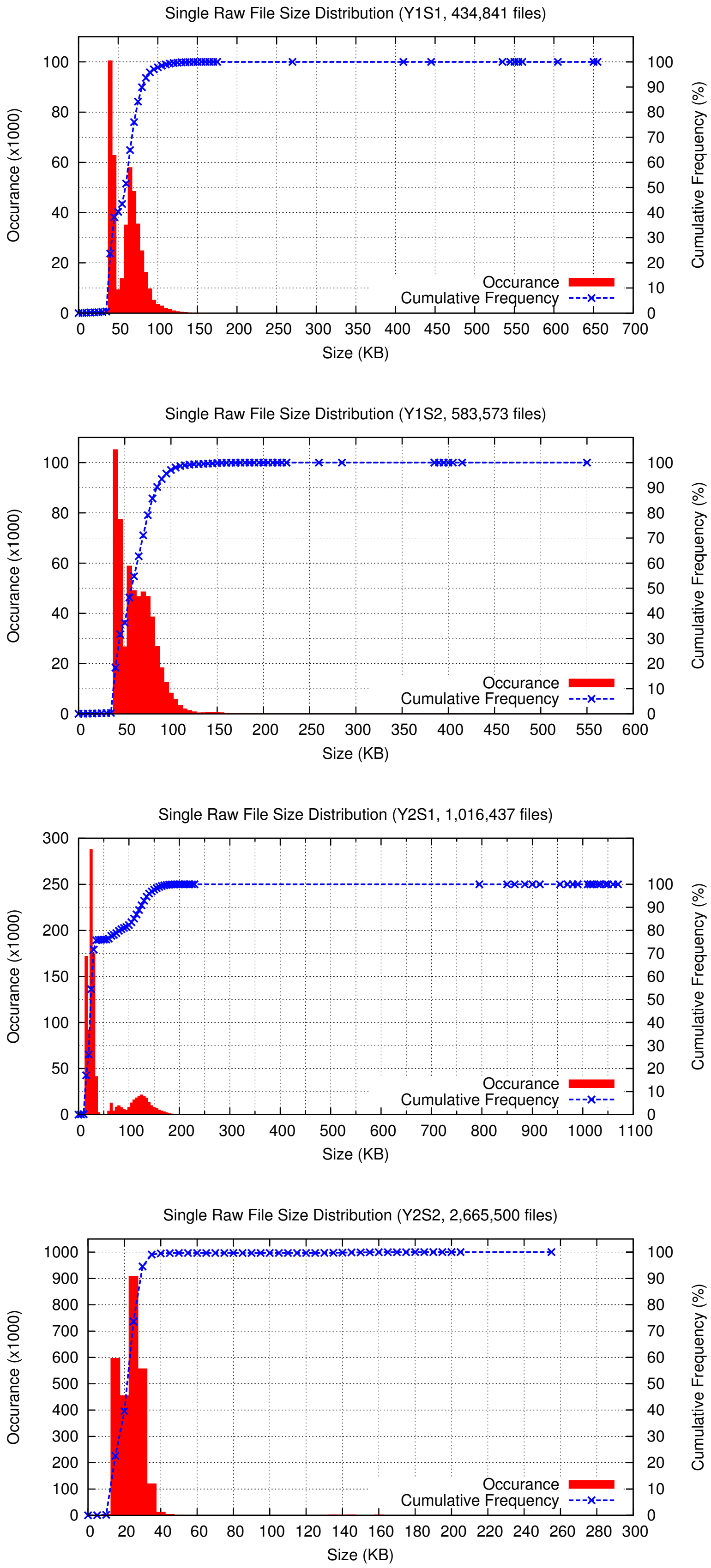

Figure 3.15. Distribution of log file sizes per semester.

Figure 3.15 illustrates the distributions of log file sizes in each semester in 5 KB granularity. Although there were relatively large log files in every semester, their occurrences were extremely low compared to the majority. In Y1S1, 43.5% of log files were under 55 KB, and 98.9% were under 110 KB. Similarly, 46.3% were under 55 KB and 98.6% were under 110 KB in Y1S2. Interestingly, inconsistent patterns were observed in Y2. As high as 75.7% of log files were under 35 KB and 22.5% were between 65 and 160 KB in Y2S1; but 99.1% of log files in Y2S2 were under 35 KB.

The largest individual log file collected was of size 1.1 MB, yields up to 123 MB data per hour. It contains system snapshots of 242 user processes as opposed to the average user processes count between 10 and 20. In this case, the power monitor consumed over 10 times more network bandwidth, CPU time and disk I/O than expected, hence could have negative impacts on user experiences. A possible change in design to tackle this issue is to limit log file size to 200 KB. Based on our statistics, over 99.99% of data will not be affected. The snapshots in oversized log files could be locally reduced to minimal process statistics and raw power measurements before they are cached and uploaded to the collector.

Another potential issue involving data generation and collection is the caching mechanism. By design, the log files are cached in disk until they are successfully uploaded to the collector under the assumption that computers have a reliable network connection. While this mechanism preserves the monitoring data while network interruptions occur or the collector is temporarily taken off-line, the log files could potentially keep accumulating on disk as long as the power monitor can not connect to the collector. This issue becomes more critical if the power monitor is deployed on portable devices such as laptops which may be disconnected from the network for hours or even days. Although computers nowadays generally have a few hundreds of GB disk space, it is still desirable to implement data storage caps and aggregation algorithms to better cope with unexpected long term off-line use of user computers or collector downtime.

3.8.2. Computing Resource Usage and Power Overhead. While it was hard to audit computing resources used by the power monitor daemon, we worked out the power overhead of the power monitor was approximately 0.77 Watts, by subtracting the total power of an idling iMac with one power monitor executing, from the total power of the same iMac with 2 power monitors executing concurrently. Although this number may vary slightly when the computer load changes, it was still a good indication of how low the percentage overhead was in the worst case, i.e. $100\% \times \dfrac{0.77\, Watts\, overhead}{32.9\, Watts\, idle\, power} \approx 2.3\%$. During normal use of an iMac, the percentage overhead decreases to less than 1%. Given the measured group average saving of 16%, the overhead is marginal.

Having said this, in a deployed system, further power overhead reduction could be achieved by only executing the power monitor when the computer is in use and its screen is turned on (so that on-screen feedback is visible). This power-saving feature was not implemented because we needed to collect system idle power as baseline data.

3.8.3. Scalability. The scalability of the power monitor system depends on the collector's (1) network downlink bandwidth that receives large amount of upload traffic; and (2) computing power for processing collected data.

A rack-mount high-end server was used as the primary data collector and processor during the 2-year experiment; and a consumer level PC was used as the backup data collector and processor. Our experience showed that both collectors coped well with 72 nodes (computers running the power monitor) each with very low CPU and network bandwidth utilisation rates. A single collector with 100Mb downlink in the university network is expected to handle at least hundreds of nodes. As the log files change in size and the data may be processed and stored differently according to new requirements, it is difficult to estimate the scalability limit of a collector. However, should there be signs of collector resource exhaustion, the architecture of the power monitor system is flexible enough to allow multiple collectors to share the workload. Individual power monitor agents can be configured to upload data to alternative collectors either randomly or in round-robin style. If it was difficult to reconfigure the power monitor agents on users' computers, a relay can be implemented to replace the original collector, which then acts as a load balancer that spreads collected data to multiple collectors to process.

3.8.4. Uplink Utilisation. Logs files are automatically uploaded to the collecting server when a usable connection is detected. In Ethernet or WiFi-based local networks, the uploads consume very small fractions of bandwidth on average (see Table 3.4), hence there it is safe to assume the power monitor for Mac does not affect the local network.

Potentially, the power monitor could be widely deployed on any Macintosh computer to collect user software and power usage, for user's self-learning and/or researcher's studies. This is where potential issue arises.

According to OFCOM [11], the average residential UK broadband upload speed has reached 1.8Mbps in May 2013. Therefore in case of a power monitor executing on an iMac at home, only 0.841% uplink bandwidth on average is consumed. However, up to 15.949% of uplink may be consumed when an exceptional amount of data are generated.

Table 3.4. Network utilisation

Uplink	Min util (%)	Average util (%)	Exceptional util (%)
	2.1MB/h	6.5MB/h	123.2MB/h
100Mbps	0.005	0.015	0.287
54Mbps	0.009	0.028	0.532
1.8Mbps	0.272	0.841	15.949

A potential design issue is that after a period of network outage, all locally cached logs will be uploaded in sequence and continuously when the network communication resumes. This may cause temporary high uplink utilisation and affect user experiences. A possible solution in future releases is to limit the rate of uploading historical logs after network outage.

[11] Average UK broadband speed continues to rise (August 7, 2013) http://goo.gl/WcZLSh

Bandwidth management - automatically determine uplink bandwidth and stay within a predefined utilisation percentage (e.g. 10%). This improvement prevents the power monitor from utilising too much uplink bandwidth, but adds some complexity to the power monitor. The computational overhead is expected to be negligible since the uplink bandwidth can be assumed stable in a given network environment (e.g. home, office), so that it only needs to be determined once when the computer (re)connects to a network or a new IP address is obtained.

Chapter 4

Power Reduction During Use of Computers

4.1. Contributions

We show that within a university computer teaching lab, feedback on users' individual power use coupled with some small financial rewards produce energy savings. We observed a mean of 16% group energy saving, and up to 56% individual energy saving. The specific novelty of our study is to consider *what change in behaviour users are willing to accept and what actions they are willing to take whilst they are using the computers.* This is complementary to existing work that considers system-level interventions and mechanisms that are designed to function without the cooperation or knowledge of users, when computers are *not in use*, e.g. send computers to sleep when not being used [27].

Incentives together with feedback about energy usage were required to sustain energy-saving behaviour: feedback alone was not sufficient, as personal preferences of completing work, convenience and/or certain workstation configuration have overwhelming priority over energy saving. We observed that there was much room for improvement amongst users who thought they were already 'green', and that the additional information we gave through a simple desktop feedback application helped them become 'greener'.

4.2. A 2-Year Measurement-Based Behavioural Observation

In this thesis, we made passive observations of user behaviour, and examined the impact of *feedback* about their energy usage with the role of *incentives*. Our intention was to observe behaviour and what impacts the behaviour of users, rather than effect permanent behaviour change with respect to energy usage.

Yun et al. [123] conducted several similar studies in 2013 with a total of 22 people across a university lab, a university office and a government research lab. Their results showed that up to 40% overall energy savings can be achieved based on 6 people's performances at the university office, provided users are (1) educated to save energy; (2) given energy saving advice whenever applicable; (3) allowed to self-monitor power usage; (4) able to compare their performances to others; (5) given easy and simple ways to control electric appliances around them; (6) given rewards for achieving target energy saving behaviour.

In our study, we have also adopted the 6 points identified by Yun. We created a simple graphical application that gave feedback to the users. We also provided energy saving 'tips' for users, as well as a briefing session for all users. We informed users of the way in which the workstation configuration could be modified for energy efficiency. We also held competitions with prizes as incentives to save energy.

We tested what changes users were prepared to make in order to be more energy efficient. We wanted to see what simple information and/or education they would respond to. We used prizes as incentives and surveys as triggers to remind users of their tasks. Also, by focussing on a whole class, even though we wanted to measure individual users, we were ensuring that such behaviour would be known to all users, (even those that eventually chose not to participate in the study), and so a social norm was established for that context.

Guided by Fogg's design process of creating persuasive technologies [53], we adapted both Fogg's behaviour model for persuasive design [52] and Geller's behaviour-change model [60]. Each run of the experiment was divided into four stages, involving three types of actions that help participants to move onto the next stage. Measurement of system usage was in progress throughout the period to determine actual energy usage, with user surveys to determine intent, motivation and perception of users during the study.

Stage 1. Unconscious incompetence, where participants do not save energy because they do not think or know about the energy issue. The first survey in the series was designed to gather general background of each participant so we know at which stages the participants considered themselves to be.

Action 1. After the first survey, S1, some general information on the negative impacts of electricity generation and six energy saving tips were given to the participants so they learnt (1) how to reduce energy consumption on lab computers; (2) why it is environmentally important to do so.

Stage 2. Conscious incompetence, where participants have been educated but still do not take many actions to save energy due to lack of motivation. We designed the second survey, S2, to find out how many of them have moved onto this stage.

Action 2. A 4- to 5-week energy efficiency 'competition', with multiple prizes (vouchers and USB memory sticks), was run to encourage participants to reduce their energy usage in their use of lab computers. Over selected periods during and after the competition, each individual's real-time power usage feedback was displayed via an on-screen applet on each lab computer.

Stage 3. Conscious competence, where participants are not only aware of why and how to save energy, but also take actions to save energy on lab computers.

Action 3. Energy efficiency competition ends. Real-time energy usage feedback remains available at all times on all lab computers. Survey S3 recorded user attitudes.

Stage 4. Unconscious competence, where participants try to reduce power consumption without the incentive of prizes. Survey S4 recorded user attitudes.

Table 4.1 shows a detailed, week-by-week breakdown of experiment activities over two years.

Table 4.1. Week-by-week experiment design over 2 academic years. Week 7 in Y1S1 was Reading Week (no teaching or coursework deadline), therefore significantly less use of the lab computers was observed. This could have led to biased results, but no obvious difference was observed. Vacation and exams periods were excluded from our observation due to low and inconsistent lab usage. A tick/check indicates in which week the relevant activity was in progress. In the 'Survey' row, S1, S2, S3, and S4 denote the four user surveys that were conducted. Note that in Y1S1, week 12 was followed by a vacation. This was changed to exams in Y2S1. As a result, atypical usage was observed in 3 out of 4 last-week-of-semester (Y1S2 week 12, Y2S1 week 12, Y2S2 week 13) due to pressure from the coursework deadlines and upcoming exams (see Figure 4.10)

	Y1S1													Y1S2													
Week	1	2	3	4	5	6	7	8	9	10	11	12	Vac.	1	2	3	4	5	6	7	Vac.	8	9	10	11	12	Exams
Recruitment	✓	✓																									
Baseline Obs.	✓	✓																									
Power Monitoring	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
Usage Monitoring	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
Tips				✓																							
Survey			S1			S2					S3		S4														
Competition						✓	✓	✓	✓	✓																	
Power Feedback								✓	✓		✓			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	

	Y2S1													Y2S2														
Week	1	2	3	4	5	6	7	8	9	10	11	12	Exams	1	2	3	4	5	6	7	Vac.	8	9	10	11	12	13	Exams
Recruitment	✓	✓																										
Baseline Obs.		✓	✓																									
Power Monitoring		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Usage Monitoring		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Tips						✓																						
Survey				S1		S2					S3		S4															
Competition							✓	✓	✓	✓																		
Power Feedback									✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	

To distinguish the effect of incentives (prizes of vouchers and some USB sticks for completing the surveys) and the power applet, we deployed and removed the power applet at certain times from week 8 to 12 in Y1S1, and kept the power applet on in Y1S2 and Y2S2 to compare between Y1S1 and Y2S1, respectively.

At the beginning of each year, over 40 participants (first and second year undergraduate students) were recruited for our study. An individual user's power consumption and activities on the workstations – 24" iMac units – were recorded using the modified power monitor described in Section 3.7. We also gathered participants' attitudes and motivations towards energy saving via 4 surveys (S1 to S4) through the first semester of each year for qualitative analysis and cross reference against measurements.

Our experiment participants (users) were all undergraduate Computer Science students, and broadly shared the following characteristics:

(1) They frequently used the school computer lab for their day-to-day work and assignments.

(2) They were enthusiastic young individuals who were eager to learn and experiment with new ideas.

(3) They had sufficient computer skills and knowledge to be able to apply the energy-savings tips that they were given, and make informed choices about their individual choices of computer usage.

(4) They did not pay directly for their electricity usage at school.

(5) They were responsive to material rewards (free food, gifts, coupons, etc.).

Among these characteristics, point (1) was verified by our measurements; (2), (3) and (5) were educated assumptions which were later verified via surveys; point (4) was a known fact.

A control group was not used because:

(1) there was no group interaction or collaboration, and so individual users may behave differently;

(2) the focus was on potential changes of individual behaviour;

(3) users do not have exactly the same workload or habits of using lab computers, therefore it did not make sense to compare one group against another.

As a result, at the beginning of each academic year, we used 2 weeks to gather baseline measurements of individual participants. This baseline was then used in the subsequent weeks of the study to determine individuals' changes in computer usage.

4.2.1. Surveys. Four surveys were conducted during the experiment to acquire qualitative data in support of the passively collected quantitative data; so that we gain insights of the reasons and motivations behind observed user behaviours.

In every survey, we asked our participants to self-evaluate their current awareness and attitude toward energy saving by choosing one out of six options that best described themselves. From this, we derived what stages in the behavioural model that each participant was at, and monitored the transitions between different stages of the behavioural model.

Background survey (S1): we recorded the general understanding, knowledge, awareness, habits and attitudes of users towards energy- saving at both home and school. We asked users: how motivated they were to save energy; what could motivate them to save energy; their thoughts on what level of information and feedback on energy usage could help them to save energy.

Survey on energy saving tips (S2): we recoded how users responded to the energy-saving tips that we gave them. We wanted to compare their declared motivation with their use of energy-saving tips, and what demotivated them from carrying out these energy-saving tips.

Energy efficiency competition feedback survey (S3): we recorded if the prizes had motivated the participants to save energy, and in what ways if the feedback application was useful to them.

Final survey (S4): the final survey recorded if participants' motivations to save energy had changed after the experiment, and how significant the menu bar power applet was as a reminder to save energy.

4.3. Results and Observations

Both qualitative and quantitative data show that our users changed their behaviour. We observed that 'non-green' users became 'green', and saw that 'green' users become 'greener'. We also observed a few exceptions. We refer to the behavioural Stages listed in Section 4.2.

4.3.1. Collected Data. Our monitoring tool captured one snapshot of computer power measurements and process status every 1 second during active user sessions, and every 10 seconds while the computer was idling. Table 4.2 shows the metadata of these collected data.

Table 4.2. Metadata of our experiment and collected data.

	Y1	**Y2**	**Unit**
Users	45	47	person
- In both Y1 and Y2	9	9	person
- First year student	28	26	person
- Second year student	13	17	person
- Other	4	4	person
Monitored Hosts	72	72	iMac 10,1
Collection Duration	24	24	week
	4032	4032	hour
User Sessions	9500	7150	session
- Duration	15388.9	11388.9	hour
- Samples	55.4	41.0	million
Collected Data	860	1220	GB
- User data	443.9	690.5	GB

There are 4 states an iMac can be in:

(1) In-use (user logged in), screen on

(2) In-use, screen powered off

(3) Idle (awaiting user log in), screen on

(4) Idle, screen powered off

We chose to separate traces of users' computer usage into sessions as the smallest unit for statistics and analysis. A valid and active user session is defined as an iMac being in state 1 for at least 5 minutes. Otherwise the use of the computer is considered too short to represent a user's behaviour. When an iMac in state 1 is left unused for 10 minutes, it turns into state 2 by automatically turning its screen off (default power saving setting), in which it is not considered an active user session and data collected in this state are ignored. A new user session begins when the user returns and the iMac resumes to state 1 from state 2. It is necessary to exclude data from state 2 because although a user has logged in and there are user applications executing, the total computer power consumption is significantly lower than state 1 and this can not be considered as a result of user's power saving behaviour.

User sessions were then grouped by weeks because teaching schedules were designed and mostly repeated on weekly basis in each semester. Researchers' interventions during the experiment were also planned ahead week-by-week.

4.3.2. Individual User's Self-Assessments. A user's change in attitude was determined by tracing their responses to the series of surveys in each year. If a user missed out one or more surveys, his/her data were considered incomplete and excluded from the analysis, so we only consider continuous, progressive trends and changes. So, another challenge was to keep users engaged throughout our experiment.

In all surveys, high percentages of users considered themselves to have good awareness and attitudes about energy saving. Based on the model in Section 4.2, users considered themselves already at Stage 3 or better. There were few users at Stage 2 (aware of the issue and possible solutions, but lacking motivation to act). Overall, the self assessment results were much more positive than we had expected. No user in our study was averse to saving energy, i.e. no one was at Stage 1.

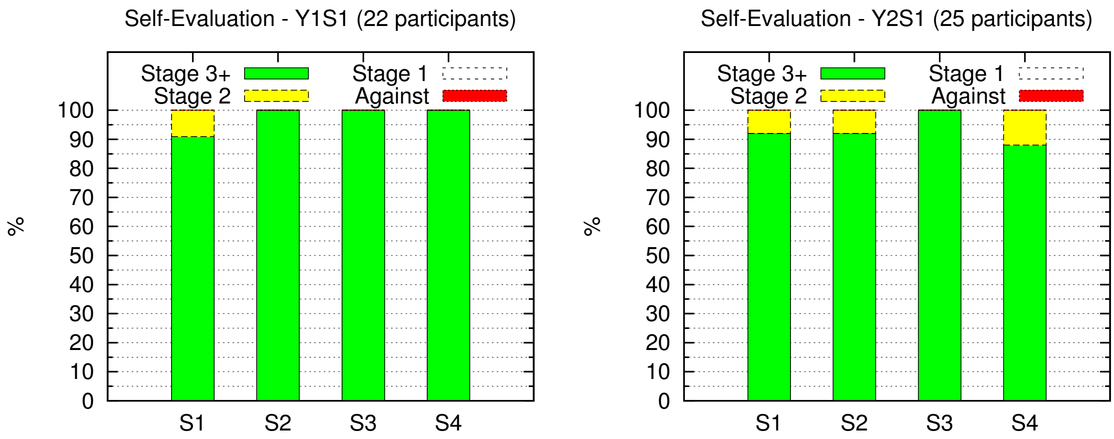

Figure 4.1. Attitude changes between surveys. Data presented are from those who completed all four surveys during our experiment. 'Sn-m' on the X axis stands for comparison of response to survey n compared to survey m.

Overall, the attitudes of users were stable, but on an individual basis, some self-assessments moved between Stage 2 and 3+. Figure 4.1 illustrates the changes between surveys. While 40% or more of users assessed themselves as being consistent throughout the study, the rest felt their attitude had either improved or worsened, with individual positive and negative responses cancelling each other out, hence little change observable in overall distributions for the group as a whole. Although up to 30% of users had expressed their attitudes or behaviours to be less positive in between surveys, they were still at Stage 2 or higher, meaning they were at least all aware of the energy issue, but perhaps lacked motivation to be more energy efficient.

Even though the sequences of changes in both years were statistically insignificant, we were able to tell that the vast majority of our users considered themselves energy-conscious throughout our study. However, as we see in the next section, their measured behaviour did not always match their self-assessments.

4.3.3. Exceptional Observations. Although most users' self-assessments matched their measured computer and power usage, a few contradictory exceptions were observed.

Better attitude but worse power efficiency – one participant, P65 (a pseudonym), reported improved motivation and attitude towards energy saving in Y2S1. However, the measured power changes for that user showed the opposite. Neither reward nor feedback motivated P65 to reduce power consumption.

Worse attitude but better power efficiency – user P03 had shifted his/her self-assessment from Stage 3 towards Stage 2 over Y1S1. However, we found P03's energy saving improvement ($> 10\%$) was consistent over the period. Similarly, self-assessments of participant P12 worsened over time, but his/her measured energy-efficiency improved.

4.3.4. Initial Survey – User Motivation. From S1 (background survey) we found our users in Y1S1 and Y2S1 were reasonably consistent in terms of how motivated they were to save energy. From Figure 4.2, similar and overall positive results were observed in both years. The majority of them expressed they were already motivated to save energy at the beginning of the study in each year. Approximately half of users claimed they actively engaged in energy saving actions in other parts of their daily lives. However, similar numbers of users lacked the motivation to save energy. They did not always remember to apply energy-saving techniques, therefore could potentially be responsive to test if our on-screen power applet could act as a reminder to save energy at later stages of our experiment.

In Y1S1, every user claimed to be motivated to save energy. Only one of them admitted not knowing how to save energy. In Y2S1, although two users expressed no motivation to save energy, they were open to receive more information on this issue.

In both years, similar behaviour of our participants at their residence and school were self-reported in the background surveys. Although in both years, only around 20% of them pay for what they use at their residence (most of them lived in university accommodation where they were not billed for utilities) and therefore were financially motivated to save energy, the majority of them claimed to actively save energy at their

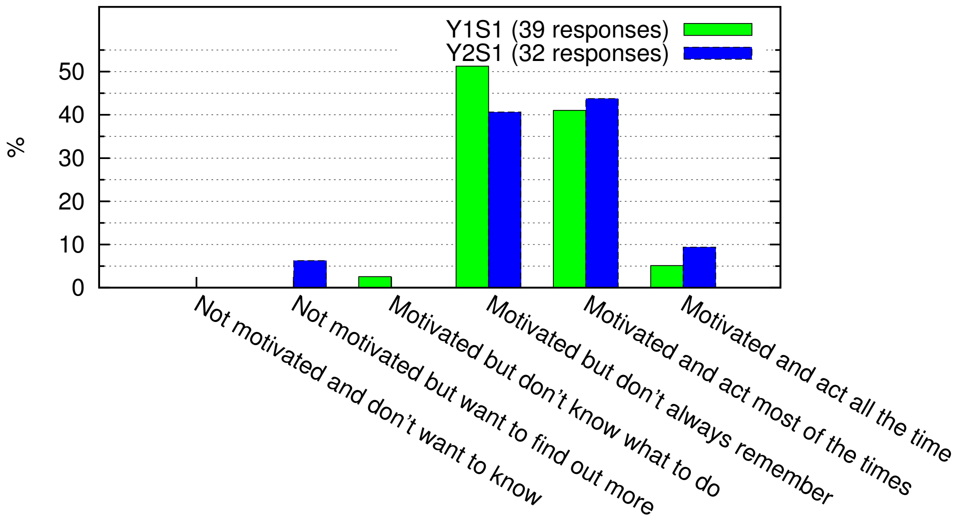

Figure 4.2. Participants' self-assessments in S1 on how motivated they were to save energy at the beginning of each year.

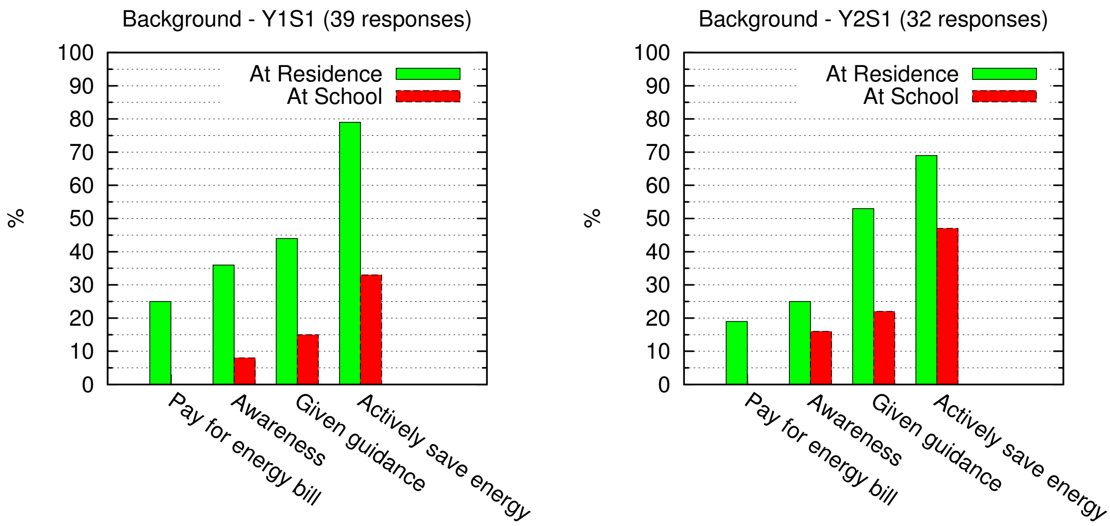

Figure 4.3. Different behaviours at the residence and school.

residence because (1) they were made aware of their energy consumption via direct or indirect feedback [39], including real-time desktop power meter, household electricity meter, and monthly electricity bills. Any saving or extra consumption could be seen and understood in common metrics (kWh, GBP, % changes); (2) there were more guidance available on saving energy at home than in public environments, e.g. turn off lights when leaving the room, switch off standing-by electrical appliances when possible, adjust central heating temperature settings, etc., but these techniques are not normally applicable in public environments. As a result, most users did not attempt to save energy at school due to these limitations.

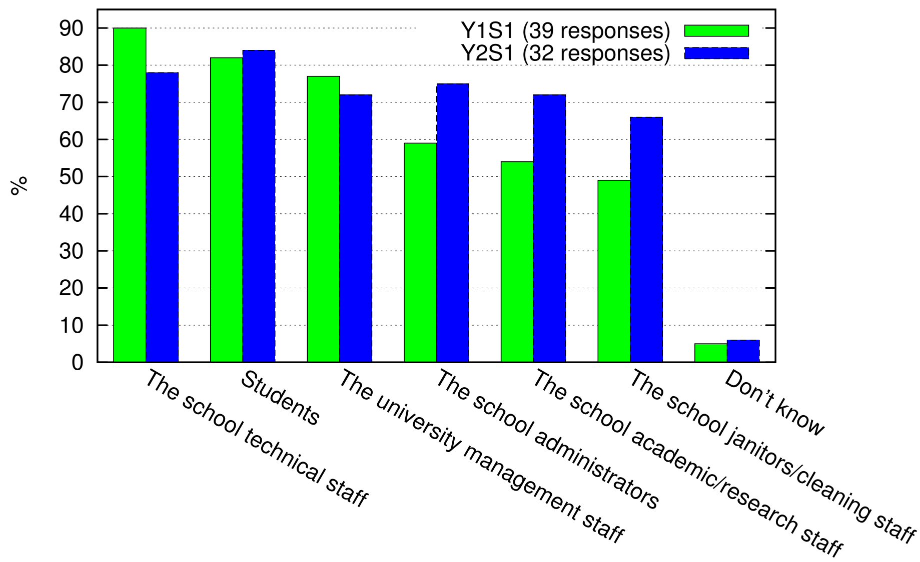

Figure 4.4. Users' opinions on who should be actively involved in energy management activities at school.

At the start of both years, participants generally behaved differently at their residence and in the lab. At this stage, some of the users who saved energy at their residence also gave other motivations: *pressure from other flat mates to save on energy bills, which is separate from my own desire to save money*; *to prevent the predicted energy crisis that will cause blackouts within the next 2 decades*; *to prevent global warming*; *moral conscience*; or simply *to protect electronic devices*.

All of the participants who completed the survey in Y1S1 and 94% of them in Y2S1 agreed that energy management was important to the School of Computer Science. Figure 4.4 shows who the users thought should be actively involved in energy management activities at school. It was encouraging to see that students did consider themselves should be involved in energy management activities at school, along with the school technical staff and university management staff. More participants in Y2S1 than in Y1S1 voted that the school administrators, academic staff and janitors/cleaning staff should also play a part to help save energy. We assume this was due to successful energy saving campaigns and informations sessions in Y2 as mentioned before.

4.3.5. Energy Saving Tips. Six energy-saving tips were given to users in order to help them more effectively reduce energy consumption when they used lab computers. Not all tips were easy to carry out, and we deliberately used these to observe how much effort the users were willing to make in order to save energy in the lab.

The six tips (in abbreviated form) are listed below. Brief explanations on how and why these tips could reduce energy wastage were given to users. Note that these tips were selected based on the fact that individual iMac's power saving settings were locked according to systems configurations, and users had limited freedom of installing applications within user space on these lab computers. Other than this, these were chosen based on the researchers' experience of using computers.

(1) Reduce screen brightness.

(2) Use 'lightweight' applications (with reduced CPU and disk usage).

(3) Reduce the use of streaming audio and video in browsers, e.g. Flash media players embedded in web pages.

(4) Block unwanted web content with a browser add-on.

(5) Quit unused applications completely rather than leaving them in the background.

(6) Turn off the computer after use.

Figure 4.5 shows the feedback on energy-saving tips gathered from both survey S2 (pre-competition) and survey S3 (post-competition). Ideally, an overall balanced pentagon shape is expected for each tip given, meaning the user finds the tip understandable (U), sensible (S), easy (E) to carry out, is motivated (M) to use it, and would actively (A) practice it. (Note that this is irrespective of how effective

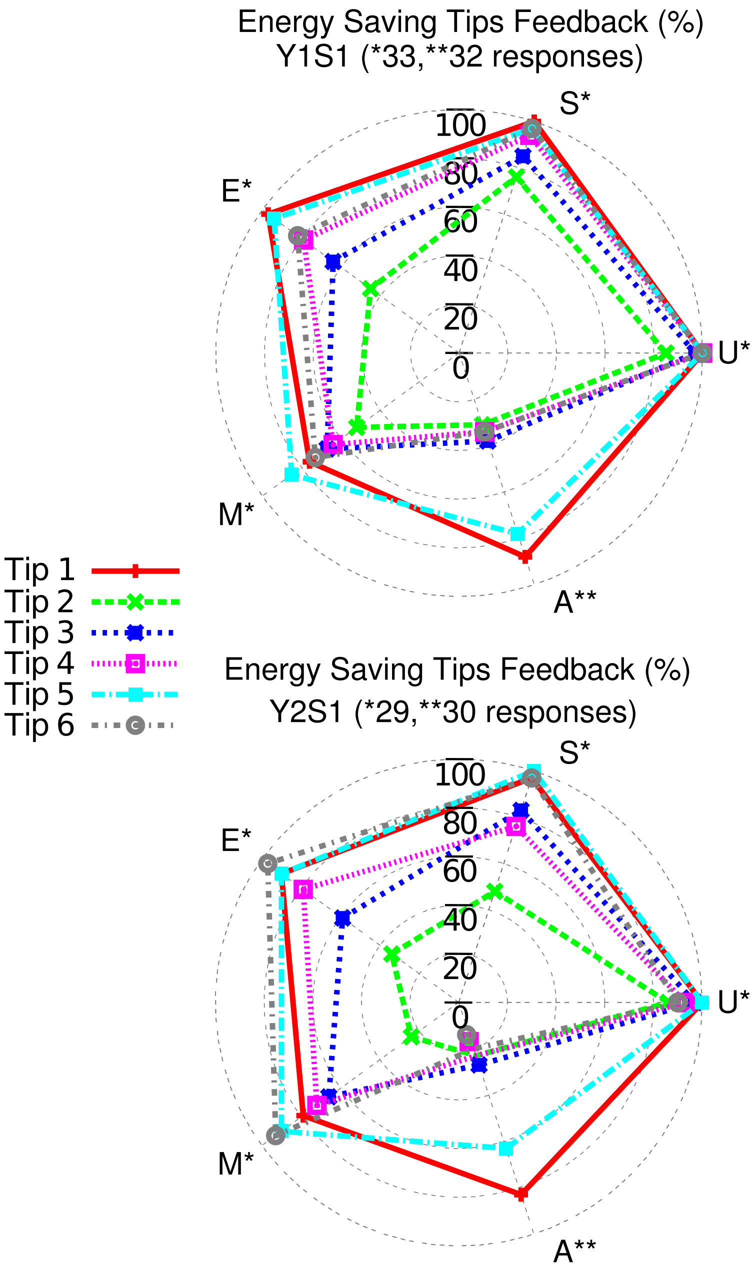

Figure 4.5. Feedback on energy-saving tips for Y1S1 and Y2S1. U: understandable; S: sensible; E: easy to carry out; M: motivated to use; A: actively practised during competition.

such tips are.) We found that only Tips 1 and 5 were successful in this respect. Tip 2 was the least successful (smallest pentagon): although it was understandable and seemed sensible, it was somewhat difficult to carry out, hence its low popularity. Tips 3, 4 and 6 gained reasonably high and balanced votes in U, S, E and M, but did not get practised much during the competition (see Section 4.4.1). Note that

Tip 6 is peripheral to our study, as our key aim was to find what actions and behaviour change users would accept *whilst using the computers*.

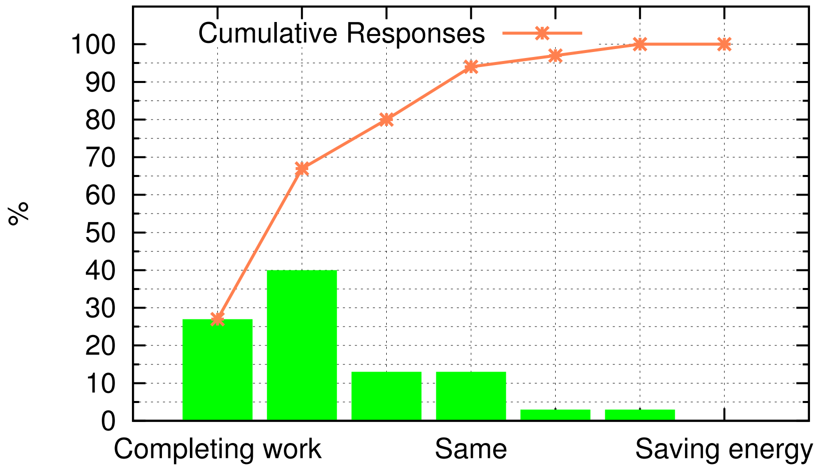

Figure 4.6. Distribution of users' personal preferences of completing their work vs saving energy in Y2S1. (33 responses)

Based on user's performances and feedback in Y1S1, we asked users in Y2S1, after the energy efficiency competition, a new question on the balance between completing their work and saving energy on a 7-point Likert scale[1]. As Figure 4.6 shows, despite being educated, energy aware and given incentives to save energy, as high as 80% of the 33 respondents gave more preference to getting their work done. 13% consider completing their work and saving energy are equally important. Only 6% of users were biased towards energy saving, but none considered saving energy to be the most important.

Our users made reasonable and balanced choices on the adoption of different energy saving tips over time. Figure 4.7 shows the evolution of the adoption rates of tips from survey S2 to S4. After high adoption rates during the 'try-out' period (before S2), use of tips dropped.

[1] Likert scale, or Likert-type scale, is named after its inventor, psychologist Rensis Likert in 1932 [81]. It is widely used in surveys to directly measure participants' attitudes with rating scales.

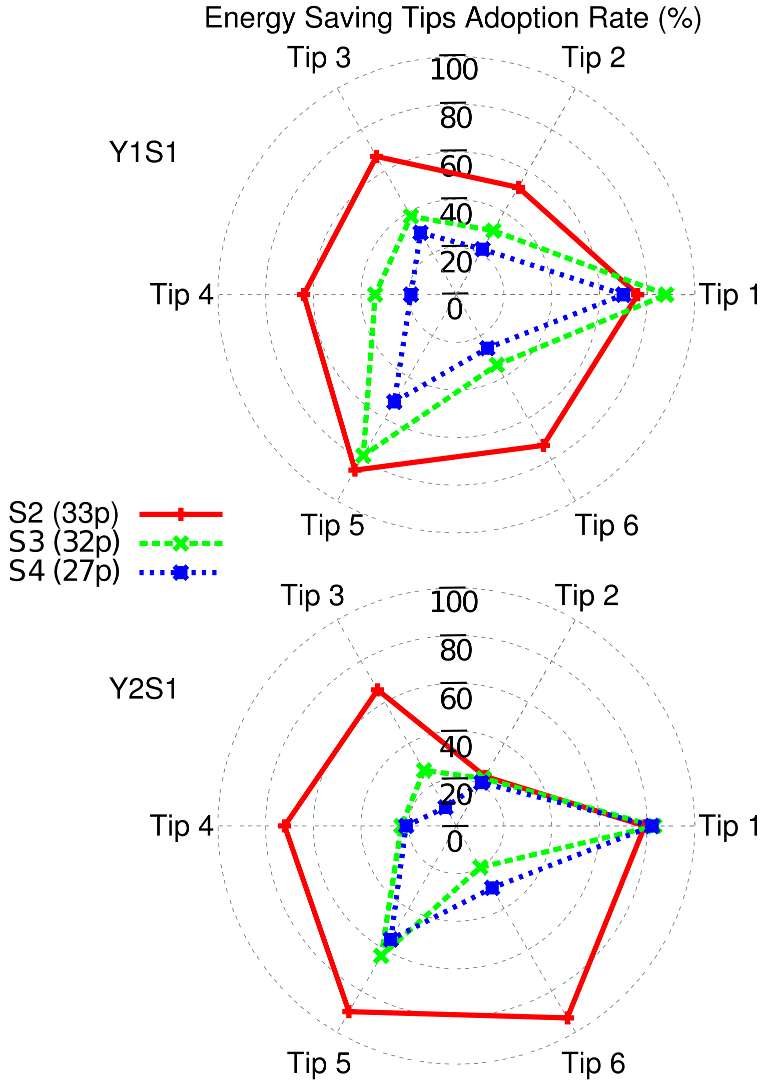

Figure 4.7. Adoption rates of energy saving tips by users who were motivated to save energy, recoded in surveys S2, S3 and S4. The overall rates decreased over time due to personal preferences, practicability and school/system restrictions. Tip 1 and 5 retained high adoption rates because they were the easiest to carry out.

4.3.6. Feedback is Welcomed and Helps Users. Measurement-based feedback is the most accurate and straightforward way to make users aware of their energy usage and potentially help improve energy efficiency.

In Y1S1, 97% of 39 users thought information on personal energy usage would help them to save energy in the lab. Also considered to be helpful was information on the School's energy usage as a whole (82% of users), and their peers' energy usage (77% of users), as well as more information on how to save energy (79% of users).

Many users responded that a reward programme would make a significant difference to them, although they were not aware of our future experiment plan.

Similar responses were received in Y2S1 (32 responses). 94% considered information on personal energy usage would help them to save energy at school; 78% wanted information on the School's energy usage as a whole and their peers' energy usage. 63% asked for more information on how to save energy (a reduction on the previous year's figure - this was likely due to an energy-saving campaign at the beginning of the semester, not as a part of our study but organised by the University).

By the end of Y2S1, 87% out of 30 users who submitted feedback on the power applet liked the enhanced version of the applet.

4.3.7. Energy Awareness. In Y1S1, some small prints of energy saving tips were kept next to each iMac in the lab in week 4. 91% of the users expressed in S2 (33 responses) that they were reminded to save energy by seeing the physical notice in the lab. Other significant feedback from the users were (1) demands of a computer application that tells when energy can be saved so users could act upon it; (2) demands of a taught module on green computing that teaches how to write low energy consuming applications.

It was encouraging to see people demand exactly what we had designed and implemented to assist them saving energy.

According to S3 immediately after the energy efficiency competition had ended, 63% of the users (32 responses) in Y1S1 and 67% (32 responses) in Y2S1 admitted they made efforts to reduce energy consumption primarily for the prizes.

Two weeks after our experiment and observations period in Y1S1 and Y2S1, 93% of the users (27 responses) in Y1S1 were still motivated to save energy, but only 76% (33 responses) in Y2S1 were the same. Figure 4.8 shows a detailed comparison between energy saving motivations across the interactive energy awareness study.

By the end of the first semester, 70% of the group in Y1, and 85% in Y2 still paid attention to their energy usage and/or practised energy saving techniques in the lab when the menu-bar energy applet was not present. Among those who were not as energy aware in Y1, 88% said they would be reminded to think about energy usage and/or practise energy saving techniques by the menu-bar energy applet.

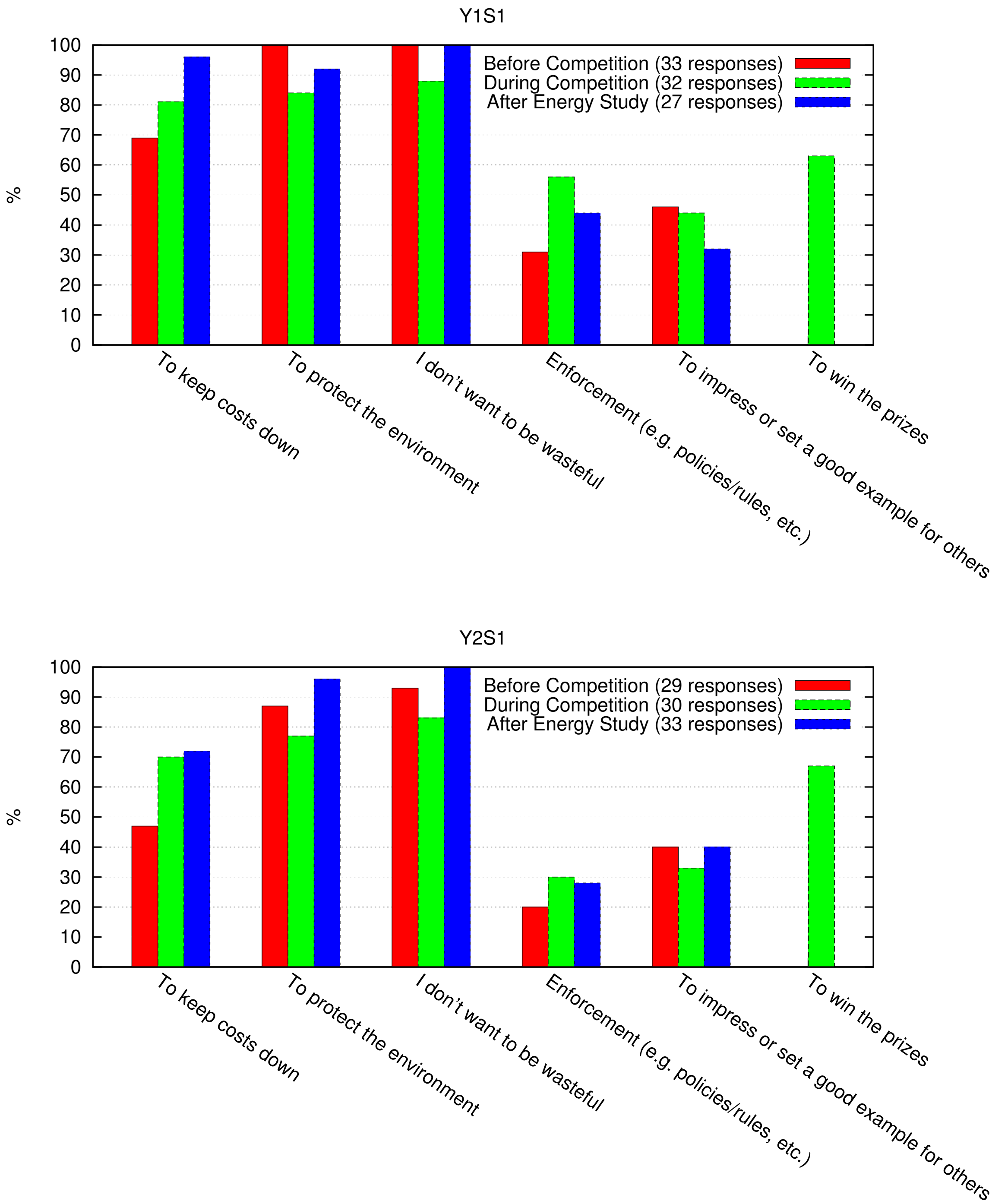

Figure 4.8. Reasons to save energy before and after competition.

4.3.8. Measured Changes in Power Consumption. While almost every user reported themselves 'green' with no significant attitude change in surveys, there were significant changes in their measured power consumption over the 2-year period. Over 75% of users in Y1S1 and over 85% in Y2S1 had a trend of decreasing power consumption when they used the lab computers. Many users were not as 'green' as they thought, and they had become 'greener' through participation in the experiment. (More discussion in Section 4.4.5.)

Trends of power consumption per semester were identified by mechanically producing the best-fit gradient from a series of percentage changes (Δ) in mean weekly power consumption, compared against the baseline:

$$\Delta = \frac{WeeklyAveragePower - BaselinePower}{BaselinePower} \times 100\%$$

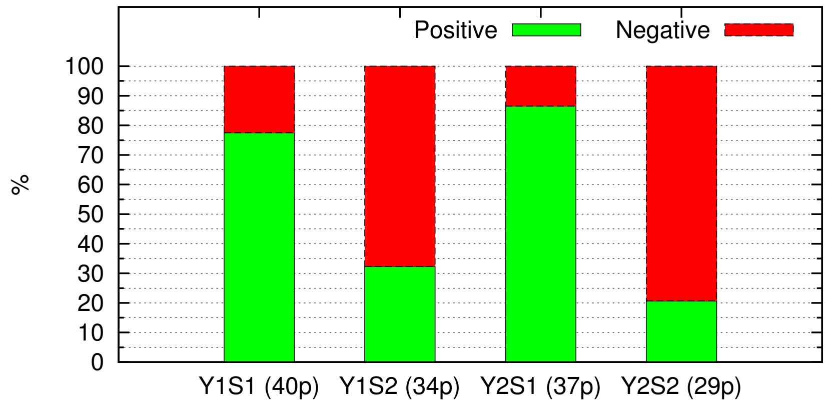

Figure 4.9. Proportions of positive (decreasing power consumption) and negative (increasing power consumption) trends in users' power usage. In both years, Semester 1 did have a competition (incentives) but Semester 2 did not.

Potentially, we might expect 4 types of pattern: (1) a series of overall decreasing measurements; (2) a series of overall increasing measurements; (3) a series of measurements with big, arbitrary variations; (4) a series of measurements with small, arbitrary variations. After eliminating incomplete data, we visually inspected each user's data per semester and saw no indication of patterns (3) or (4).

Therefore, we were able to summarise our observation in one simple plot (Figure 4.9).

From Figure 4.9, an overall positive result was observed in Y1S1 and Y2S1. A reduction of power usage can be observed through the competition periods when the feedback and information were both provided, and sustained till the end of the semester (Figure 4.10).

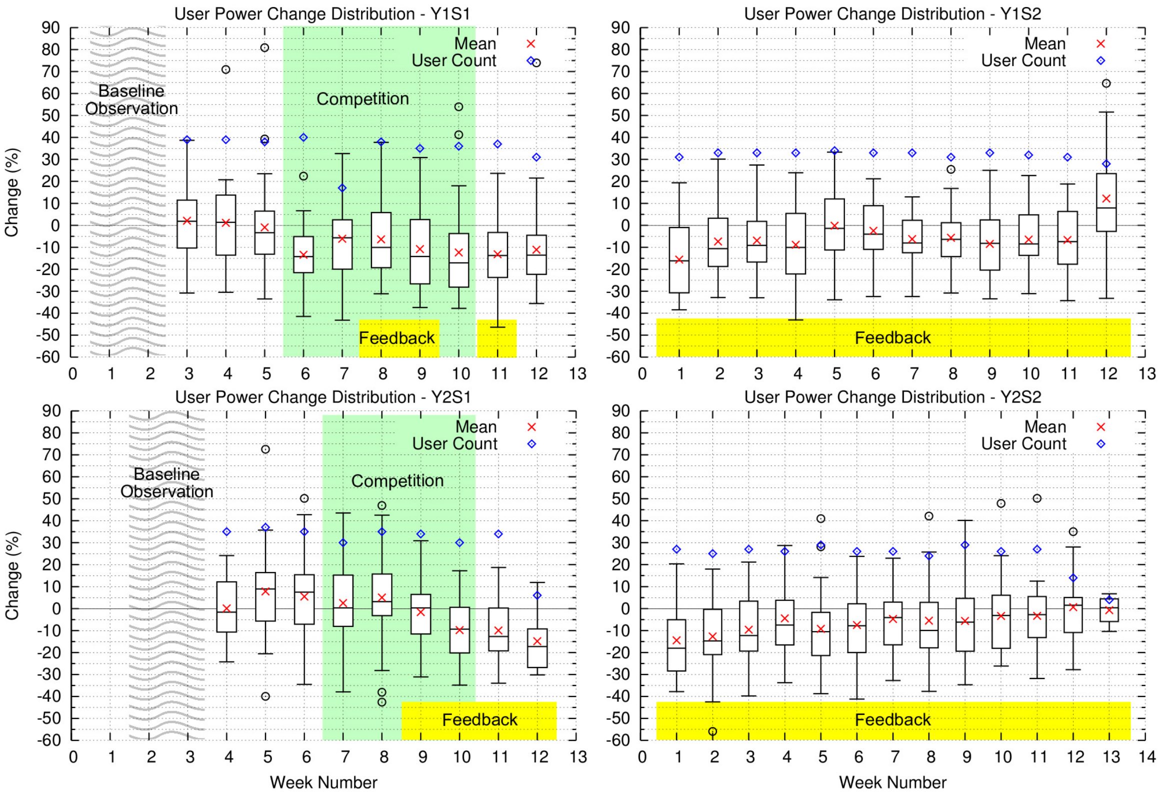

Figure 4.10. Distributions of users' power changes per week per semester using boxplot. A user's power change in a given week is calculated using the equation and description in Section 4.3.8 (the mean values taken over the duration of individual user sessions). The 'Change (%)" on the vertical axes are with respect to the baseline measurements in the first semester. Both range and mean of power usage in Y1S2 week 12, Y2S1 week 12 and Y2S2 week 13 were atypical due to the way the semester is organised (coursework deadlines, upcoming exams and low user counts in the labs). Therefore, these three figures (plotted for the sake of completeness) should be ignored in considering trends.

In the second semester of each year, the feedback (power applet) was available, but there was no incentive (no competition with prizes). As high as 65% of users Y1S2 and

75% of users in Y2S2 seemed to forget about saving energy and gradually increased their power consumption towards the end of semester.

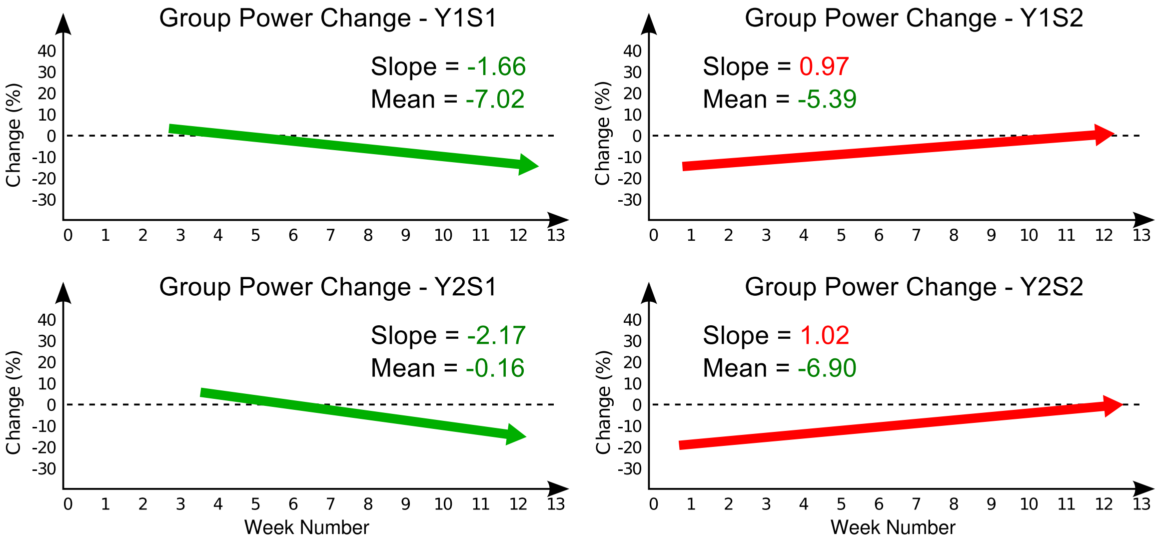

Figure 4.11. Approximate sketches of trends of weekly mean power changes in each semester shown in Figure 4.9. Slopes were obtained from linear regression analysis.

The repeating power change patterns are more obvious as sketched in Figure 4.11 based on liner regression analysis. Although average weekly group power consumption increased to exceed or match the baselines by the end of second semesters, the average group power consumption over the entire second semesters were still negative, indicating overall savings were achieved without added incentives.

4.4. Analysis and Discussion

4.4.1. Choosing Effective Energy Saving Tips. During the competition (Figure 4.5), Tips 1 and 5 gained significant popularity in both years due to their simplicity and ease of use. Other tips were only practised by around 30% to 40% of users in Y1S1 and even fewer in Y2S1, despite incentives provided. These numbers were much lower than those who claimed to be motivated to want to adopt energy saving actions prior to the competition. The primary reasons why users may be averse to using the tips varied.

Tip 1 (Reduce screen brightness.) Personal preference of bright, high contrast screens over energy saving.

Tip 2 (Use lightweight applications.) In both years, this was voted the most difficult tip to carry out. One example we gave was to use a simple text editor to write programmes instead of using complex, graphical IDEs. The users have argued that (a) they did not have a choice since first and second year students are required to use Eclipse, a relatively heavyweight IDE, to complete their coursework; (b) personal preference of tools/software that is most appropriate or convenient for the task, as it is believed that power could also be saved if the task was completed quicker. (c) There is no standard metric to tell which programs are more lightweight than others. Our power applet does not provide sufficiently fine-grained feedback per application to assist users to make such choices.

Tip 3 (Reduce use of audio and video.) Personal preference of online entertainment services. Some users did not often stream audio or video in labs anyway hence this tip did not apply to them.

Tip 4 (Block unwanted web content.) (a) Some users mistook that if they installed a browser add-on on a lab computer, other users who use this machine would be affected, hence were reluctant to do so out of goodwill. (b) It was troublesome to install browser add-ons on lab computers, or the installation would not succeed due to system configuration restrictions. However, we found out that 60% to 80% of users were willing to make such efforts to save energy. (c) General unpleasant experience with browser add-ons, hence rejecting all of them. (d) Unwillingness to block advertisements, in order to support websites, developers and free online services that rely on revenue from advertisements.

Tip 5 (Quit unused applications.) Personal preference for quick access to background applications (i.e. work efficiency) over energy saving (see Figure 4.6).

Tip 6 (Turn off computer after use.) This was peripheral to our study, as we were concerned with energy savings during use of the computers. However, it is interesting to note the large impact it can have, as has been observed by others, e.g. [27]. Some users did not want to cause inconvenience for other lab users out of goodwill, although we made it clear that the iMac in the lab only takes about 50 seconds from being powered-down to ready-to-use. Approximately two thirds of lab computers were kept on between 8am (auto-powered on) and 6pm (auto-powered off). The rest were kept on 24/7 because they were in use at 6pm and did not automatically power off. This gives a total of 822,528 'iMac-on-hours' (including both stand by and in use hours) in two academic years. Our experiment participants (approximately one third of all students who used the lab) utilised a total of 26,777.8 iMac-hours, which makes an estimated total of 80,333.4 hours of active use by all lab users. This only accounts for ∼9.8% of total iMac-on-hours for the lab. So, an estimate of at least 16,328.3 KWh[2] could have been saved from our lab over the two years if the iMacs did not automatically power-on daily, and every student turned off the computer immediately after use.

4.4.2. Rewards Are Good Incentives. During the first two weeks of the energy efficiency competition, the following pattern was observed in both years (Y1S1 week 6-7, Y2S1 week 7-8): (1) average power use in both weeks was lower than the week before the competition started. This indicates the competition and prizes worked well in motivating users to save energy. However, (2) average group power usage started to increase in the second week of the competition. We consider this an indication that the effectiveness of prizes was not long-lived, as users soon started to prioritise other factors or 'forget' about the competition.

The gradients of power changes declined from the third week of the competition until the end of the competition in both years. The overall energy consumption during the competition was significantly lower than pre-competition usage. Approximately 65% of users in each year reported they were motivated to save energy during competitions because of the prizes, so we conclude that rewards do encourage energy saving behaviours. On the other hand, the level of rewards should

[2]An iMac's minimal standby (not in use) power is ∼22 Watts, with screen automatically turned off.

be carefully selected to be: (1) high enough to stimulate energy saving behaviours; (2) not too high to distract users from their primary tasks, e.g. stop studying/working to save energy for the rewards. Unfortunately, there is no single solution. The choices vary from case to case.

In our case, from Figure 4.6, we see that users in our experiment prioritised completing their work. Assuming the level of rewards is a primary determining factor affecting users' choices, and offering bigger prizes could attract more attention on saving energy; we could then use the skewness of the distribution as a metric to adjust desirable level of rewards. For instance, we would expect to encourage our participants to make more balanced choices by slightly increasing the rewards we offer. However, is it worth trading off work efficiency of students (or employees in an organisation) for energy savings? Indeed, a trade-off must be made so that the cost of the compromise made does not exceed the gains of saved energy. However, it not easy to compare the loss and gain. We leave this as one of future extensions of this study.

4.4.3. Feedback Helps Reduce Power Usage. Per host live power feedback was displayed via an on-screen menu bar applet from the second half of the energy efficiency competitions (see Figure 4.10). A decrease in group mean power usage was observed compared to the previous week, when the applet was not in use. So, power usage feedback helped users to further lower their power usage.

In the second semester of each year, having feedback alone without incentives (the competition) still helped users to keep their mean power usage lower than without the feedback, although the average power consumption slowly and steadily increased from week 1 (lowest) till week 12 (highest) in both years. We consider this good evidence that our energy feedback promotes energy saving behaviour and delays the resumption of non-energy efficient computer use. It also shows that feedback alone is insufficient to sustain energy saving behaviour in this context.

We also observed that 75% of users in Y2S2 performed slightly better than those in Y1S2. In Figure 4.10, the variation of mean and the 75th percentile are similar. As the only major difference in the experiment between Y1S2 and Y2S2 was the design of the power applet, this is a good indication that improved feedback was more useful in promoting energy saving behaviour. However, as the experiments ran in consecutive years, there were 9 students in the second year that had already undertaken the experiment in the first year. This potential bias is checked by observing that their baseline measurements at the start of Y2 were similar to Y1's, i.e. the 9 students demonstrated no permanent behaviour change from their previous participation in the experiment.

4.4.4. Rewards and Feedback Together are Better. As discussed in Section 4.4.2 and 4.3.6, although helpful, none of rewards or feedback alone yields sustainable energy saving behaviour. However, consistent decreasing and low power power consumption were observed in Y1S1 weeek 8-9 and Y2S1 week 9-10, when both rewards and feedback were present. Although it is desirable to provide both rewards and feedback for longer periods to obtain more convincing trends of change, what we have observed so far are still good indications that rewards and feedback together produced the most effective energy saving.

4.4.5. Inflated Self-Assessments. In Section 4.3.2, we presented our users' very positive self-assessments. Later, by evaluating their real computer and energy usage, it appeared that about 70% participants (out of 23 who completed all four surveys in either year of study) had over- estimated their energy saving practices. They either became 'greener' while they have considered themselves already the 'greenest', or our measurements showed they were not energy efficient, even though they had considered themselves as 'green'.

This type of cognitive bias towards mistakenly over-rating one's ability higher than average is known as the Dunning-Kruger effect [43]. It is frequently observed among human subjects, which makes self-assessment on its own unreliable. As a result, it is important to collect both qualitative and quantitative data in this type of study to be able to draw more accurate conclusions.

4.4.6. Potential Energy Savings During Use. With a mean group saving of 16% and a mean power usage of approximately 60 Watts, over 10 Watts could be saved on each iMac during use. Over our 2-year experiment, an estimated saving of approximately 250 KWh was achieved by our users *during the use of iMacs*, excluding any saving by manually powering off the computers when not in use. If all of first and second year students had participated in our experiment (approximately half of them chose not to participate), the savings would have been even more.

We can translate this saving to a global scale in the spirit of a Fermi estimate[3]. Bloomberg[4] reported that Apple iMacs sales in 2012 were expected to reach 3.8 million, according to the research firm DisplaySearch[5]. Again, based on the estimate of 10 Watts power saving per iMac during active use (excluding savings by turning off the computer), over 38,000 KWh saving per hour could be achieved from all of the iMacs sold worldwide in 2012. Ofcom[6] estimates that the average time spent using computers to access the Internet at home is ∼5.5 hours per week per person in the UK and USA in 2012 (which is probably a conservative estimate). This makes an estimated annual saving of 10,906,000 KWh. An average UK household consumes about 4,226 KWh of electricity annually [25], which means the energy saving from the iMacs worldwide is enough to power approximately 2600 homes in the UK for a year. It is equivalent to approximately GBP 14.6 million[7] (USD 24.1 million[8])). Note that this is only for new iMacs sold in 2012[4], and does not include any other iMacs, or other desktop computers: the potential total global savings are significant.

[3]To make justified guesses and approximate calculations with little or no actual data.

[4] *HP Aims to Stand Out From Mobile-Device Frenzy With Desktop PCs*, http://goo.gl/zc7Z4D

[5]http://www.displaysearch.com

[6]Independent regulator and competition authority for the UK communications industries: http://goo.gl/6JUxsY

[7]Based on British Gas standard electricity price at 13.38 pence per KWh in 2013. http://www.britishgas.co.uk/

[8]At exchange rate of GBP 1 = USD 1.65

4.5. Limitations and Improvements

Although we have seen satisfying outcomes from this study, we discuss a number of limitations, biases and potential improvements.

The scope of this study is limited to an institutional environment with a group of frequent users all performing similar work: users did not have exactly the same tasks to accomplish, so their individual behaviour is not directly comparable. It would be worthwhile carrying out a similar study in a more diverse environment. However, the set of users represents a typical set for our institution, and perhaps other similar institutions, so is a useful indication.

Due to considerations of personal privacy and constraints arising from our ethical approval, it was not possible to distinguish between cohorts of students – first year or second year students. There is a possibility that the two cohorts behaved differently. A more detailed tracking of usage may yield finer-grained analysis, at the risk of reduced privacy and so the risk of fewer volunteers.

MacOS 10.6 was installed on the iMacs used for our experiment in Y1, and then upgraded to MacOS 10.7 in Y2. While there was no significant difference in energy consumption between Mac OS 10.7 and 10.6 observed with respect to our study, we still used normalised percentage power changes rather than raw measurements in our analyses to reduce any bias caused by either the operating system or individuals.

Lack of user control of the workstations due to institutional system administration policy reduced possibilities of even greater energy saving by allowing more control of the lab computers. Indeed, our institutional policy implicitly and indirectly prioritises systems security, system integrity, and operational stability, over energy efficiency.

The power applet consumed approximately 0.77 Watts of power (mean) during active sessions (See Section 3.8.2 for overhead analysis). Given that the iMac consumes ~32.9 Watts power during an active session when idling with lowest screen brightness, the overhead of power monitoring accounts for up to 2.3% of total power. This percentage figure is much lower during users' normal use of an iMac. On modern laptops, idling power could be as low as approximately 20 Watts, which makes the overhead slightly higher – up to approximately 3.9% in the worst case. Again, the percentage overhead decreases during users' normal use of computers. Although possible, we did not optimise the power monitor in terms of power efficiency for this study because we needed frequent measurements (once a second) to best gather detailed data for our experiment. Users achieved a mean of 16% group power saving (and up to 56% individual power saving) with our monitor executing. In summary, we achieved a mean saving of (just over) 10 Watts per user, even with the power applet running, so the 0.77 Watt used by the power applet is considered an acceptable cost.

In terms of the energy saving tips given to the users, our intention was to see specifically which tips the users, through their own preferences, would want to employ. For example, would being green have a greater importance for them than the possible inconvenience of using a particular tip to save energy? Another way of presenting the tips would have been to provide some quantitative information about the energy saving potential. For example, reducing screen brightness has the greatest impact on energy usage, unless very CPU-intensive jobs were running. However, this may have biased a user's behaviour: the screen brightness tip was the easiest to perform, as well as having the highest impact, and so users may not have tried other tips that had lower impact. Our unbiased presentation of the tips let us discover which tips the users would gravitate to naturally.

There has also been work in considering system level interventions, which can also result in large savings (e.g. [27]) and complements our study. Clearly, it would be useful to investigate and understand the compatibility between different user interventions and system-level interventions when used together.

4.6. Conclusions

In our 2-year study of energy usage in a University Computer Science teaching lab, we have found that when users are given a combination of incentives and measured feedback of their energy usage, they can be motivated to improve their energy efficiency. We find that incentives or feedback alone is not sufficient, but incentives with feedback produces and sustains energy-efficient practices. We show the possibility for, and quantify the gains from, having users save energy while the computers are in use, in complement to other systems controls and interventions when the computers are not in use. Our study also showed that some users, even if self-motivated by altruistic or environmental factors, still respond better when both feedback and incentives are present. However, we also find that 80% users do prioritise the tasks they have to perform over energy savings in our case.

Chapter 5

System-Level Energy Usage and Interventions

5.1. Contributions

This chapter presents and discusses computer hardware and software component level power usage as observed through the 2-year experiment as described in Section 3.7. We propose that system-level interventions and actions can help reduce energy wastage. Ideally, high level 'green' policies should be developed to coordinate system administrators and users, in order to regulate and encourage energy saving in the following ways:

(1) By observing users' preferences, lab computers can be configured with more aggressive power saving policies without affecting the quality of experience (QoE) of the majority of users, such as lower default screen brightness and shorten the waiting time of automated sleep/shutdown of systems.

(2) Users can be better educated on how to appropriately configure the OS they use. For example, launch their favourite code editors to edit source code files *by default* after double clicking on the files, instead of mistakenly launching unwanted applications and having to close them, which wastes time and energy.

(3) While users are given options of alternative applications for the same tasks (e.g. *Firefox*, *Safari* and *Google Chrome* for browsing the Internet), per application performance/energy evaluation should be provided to assist users make more informed choices. For instance, over two applications of same features but different energy efficiencies.

(4) Adjust users' privileges of installing/executing new applications. We have observed that while some users installed high power consuming applications for entertainment purposes, e.g. games, music players, others failed to install browser plug-ins that could help reduce network traffic and browsers' system resource usage, therefore energy consumption.

(5) Collaborate with academic staff in the selection process of applications used in teaching, and provide high quality applications in terms of reliability and power usage to both academic staff and student users.

5.2. Observations and Analysis

In this section, we present system-level observations drawn from the dataset collected over the two-year experiment. We show users' detailed hardware component level usage as well as application level usage, and discuss their relevance to system level power consumption.

5.2.1. North Bridge. The North Bridge chip controls high speed data exchange between CPU, RAM and graphics card. Although its power consumption is proportional to the rate of data exchange, its measured power dynamics were insignificant, from ~5.8 to ~6.9 Watts. More importantly, it is unclear how to reduce its power usage at user/application level. Our assumption is that the power performance of North Bridge could be optimised at the OS/kernel level, which is far beyond the control of average end-users and application designers.

5.2.2. Screen Brightness. Figure 5.1 presents weekly distribution of average user screen brightness settings over the entire experiment; and Figure 5.2 shows the derived screen power measurements using the chart in Figure 3.7. Since screen power increases near- linearly as brightness level is increased, we see nearly identical patterns in these two figures.

The participants were made aware of the screen being the single most power consuming element in the iMac. They were suggested to reduce screen brightness when possible while remain comfortable in order to save energy. Interventions involving feedback and rewards were used in an attempt to promote user behavioural changes, hence the repeating patterns of decreasing measurements in Y1S1/Y2S1, and increasing measurements in Y1S2/Y2S2. For more discussion and analysis on this see Chapter 4.

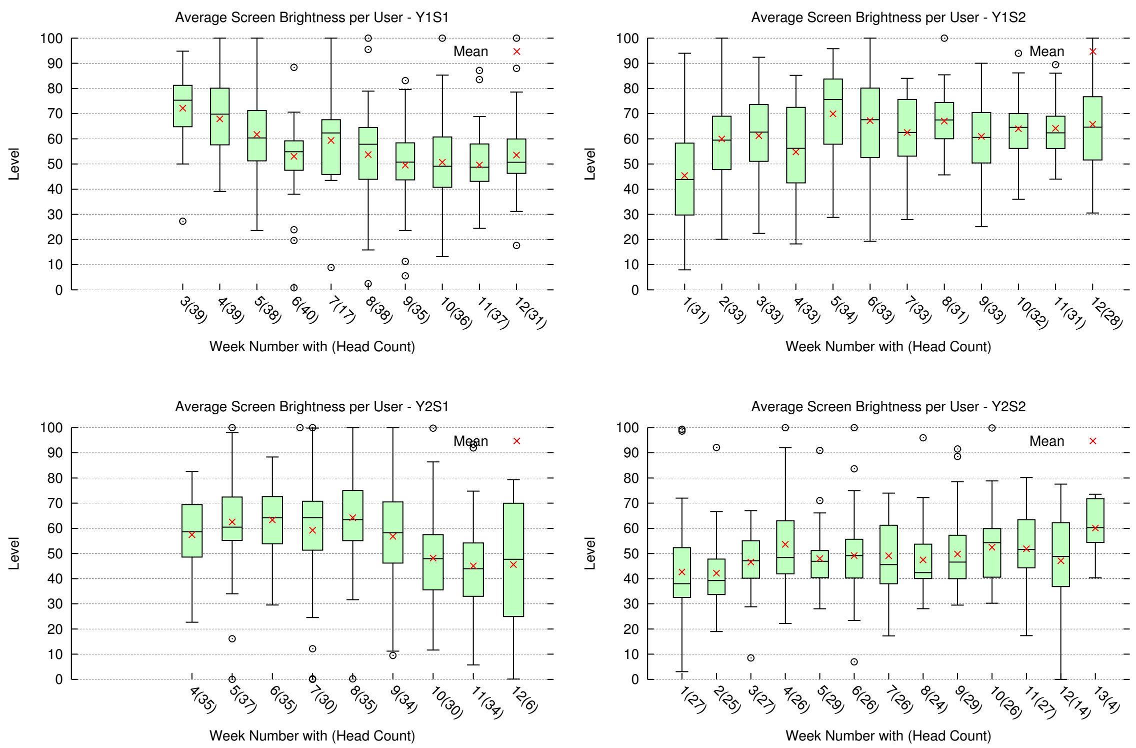

Figure 5.1. Average screen brightness settings by users over 4 semesters in 2 academic years. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

From a systems perspective, we see that the group mean screen brightness levels varied between 72 and 46 in Y1, and between 64 and 43 in Y2, which translate to ∼15 Watts and ∼10 Watts differences in power consumption respectively. Given an

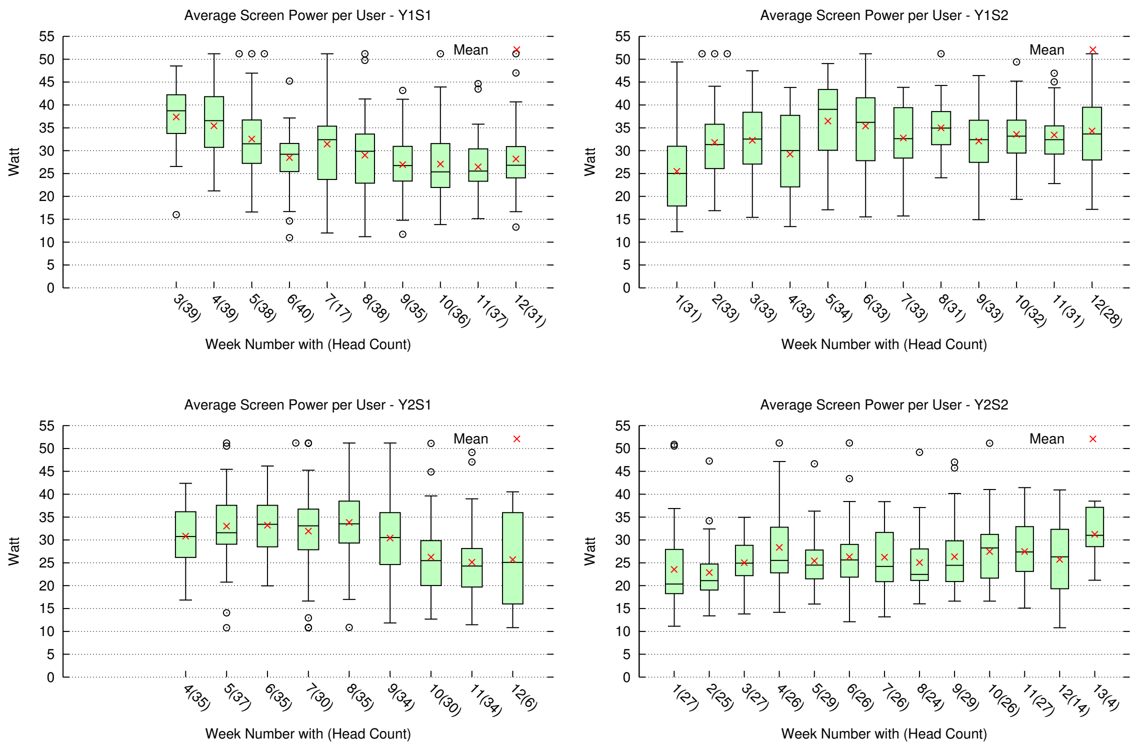

Figure 5.2. Average screen power by users over 4 semesters in 2 academic years. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

iMac's average in-use power consumption was between ~50 to ~60 Watts throughout each year, up to 15 Watts average group power saving by simply adjusting screen brightness alone is both significant and convenient.

During the entire experiment, three quarters (top of the box in each boxplot) of the users in each week voluntarily set their screen brightness to level 60 or lower for a total of 16 weeks. Half of the users in each week set their screen brightness to level 50 or lower for 16 weeks. Assuming the users dimmed their screens as low as they still felt comfortable with, level 50 could be a good candidate for the default screen brightness that satisfies at least half of the users, while may be accepted by users who would normally accept default screen brightness higher than level 50, especially the 25% users who chose brightness level between 50 and 60.

The mean and median in each week's boxplot almost overlap with very few exceptions in Figure 5.1 and 5.2, indicating user data were normally distributed, hence our observations are potentially representative of larger user groups.

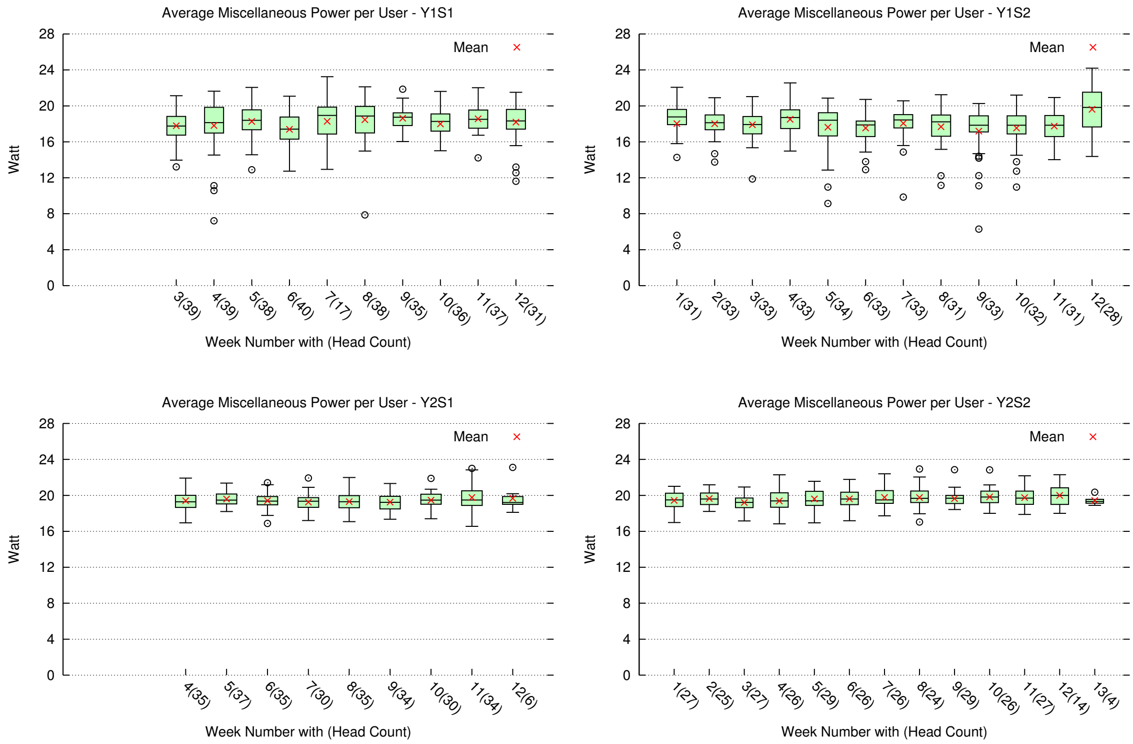

Figure 5.3. Boxplot of average total computer power minus screen and CPU power per user per week. Effectively, this is the average power of all other miscellaneous computer components. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

5.2.3. Machine Power. Since iMacs are all-in-one computers, the total power is naturally dominated by the built-in screen as well as CPU. Discounting the screen and CPU power, we get the power usage by all other 'miscellaneous' components as shown in Figure 5.3. The miscellaneous power of iMacs was reasonably constant with very small variance through out all the use cases over the 2-year study, especially in Y2. We assume the difference was due to updates of the OS (from version 10.6 to 10.7) and firmware (unknown version), which improved the control and operation of hardware components. This observation shows that: (1) it is potentially beneficial to keep machine software and firmware up to date. Although in reality, system administrators are mostly reluctant to upgrade systems that are already working and stable, albeit for serious issues, such as security patches and bug fixes; (2) it is unrealistic to attempt to save energy from miscellaneous hardware components other than the screen and CPU with the current level of system exposure to applications, OS and the users.

5.2.4. User Process Counts. User process count was a candidate metric to estimate user's computer power usage, based on the assumption that more processes would consume more system resources, hence more power. Our observations have shown this is a false assumption.

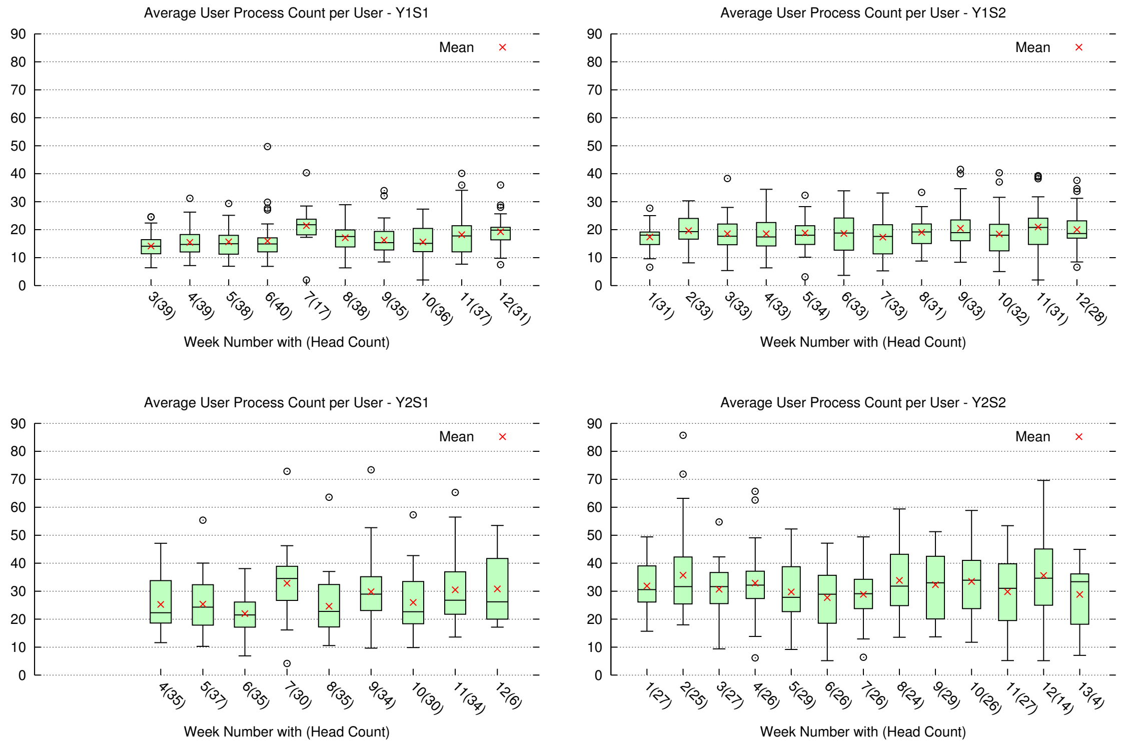

Figure 5.4. Boxplot of average user-process count per user per week. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

User process counts in Figure 5.4 show no significant correlation with CPU power (Figure 5.5) or miscellaneous components power (Figure 5.3) in the same period. Annually, user process counts in Y2 varied in larger ranges than those in Y1, but the CPU power usage showed an overall opposite pattern – CPU power measurements in Y1 were more spread out than Y2's measurements. On weekly basis, user process counts and the CPU power measurements show no significant relationship. For instance, distributions of user process counts in Y1S1 week 4 and 5 were almost identical, but the CPU power usage in week 5 were noticeably higher than that in week 4. User process counts in Y2S1 week 6 and 7 were off by ~10, but the CPU power usage had smaller differences. Clearly, the OS here is dealing with scheduling reasonably well, such that background processes that do not need to consume resources are suspended, even though they have been invoked by the user.

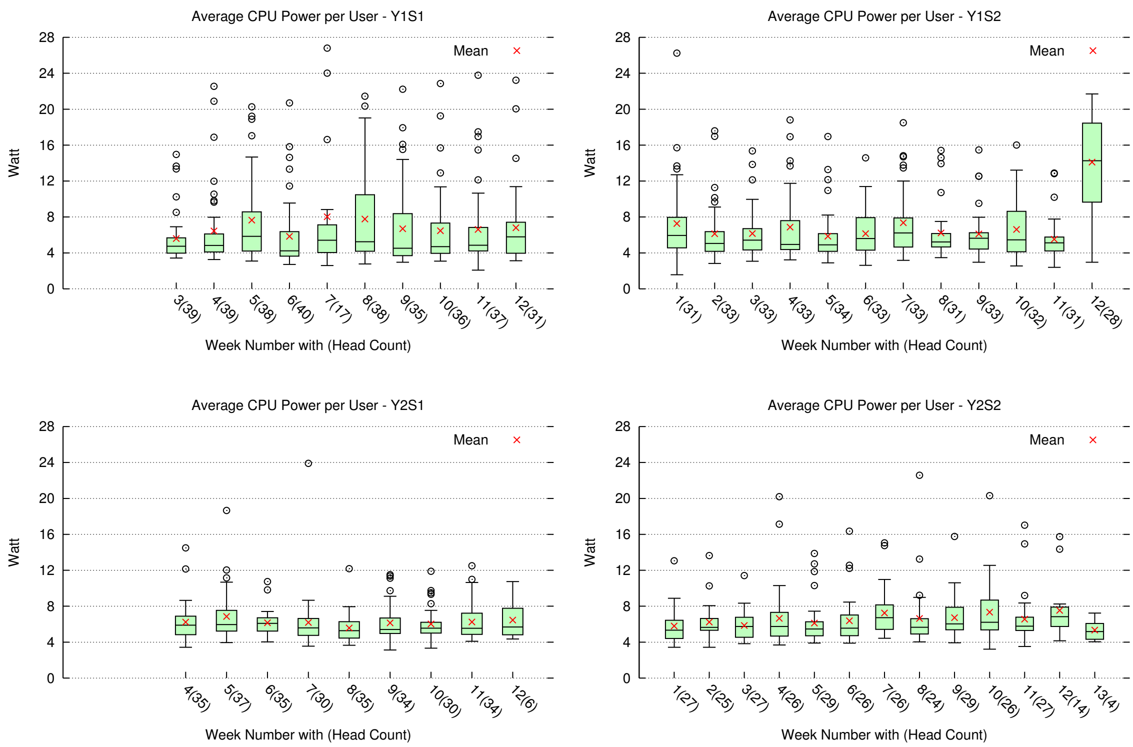

Figure 5.5. Boxplot of average CPU power per user per week. CPU baseline consumption, system applications/services and user applications all contribute to the total CPU power as a whole. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

5.2.5. CPU Utilisation. CPU utilisation can be momentarily high, but its average utilisation is normally very low for most personal computers. Figure 5.6 shows that except slightly higher overall CPU utilisation in Y1S2 week 1, over 75% of the users utilised less than 20% of their CPU time per week in Y1, and over half of the users utilised less than 10% of their weekly CPU time in the same period. In Y2, the group CPU utilisation rates were even lower with less variance.

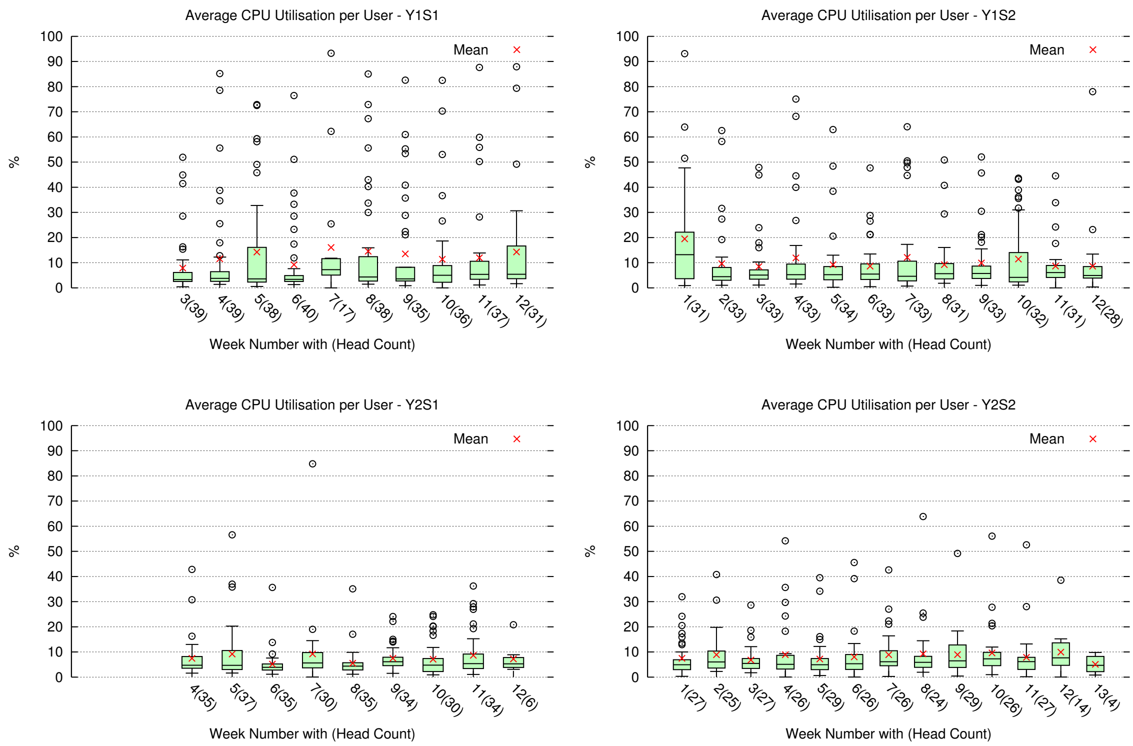

Figure 5.6. Boxplot of average CPU utilisation by user-processes per user per week. CPU utilisation by system applications and servers is excluded. Data in Y2S1 week 12 and Y2S2 week 13 are not representative and should be ignored due to small sample size. Data in Y2S1 week 12 and Y2S2 week 13 are not representative due to small sample size.

Since the data points in Figure 5.6 show users' weekly *averages*, any value over 50% could be considered much higher than the normal range of under 20%. Given the users' background of entry level Computer Science students, the primary reason for so many cases of high CPU utilisations is due to buggy programs they wrote and executed on lab computers (based on years of my experiences of being a tutor and lab demonstrator). A simple mistake in source code can easily lead to 100% CPU utilisation till the program terminates. What makes it worse is that programs often 'silently' run into such problems without any visible indication. For example, an infinite background search loop that never returns any result. In this case, the user may either wait for a while before realising something is wrong and manually terminate the program, or simply forget about it and just leave it running[1]. Much

[1] This is an anecdotal observation from (a) my own experiences as a lab assistant and tutor; (b) similar observations by other fellow lab assistants and tutors. Such mistakes and usage is typical of

energy is then directly wasted from hot CPUs, and indirectly from the thermal controlled internal computer cooling system (i.e. fans), and the external building air conditioning system that keeps the lab cool. It is impossible to prevent students from making programming mistakes that cause high CPU usage, but we can reduce unnecessary power wastage by making users more aware of their real-time computer/power usage with on-screen feedback.

While the utilisation of consumer-level CPUs could be a good metric to approximate computer power usage as previous study has shown[2], it does not accurately reflect how applications affect total computer power usage as a whole in this case. i.e. the pattern of user CPU utilisations observed in Figure 5.6 does not correlate directly with Figure 5.3 or Figure 5.5. This is because other hardware components of an iMac, e.g. screen and GPU, are also significant contributing factors of total computer power. Therefore from systems management's perspective, it is desirable to provide students with measurement-based power feedback, which directly indicates the accurate overall impact on computer power usage of their programs, in order to help improve or quickly identify unexpected behaviours, as well as raise awareness of energy-efficient computing.

5.2.5.1. *Exception.* A noticeable exception of low user CPU utilisation, but high CPU and miscellaneous power consumption was observed in Y1S2 week 12 (Figure 5.6 and 5.5). The users were not responsible for the high power usage. The abnormal computer and power usage was caused by misconfiguration of *system* services and/or applications. The significant rise of ∼2 Watts in miscellaneous power (Figure 5.3) was likely from the internal cooling system due to high CPU power/heat in the the system. Monitoring of computer and/or power usage of lab computers could have raised alerts

the user population we have observed, but other user populations may not have such behaviour, e.g. those using only installed applications rather than performing their own development tasks.

[2]Appendix A shows measurement-based computer power profiles of 2 high-end server CPUs and 2 low-end desktop computer CPUs. It is clear that server CPUs power consumption is not as proportional to its utilisation as it could be for the purpose of low latency and high availability. On the other hand, low-end CPU's power consumption can be more proportional to its utilisation level.

and helped system administrators debug the lab computers sooner, therefore reducing the energy wastage.

5.2.6. User Applications. Each iMac has system applications/services (e.g. *Dock*, *Core Services*) that are required by the operating system, pre- installed applications shared by users (e.g. *Eclipse*, *Firefox*) and personal applications installed in private user space (e.g. *TextMate*, *MacVim*). Apart from those system applications and services that run automatically without user control, the users are accountable for the launch/use of any other applications.

In the following sections, non-system applications used by student users are divided into four categories based on their primary purposes: browsers, code editors, document processors and media players. Applications in the same category are alternatives to each other, and users are free to use any of them to complete tasks.

Plots in Figure 5.7 to 5.10 illustrate the weekly use of user applications over 4 semesters in (1) user head counts regardless of how much/long exactly the application was utilised (the left column of each set of figures); and (2) the weekly mean CPU usage per application per user, calculated using Equation 4 (the right column of each figure). Note that the calculation does not necessarily reflect the true efficiency of each individual application, since we are missing key information to properly normalise application's resource usage including the duration each application was actively used or idling in the background, and the exact tasks it completed. What (2) shows (i.e. the right column of Figure 5.7-5.10) is the amortised CPU usage per user of the application, which helps to estimate the total CPU usage expected from similar group of users.

$$Mean\,Application\,CPU\,Time = \frac{Weekly\,Total\,CPU\,Time\,of\,Application}{Weekly\,User\,Count\,of\,Application} \tag{4}$$

5.2.7. Browsers. Three browsers were installed on the iMacs for everyone to use: *Firefox*, *Chrome* and *Safari*. All the browsers support plug-ins for extra features. Our energy saving tip suggested users to install advertisement blocking plug-ins and/or *Flash* contents blocking plug-ins. However, users have reported that not all plug-ins could be installed successfully on lab computers due to system privilege restrictions.

According to Figure 5.7, consistent patterns of browser popularity have been observed in 3 semesters during the two-year experiment except Y1S1:

- *Firefox* was used by the least number of participants, but utilised significantly more CPU time per user than other browsers, hence consumed more energy.
- *Chrome* was the most popular browser in the lab for 3 out of 4 semesters, and consumed significantly less CPU time (power) than *Firefox*. Students prefer *Chrome* for its deep integration of Google search and optimisations crafted by the internet giant especially for browsing.
- *Safari* was the most *launched* browser in Y1S1 due to Mac OS default setting for opening web pages/hyper- links, as well as the browser short cut that already exists in every user's *Dock*[3] when they first used the iMacs. It dropped to the second place for the rest three quarters of the study, which reflected its real popularity among student users. *Safari*'s CPU time (power) consumption was close to *Google Chrome*'s, but even less. According to Apple's documentation [4], its *Safari* browser takes advantage of a number of native Mac OS power- saving technologies, including intelligently suspending web videos and other plugin contents when they are not displayed in front and centre of the current browser tab.

It was not possible to exactly determine and compare how energy efficient each browser was based on the data collected (i.e. CPU time) without user browsing

[3] The *Dock* utility of Mac OS.

[4] http://www.apple.com/uk/safari/

context. Although we did not ask participants for the details of their browser use via survey, given that our participants were mostly first and second year students, and they had weekly or bi-weekly deadlines for coding assignments and reports/essays, our assumption is that the majority of them would access similar composition of web contents with browsers. For example, programming language documentations, tutorials and/or snippets of code for certain functions. In addition, some of them also spend a reasonably small fraction of their time on the lab computers on social media such as *Facebook*[5], *Twitter*[6], and/or on-line video/music services such as *YouTube*[7] and *Spotify*[8]. With similar workload, the mean weekly browser CPU time per user is sufficiently indicative. *Firefox* was the least energy efficient browser. *Chrome*, equipped with cutting edge technologies from *Google*, and *Safari*, which is optimised for its native operating system, have very similar performance in terms of CPU usage hence power consumption.

[5] A popular online social networking service `http://www.facebook.com`

[6] A popular on-line social networking and micro-blogging service `http://twitter.com`

[7] An on-line video sharing service `http://www.youtube.com`

[8] A popular on-line music streaming service `http://www.spotify.com`

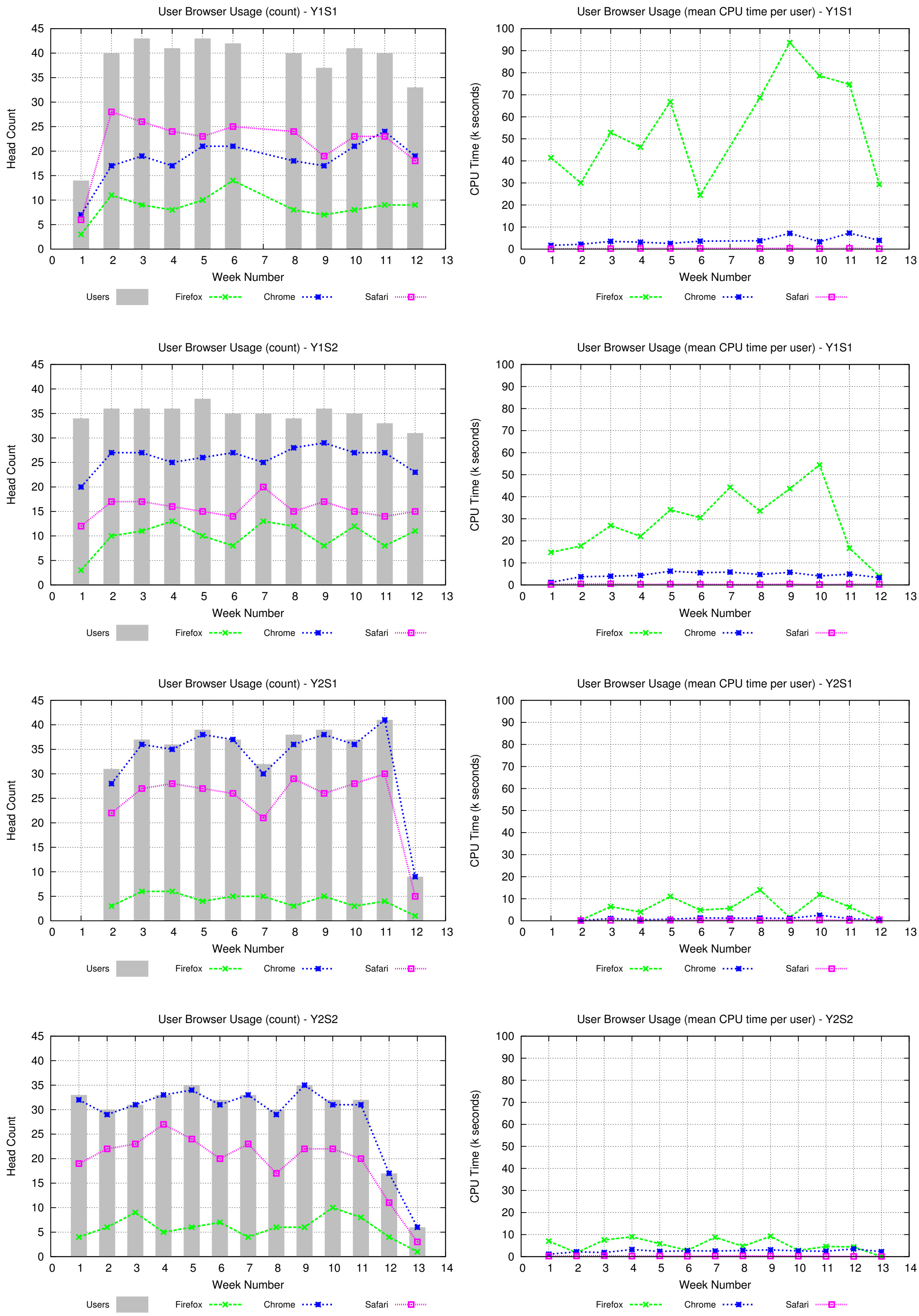

Figure 5.7. User browser usage. Data in Y1S1 week 7 are omitted because it was the university's (last) reading week. Students were not required to come to school during then, hence monitored computer usage was not representative.

5.2.8. Code Editors. A total of at least 10 different text editors and Integrated Development Environments (IDEs) were used by students to complete their programming tasks. The students were informed that IDEs generally consume more system resources therefore energy due to their rich and complex features. Simpler text/code editors are expected to consume less system resources therefore less energy. However, there has been no evaluation or measurements of code editors' power consumption to either support the assumption or to help participants choose power efficient code editors. This was part of our intention to observe (1) if the participants would change their code editor to use those that are expected to be more energy efficient; (2) what code editors the participants would use throughout the year.

In Y1S1, the most used code editor was *Together*, an IDE built upon *Eclipse* ($\sim$235MB binary size) with additional UML utilities. The first year students were required to use it for their coursework, hence the high usage. Its usage kept decreasing through out Y1S2 since students were no longer required to use it for coursework. Compared to *Eclipse*, *Together* provides exactly the same Java development assistance apart from built-in UML support, but is less stable. As a result, many first year students switched to *Eclipse* like most second year students did. In terms of energy performance, *Together* and *Eclipse* consumed significantly more CPU time per user than other code editors, hence more energy. This is expected since Together and *Eclipse* are both Java based large programs that provide rich features. Their execution naturally requires more system resources including memory, CPU and disk IO. *Eclipse* replaced *Together* completely due to changes in first year course set up, therefore significantly high *Eclipse* usage was observed in Y2. Again, its CPU usage was much higher than most other code editors.

Xcode (sim3.5GB binary size), the native IDE for developing software for Mac OS and iOS, was another popular code editor used by up to approximately half of our participants all year round. We know that no participants were required to develop software specifically for Mac OS or iOS as part of their course. *Xcode* was launched by many participants only because it was the default application to open C source code files, and not everybody knew how to change the default application to open certain type of files. As a result, participants either decided to use *Xcode* to edit their C source code, since it had launched and open the source code file already, or closed *Xcode* and reopened the source code file with their desired code editor. In contrast to *Together* and *Eclipse*, the mean CPU time per user of *Xcode* was very low (close to 0 second per user). This indicates: (1) although *Xcode* is a rather large program, it launches efficiently and consumes less system resources than we normally anticipate based on its binary size. i.e. *Xcode* occupies a few GB of disk space, *Together* and *Eclipse* only take hundreds of MB. One of the reasons is that *Xcode* is likely to be more modular in construction, as well as having better integration with the native Mac OS, hence leading to lower power usage. (2) since our participants only used *Xcode* to edit C source code, but did not even compile the source code with it, the majority of its functionalities as an IDE were not triggered or utilised at all. Therefore the low CPU usage as we observed. This observation indicates that if the users were taught how to change the settings of Mac OS, i.e. set default application for opening certain type of files, the small amount of energy used by launching *Xcode* rather than the users preferred editor could be saved, which scales up when taking the number of users and the number of C source code files each user opens into account. On the other hand, it is known that users of any product tend to use the default settings. Therefore, system administrators could improve the current situation by uniformly set up users' default file- application associations to something more appropriate, and let the users decide later on if they wanted to change these settings.

A common interpretation of 'lightweight' software among computer users is that the smaller a binary size the application has, the less system resources it requires hence less power is used. i.e. executing a 10MB application is expected to require less system resources than executing a 100MB one. While this simple metric stands valid in most cases under the assumption that an application is a monolithic piece of executable code/binary, it does not apply to modular, suite-based applications, which could have a large disc footprint but a small CPU footprint, depending on how it was used.

Xcode was one of the exceptions showing that a large program does not necessarily consume more power. As long as its CPU usage remains low and only limited modules are used, other system resource usage such as RAM and disk I/O only contribute little to its total power usage. On the other hand, *Smultron* (∼10MB binary size) and *Sublime Text* (∼27MB), two popular code editors for Mac OS, demonstrated the opposite. In Y1S1 and Y2S1, *Smultron*'s CPU usage was noticeably higher than other comparable small code editors. Its CPU usage in Y1S1 week 11 even exceeded what large IDEs (*Eclipse* and *Together*) had consumed. Similarly, *Sublime Text* in Y2 had consumed significantly more CPU time that other comparable small code editors did, including *Smultron*. In particular, *Sublime Text*'s CPU usage in Y2S1 week 10 was approximately 2.5 times what *Eclipse* had consumed; and in many other weeks during Y2, its CPU usage was close to *Eclipse*'s. Due to the ethical restrictions and limitations of data collection, it is not possible to determine how these lightweight in binary-size code editors were used that lead to such high CPU usage. Based on users' general feedback on *Smultron*, we know that it can be unstable during normal use. e.g. saving a file, cut and paste texts. It sometimes freezes and becomes unresponsive temporarily, or simply crash. The experiences with buggy applications tell us that it is most likely the abnormal behaviours that increase CPU utilisation, therefore consume/waste extra power.

In addition to avoid buggy applications that potentially could waste energy, users should also not always believe in a developer's claims without convincing evidence. For example, *IntelliJ IDEA*(∼350MB), '*a lightweight IDE for Java development*' according to the multinational company that develops and sells this software, performed badly in terms of efficiency in Y2S2. Its lowest CPU usage was close to *Eclipse*'s mean CPU usage; and its highest CPU usage was over 3 times *Eclipse*'s highest record.

From a user's perspective, application size could be used as an approximate metric to identify applications that are likely to be low power. Stability is another measure of both application's implementation quality and efficiency. Some good examples that were used by the users are *Vim*[9] and *Nano*[10]. Since most users tend to use provided applications in public computers, a system administrator's choices of applications play an important role that determines the overall computer system energy efficiency, system stability and user experiences. In most cases, system administrators are unable to thoroughly test applications for all possible use cases before deployment. A possible solution to identify problematic applications is to monitor application execution status per host at wide scale. To reduce overhead of monitoring, logging and detailed data collection may only be triggered by abnormal application behaviours, e.g. high CPU utilisation or crashes. The context as well as application metadata are both required to possibly determine the cause of abnormal behaviours. However, the monitoring and data collection should be carefully and ethically engineered to eliminate or minimise users' privacy concerns. Users should be made aware of the monitoring and given the choice to opt out.

[9]A popular command-line text/code editor, often called a 'programmer's editor' `http://www.vim.org/`

[10]Another popular command-line text/code editor `http://www.nano-editor.org/`

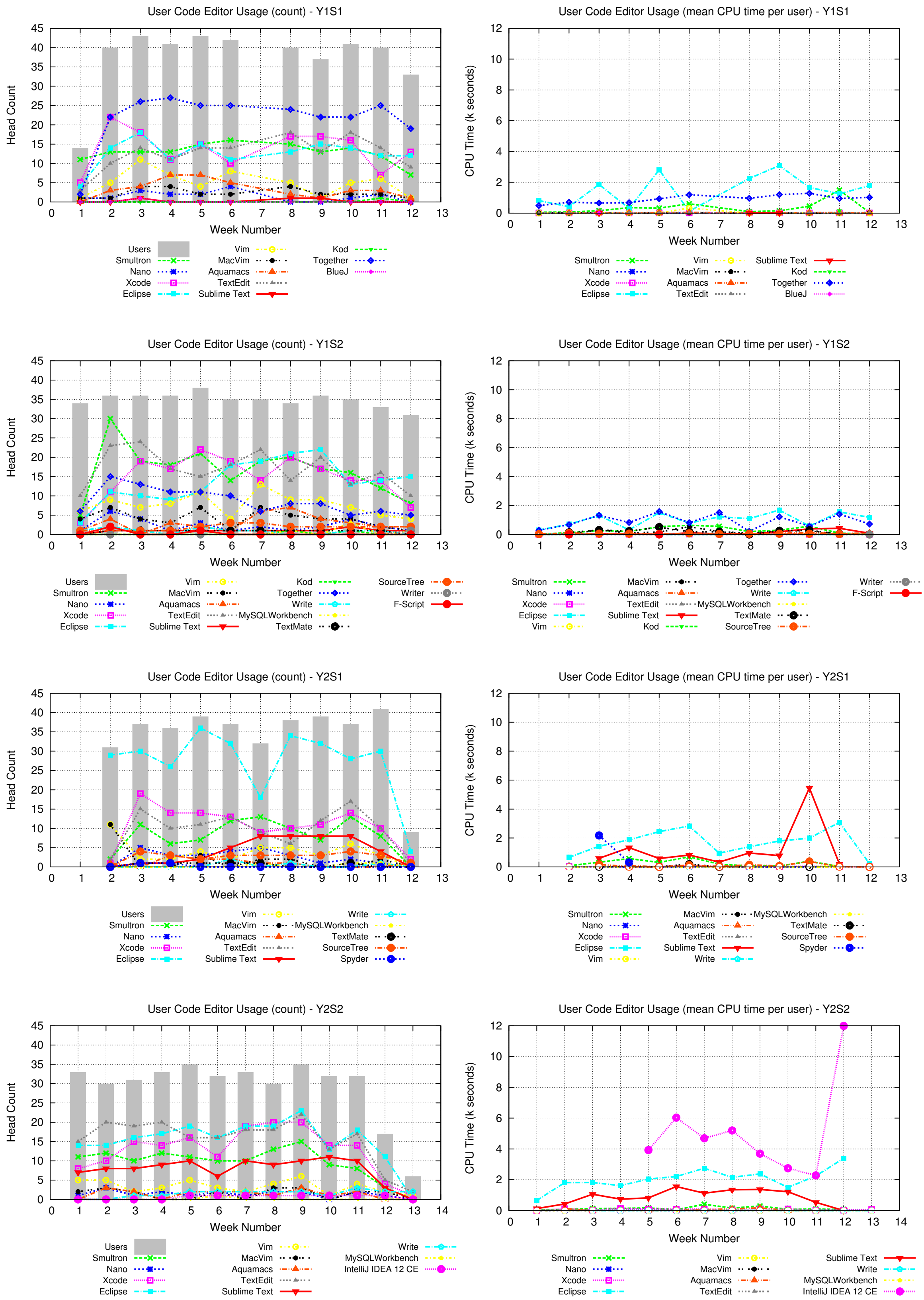

Figure 5.8. User code editor usage.

5.2.9. Document Processors. There were not many alternatives of document processors available to the users. Users' choices of document processors fall into two categories:

(1) What You See Is What You Get (WYSIWYG) style, i.e. *Microsoft Office* suite. The vast majority of users used *Microsoft Word* for writing lab reports, and *Microsoft PowerPoint* for making presentation slides. This is more to do with users' *habits* and *experiences* rather than their choice, since *Microsoft Office* suite dominates the document processor market, and have become one of the widely accepted document format standards. e.g. other office suite such as Apple's *iWork*[11] and *OpenOffice*[12]/*LibreOffice*[13] are all compatible with *Microsoft Office* document formats, but not the other way around. According to personal experiences in China and the UK, most computer users were taught to use *Microsoft Word* and *Microsoft PowerPoint* for such tasks in their early IT classes, and they kept using these applications either because there was no better alternative or they did not even consider using alternative applications.

Microsoft Excel was used by fewer users to process small amount of data and/or plot charts. The temporary increases of use of *Microsoft Excel* in Y1S1/Y2S1 week 3/10, Y1S2/Y2S2 week 2/3/9 were due to students' coursework that either specifically required using *Microsoft Excel*, or it was unexpectedly launched to open rather large datasets in CSV (comma-separated-values) format because of the default file-application association. As a result, Microsoft Excel's mean CPU usage per user was sometimes significantly higher than usual.

A few users used web browser-based online document processors, e.g. *Google Docs*[14] and *Microsoft Office Online*[15]. Is was impossible to distinctively track the use of online document processors among the limited data that we collected. Therefore,

[11] https://www.apple.com/uk/pr/products/iwork/iwork.html

[12] https://www.openoffice.org/

[13] http://www.libreoffice.org/

[14] https://docs.google.com

[15] https://office.com

potential use of online document processors would have been treated as browsing with web browsers.

In Y2S1 week 6, *LibreOffice* was installed and used by 1 user. It was likely a user wanted to try out the popular alternative to *Microsoft Office* suite, but for some reason did not carry on using it afterwards. Although *LibreOffice* is highly compatible with *Microsoft Office* suite and its user interface is intentionally made similar to *Microsoft Office* suite, there is no convincing evidence to show if *LibreOffice* is better or worse than *Microsoft Office* suite in terms of stability and power efficiency.

(2) Plain text/coding style, using *LaTeX*[16]. Although *LaTeX* can be a relatively non-straightforward tool of editing documents or presentation slides to many student users, it is widely used for producing scientific papers by professional users. *LaTeX* documents can be edited with simple text/code editors, hence are expected to be edited in a low power manner. However, most entry level student users prefer to use *LateX* front-end applications with convenient graphical user interface and rich features to assist their editing. e.g. *TeXworks*[17], *TeXShop*[18] and *LyX*[19]. These front-end applications are similar to IDEs, which could consume a lot more system resources than expected. An example is the mean CPU usage per user by *TeXShop* in Y1S2. Its highest CPU time was approximately 3.5 times that of *Microsoft Word*'s maximum CPU usage in the same period.

[16] A document preparation system and document markup language.

[17] http://www.tug.org/texworks/

[18] http://pages.uoregon.edu/koch/texshop/

[19] http://www.lyx.org/

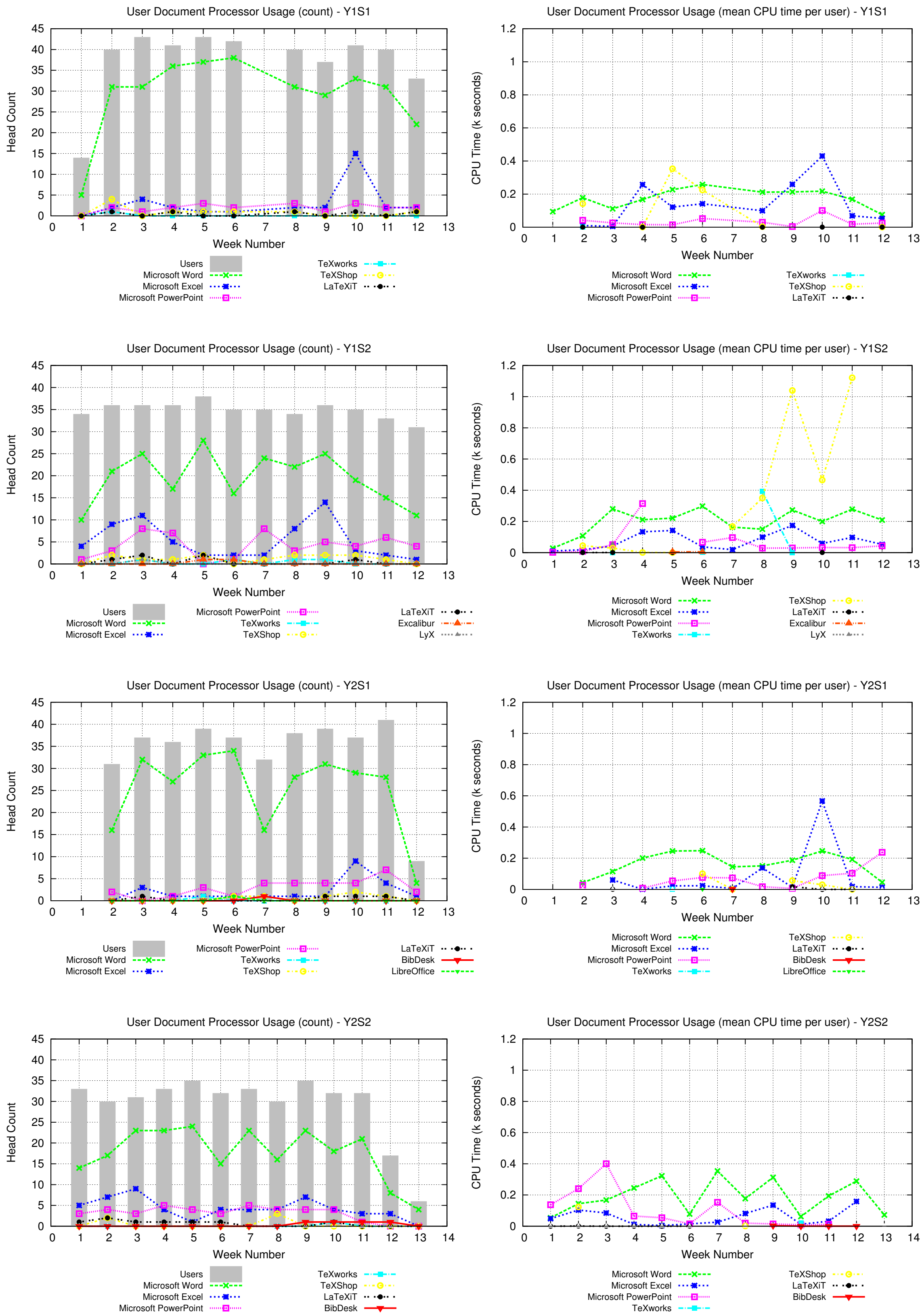

Figure 5.9. User document processor usage.

5.2.10. Media Players. Students use lab computers for studying as well as entertainment. Not to our surprise, up to over half of the participants used *iTunes* to either play local music (mp3 files) or stream internet radio in the background while they were coding or browsing[20]. While *iTunes* is well over 300MB in size, its mean CPU usage per user is mostly below 0.1 second, very close to 0 (see Figure 5.10). This is another example that shows application CPU usage is not necessarily proportional to its binary size.

In each academic year, the percentage of participants who used iTunes gradually increased from around 20% at the beginning to over 60% by the end of the year. Such a repeating trend demonstrates how (new) lab computer users were socially influenced by each other and learnt other's behaviour, i.e. to listen to music with *iTunes* while working on other things on lab computers.

In contrast, *Spotify*, the official application of *Spotify* online music service that streams music from the internet, was used by only 1 user in Y1S1 week 10/11 and Y1S2 week 11; by up to 4 users in Y2S1 week 10/11; and by up to 5 users throughout Y2S2. Note that this is a user- installed native Mac OS application as an alternative to *Spotify*'s web-based GUI accessible via browsers. Although this application is small (∼20MB), its CPU usage was significantly higher than any other media player (see Figure 5.10). Given the fact that *Spotify* is a popular music service and students tend to pick up habits from each other as discussed above, we assume more participants had used the web-based *Spotify* player. Unfortunately, only limited data was collected so that it is impossible to trace the use of *Spotify* services in browsers.

[20]The iMacs have headphone sockets so users are allowed to do this without disturbing others.

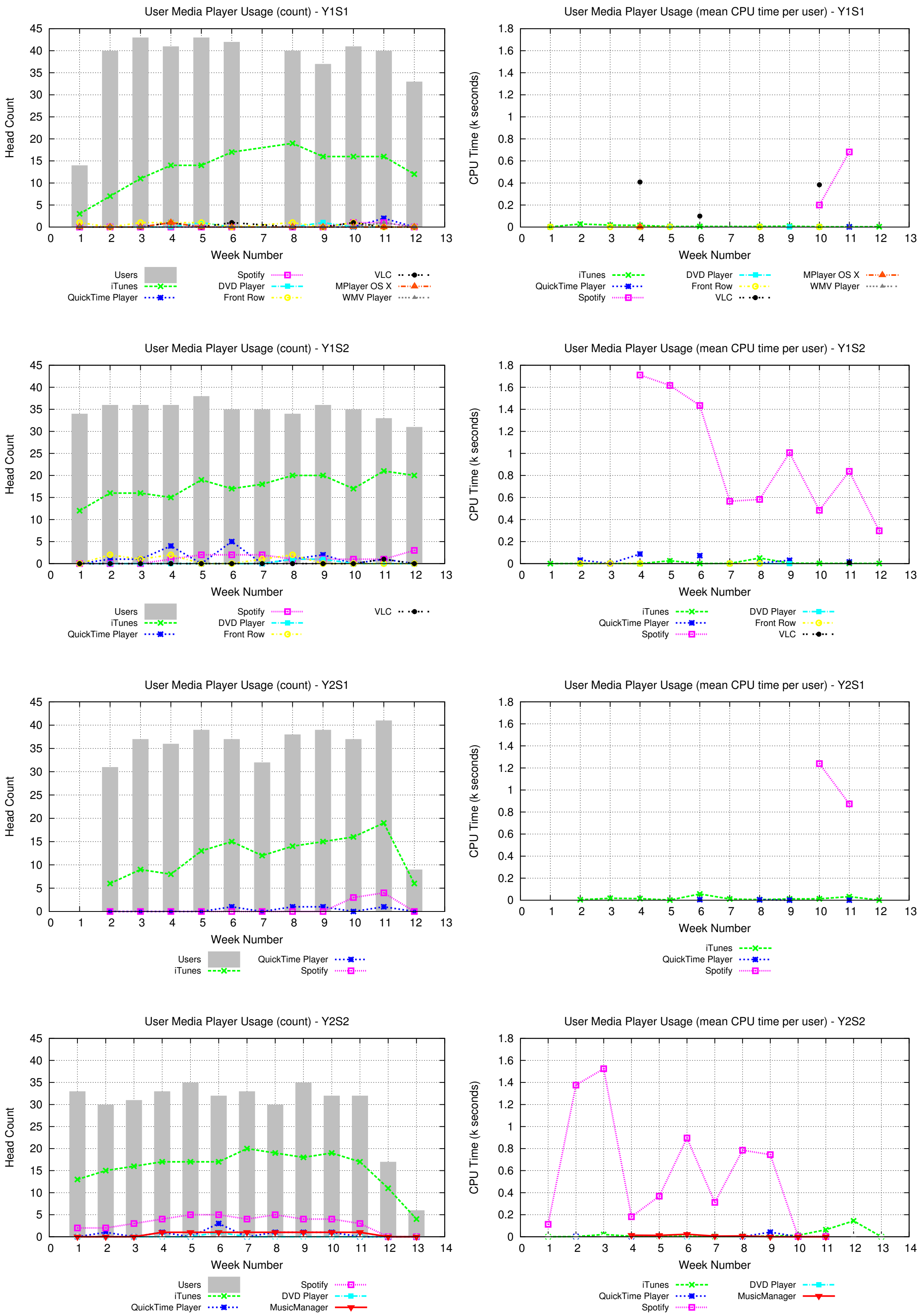

Figure 5.10. User media player usage.

5.2.11. Relative Greenness of Applications. Based on our observations, we listed approximate 'greenness' rankings of some typical user applications by category in Table 5.1 just by looking through their mean CPU time per user. Note that these figures are very rough indications based on non-uniform workloads of our participants as a group. Some applications of lower ranking could in fact be well implemented and more energy efficient than others, but are ranked lower for the particular good or bad use by the user group.

Table 5.1. Approximate power usage of some typical applications used by students on lab computers. Applications in each category were not tested using uniform load, but assessed by their real-life group usage.

Power Usage	Browser	Code Editor	Document Processor	Media Player
Low	Firefox, Safari	Vim	LaTeXIt	iTunes, QuickTime Player
Average		Smultron, Sublime Text	Microsoft Excel, PowerPoint	
High	Chrome	IntelliJ IDEA, Eclipse, Together	Microsoft Word, TexShop	Spotify

5.3. Interventions and Actions

Through observations and comparisons, we discovered possibilities for energy saving at the system level, in complement to user level energy savings actions as presented in Chapter 4. It requires joint effort of both system administrators and users to minimise energy wastage. The majority of users have already expressed their aspirations to be involved in more effective energy management activities (see Figure 4.4 in Section 4.3.4), but lack of system level information or coordination reduced the impact of their energy saving attempts.

In the following sections, we discuss possible interventions and actions to help system administrators and users control system hardware and software components differently, and therefore reduce energy wastage.

5.3.1. Make Default Settings Right. Behavioural economics tells us that individuals tend to go with the default options/settings, often regardless of whether it maximises individual or collective well-being [17]. This include both system hardware and software settings.

We have discussed how default hardware component configurations (e.g. screen brightness) could be improved to both satisfy users' needs and lower energy consumption; and how default application launch options could be changed to best suit personal preferences and reduce energy wastage. These interventions solely rely on system administrators' best judgement based on observed popular user preferences, requirements of teaching/academic staff, or personal experiences. Continuous system monitoring or frequent communications with student and staff users could also help improve the 'suitability' of default system configurations in terms of QoE and energy efficiency.

5.3.2. Users Need Clear Instructions. The participants were advised in Y1S1 week 4 and Y2S1 week 6 to use lightweight applications, which may use less system resources, hence reduced energy consumption. Although this sounds perfectly reasonable, it was unclear to users which application alternatives consume less system resources, or how to easily compare one application to another. e.g. *MacVim* compared to *TextMate*. As a result, there was no statistically significant change in users' choices of applications that could be linked to the energy saving advice.

A possible solution to help users make informed choices is that system administrators could benchmark and rank the pre- installed applications by category beforehand, and explicitly suggest users to use or avoid certain applications for better energy efficiency. While this could be a large amount of work, we could prioritise and focus on applications of potentially higher gain in energy saving. For example, code editors, document processors and media players all have very low CPU consumption compared to web browsers on lab computers, therefore we omit them for now since the gain in energy saving is marginal. The use of web browsers on the other hand, could save up to over 90 seconds of CPU time per user per week by not using Firefox but choosing Chrome or Safari instead. However, these energy usage rankings only stand valid for the specific use patterns by our participants, i.e. first and second year undergraduate Computer Science students working on their coursework. Other user groups, for example, library users or office workers, are expected to use computers quite differently and therefore require separate benchmarks tailored for their use patterns.

5.3.3. Academic Staff's Shared Responsibility. Students' choice of applications are influenced by not only their peers, but also the academic staff who teach them. Students trust their lecturers to be experienced experts with the knowledge they deliver, as well as knowing what are the best tools/applications for different tasks. For instance, if the lecturer used a very basic code editor and *Terminal*[21] rather than an IDE to teach programming in C, the students are more likely to use the same applications and not rely on IDE to program. The potential consequences of teaching staff's choice of problematic applications could be magnified if more students were required or suggested to use the same applications during their study.

An example we have observed was the use of *Together* and *Eclipse* for Java development. First year students in Y1S1 were required to use *Together* simply because their lecturer found it convenient to have UML diagram utilities integrated into the IDE, and so he set up practicals and coursework to be done with Together explicitly. After experiencing frequent issues with *Together* in Y1S1, the course was reorganised to use the combination of Eclipse and web-based UML diagram utilities[22] instead. As a result, significant increase in the use of *Eclipse* (head count) was observed in Y2 compared to the same periods in Y1 since all first year students in Y2 were told to use *Eclipse* instead of *Together*. In fact, *Together* was removed from lab computers in Y2 because it was no longer required for teaching.

[21] The terminal emulator included in the Mac OS X operating system.

[22] https://www.draw.io/

In the following year after our experiment, the first year programming course was changed again. Students were instructed to use *jEdit*[23], a lightweight in binary size code editor of ∼28MB, to learn and write Java programs; and use *Terminal* to manually compile and debug their programs. Again, this was the lecturer's choice to intentionally train first year students not to rely on IDE's assistance features when programming, such as automatic project management and code completion/generation. Students followed it to learn programming and completed their coursework as expected.

We do not know how energy efficient *jEdit* was compared to *Eclipse* or other code editors since it was used outside our experiment time frame. However, these annual changes have demonstrated that academic staff have flexibility over the applications used for teaching the same course, and such flexibility affects student users' energy usage indirectly. It is therefore desirable for the systems staff to collaborate with academic staff to reduce application level energy wastage.

5.3.4. 'Green' Policies. Unfortunately, most existing systems management policies prioritise system stability and future expansion planning. Energy awareness and concerns are only raised when pressured by legal and/or financial liabilities. Moreover, there is lack of collaboration between system administrators and users targeting energy saving. For example, a new datacentre was co-developed by the IT Services and Estate units at the University of St Andrews. It "saved 65,000 GBP on power costs and reduced the University's carbon output by 375 tonnes" in its first year of operation, and won the Gold Award in 2012 under Certified Energy Efficient Datacentre Award scheme [23]. This achievement was without the collaboration of users across the entire university. Users were not involved or even aware of the datacentre level attempts of energy efficiency improvements. Imagine how much more saving could have been made if institutional green policies and interventions were in place to encourage or enforce user level energy saving actions.

[23]A multi- platform text editor for programming. http://www.jedit.org

'Green' thinking needs to be incorporated into organisational/business polices in a way that cuts across organisational activities. This is similar to the way how staff are trained to handle security and privacy in such policies. Academic staff's shared responsibility to be green shall be reinforced and regulated. As future work, policies of general constraints on the use of applications in teaching materials should be developed by systems staff, in order to help set up good examples of energy efficient use of computers for students. To assist computer users make more informed decisions, requirements of features and insights of applications' performance and quality need to be effectively exchanged between academic and systems staff. Systems staff play a crucial role here to provide accurate and up to date evaluations of the applications-of-interest, and work out balanced options between 'greeness' and practicality with academic staff collaboratively.

As an example in our 2-year study, had an institutional green policy priority existed, then there could have been better cooperation between student users, academic staff and system administrators (see Sections 5.2.6-5.2.10 above) to coordinate such things as:

- Use of power efficient applications in teaching.
- Training of end-users for energy efficient use of lab computers.
- Use of power efficient applications for common tasks.
- Systems configurations of lab computers that reduce energy wastage.

Chapter 6

Conclusion

We conclude this dissertation with a summary of our novel contributions and directions for future work.

6.1. Contributions and Summary

This thesis argues that in order to effectively improve energy efficiency in ICT systems, end users should also be involved, who could potentially make additional energy savings that are complementary to savings already being made in datacentres and facilities by system administrators and energy efficient hardware. However, end users require detailed energy monitoring and feedback to keep them informed and therefore be able to make observable adjustments of behaviours for better energy efficiency.

We propose our own proof-of-concept energy monitoring infrastructure that works with different types of power meters, and potentially can be extended and integrated into existing popular system monitoring software as plug-ins for quick and reliable deployment (Chapter 3).

We believe users should be included in the attempts to save energy, and take the position that: (1) most users do not naturally attempt to save energy unless direct incentives are given. Therefore there is the potential to reduce users' energy wastage. (2) it is possible to motivate users to improve energy efficiency, both through encouraging change in user behaviour, and not just relying on systems-level (hardware and software) interventions. We modified and extended our flexible energy monitor prototype to collect process level computer usage as well as power consumption from 72 iMacs over 2 academic years in a student lab at school, to investigate: (1) if end-users can change their behaviour in using computers and improve energy efficiency; (2) what changes in their use of ICT systems are they willing to make to improve energy efficiency; and (3) how feedback on energy usage and incentives (rewards) help them to improve their energy efficiency. (Chapter 4)

By the end of the experiment, we draw additional system- level insights from collected data, discuss how system-level coordination between users and system administrators and 'green' policies could help further reduce energy wastage in ICT systems (Chapter 5).

The key findings and contributions of this thesis are summarised as follows::

(1) We have developed a flexible energy monitoring infrastructure for ICT Systems, that is capable of gathering energy information on a system-wide basis, at scale, including heterogeneous devices and infrastructure.

(2) We have built simple working prototypes of the flexible energy monitor as proof-of-concept, and successfully extended it to collect additional process level computer usage as well as providing meaningful power feedback to users.

(3) We have designed and conducted an experiment with human subjects, and shows that within a university computer teaching lab, feedback on student users' individual power use coupled with some small financial rewards produce energy savings. This is complementary to existing work that considers system-level interventions and mechanisms that are designed to function without the cooperation or knowledge of users.

(4) We have shown that incentives together with feedback about energy usage were required to sustain energy-saving behaviour: feedback alone was not

sufficient, as personal preferences of completing work, convenience and/or certain workstation configuration have overwhelming priority over energy saving.

(5) We have demonstrated that system administrators could adopt more aggressive power saving policies without affecting the quality of experience (QoE) of the majority of users, such as lower default screen brightness and shorter waiting time before switching computer to power saving mode or turned off completely.

(6) We have pointed out that energy is wasted by users' misconfiguration or misuse of applications. Therefore, energy wastage can be reduced if system administrators could provide users sufficient information or training on how to appropriately configure the computers they use.

(7) We have suggested that system administrators could provide per application performance and energy evaluation to both student users and teaching staff, in order to help them make more informed choices over what alternatives applications to use for the same tasks.

(8) We have proposed that high level 'green' policies should be developed to coordinate system administrators and users, in order to regulate and encourage energy saving.

Above points (1) to (5) are based on observations and analyses using real data. Points (6) to (8) are potential inventions and actions based on the observations and analyses, which could be beneficial if practised in real life.

In addition to the above contributions, we would like to highlight the *novelties* of my work as follows:

(1) A scaleable, user-side energy monitoring and feedback system. Although only tested on Mac OS, the architecture is not constrained to a specific platform,

and so it could be extended to other Unix-like systems (with small amounts of re-engineering), and Windows (with a significant amount more engineering).

(2) The first, longitudinal study (2 years) with human subjects on lab-based energy usage was carried out. 83 human subjects (45 in Y1, 47 in Y2) were involved in this experiment. A total of 26,778 hours of active computer use was monitored, and $\sim$2TB data were collected and manually processed using custom scripts.

(3) Insights were made into the energy usage of applications by users, amongst a category-based analyses of systems energy measurements. This has highlighted where responsibilities for energy savings can be distributed across an academic organisation (end-users, system administrators and teaching staff), but the analyses could be applied to other organisations.

We elaborate on our contributions as below:

We firstly described an agent-based flexible system monitoring infrastructure with a focus on collecting power information from heterogeneous devices. It is designed to support legacy devices, be vendor-independent and scaleable. Its basic components consist of the Agent, the Collector and the Relay. The Agent is designed to support multiple types of power meters. It polls raw energy information from power meters and uploads it to the Collector. The Collector has three functions: (1) to collect energy usage information from Agents; (2) to control and configure Agents; and (3) to pass on to the Agent energy-related actions to invoke upon the real resource (not yet implemented). A Collector will store information received from Agents for applications such as Web-accessible graphing. The Relay hides the heterogeneity in communication and offers network penetration benefits for communications. It is used to provide a gateway facility for communications, for example, exchange information between private and public networks, where direct communication to the Collector is not permitted. In case the Agent(s) use an underlying communication technology that does not support the Internet Protocol, the Relay is expected to be deployed on a node that is able to communicate with both Agents and the Collector directly. These functional components may be combined to form hybrid components, permitting scaling for the information model and for communication. For example, an Agent/Collector hybrid collects data from other Agents as if they were power meters, aggregates the data and forward them up via its Agent half.

This power monitor shares similar hierarchical, agent-based data collection architecture with Ganglia. Potentially, it is possible to integrate the energy monitor with Ganglia for quick deployment. The prototypes were implemented to work with ACPI, IPMI and CC128, an off-the-shelf domestic power meter. As the power monitor was extended for the 2-year experiment, support of iMac's SMC power sensors was implemented, which demonstrated the flexibility and capability of the power monitor.

We then presented user level data and analysis of the 2-year observation. It shows that students in a school lab environment will change their behaviour to be more energy efficient, when appropriate incentives (i.e. financial rewards) are in place, and when measurement-based, real-time feedback about their energy usage is provided. According to our measurements, weekly mean group energy usage as a whole reduced by up to 16%; and weekly individual user energy consumption reduced by up to 56% during active use of computers. This is a different approach to most existing system-level interventions that are designed to function independent from human users when computers are idling. Timely and accurate measurement-based feedback improves user energy awareness and helps users to explore and adjust their use of computers to become 'greener', but is not sufficient by itself. Our observations show that when rewards are removed, users' energy-saving behaviour gradually disappear as if they are forgetting about energy saving.

We observed that rewards incentivise 'non-green' users to be 'green', as well as encouraging those users who already claim to be 'green'. In fact, one of the findings is that about 70% users tend to over estimate themselves. This type of cognitive bias towards mistakenly over-rating one's ability higher than average is known as the Dunning-Kruger effect. Dunning-Kruger effect is frequently observed among human subjects, which makes self-assessment on its own unreliable. As a result, it is essential to collect both qualitative and quantitative data in user-oriented studies, to be able to draw more accurate conclusions.

We showed hardware and software component level energy usage analysis using the data collected from the 2-year experiment. On a higher level, system administrators, academic staff and student users are all responsible for reducing energy wastage in ICT systems. We observed that energy wastage can be reduced by end-users taking simple actions such as dimming unnecessarily bright screens, using more energy efficient applications and correctly configuring the OS and applications according to personal preference and habits. However, end-users rely on information provided by system administrators such as instructions of changing OS configurations and per application power profiles, before they can make more informed choices to be energy efficient. It is also important for the academic staff to gain similar knowledge, and consider energy efficiency when selecting applications for teaching and coursework. Due to lack of experiences, students tend to unconditionally accept and carry on using applications suggested or required by the teaching staff. Therefore, energy saving or wastage from a single application could potentially scale up and make significant impacts on the total lab power consumption. There is the need for institutional 'green' policies to enforce and regulate energy efficient use of ICT devices and better collaborations between system administrators and end- users, similar to existing security and privacy policies that are widely known and followed by both staff and students.

We also observed that other than the screen and CPU, other system hardware components consume almost constant power with very little variance at all times. We suggest that it is not worthwhile or practical to attempt to further reduce power consumption from other hardware components by end- users. On the other hand, firmware updates seemed to improve system power usage. Therefore it could be beneficial to keep ICT devices up to date with the latest software/firmware updates.

6.2. Critical Evaluation and Future Work

The scope of this study was largely limited by the user group and devices available, and there were a number of unexpected variables due to lack of experience. Although we intended to carry out a passive observation of user behaviours and power usage without system level intervention, better coordination with the systems administrators could have improved the quality of our longitudinal study in the following ways:

- User privileges could have been elevated – users of lab computers were unable to install browser plug-ins as one of our energy saving tips suggests. This reduced possibilities of energy saving from browsers and various browsing activities.

- Annual OS upgrades could have been postponed – Mac OS on the lab computers was scheduled to upgrade every year during university summer holidays. During our 2-year experiment, the OS was upgraded from version 10.6 to 10.7 after the the first year of experiment, in August 2012. Although this had limited impact on the observations since each individual user's data were compared against his/her own baseline usage, application level power usage may still be affected by OS/kernel level changes, e.g. better scheduling algorithms, improved hardware component level power management software and/or firmware.

The following three factors may have introduced biases to the outcome of this study. They should be considered in future studies:

- Approximately half of the students we spoke to decided to participate in our study; and we later found their attitudes towards energy saving were mostly positive. This could be biased due to self-selection during the recruitment process. i.e. those who choose to participate in an energy efficiency study are more likely to save energy. There are two common solutions to avoid self-selection: (a) to recruit all students; (b) do not disclose the real purpose of the study, so participants are less likely to focus on the KPI – in this case, their energy usage. However, both of these solutions may involve higher level of ethical approval, which should be considered before commencing the study.

- The level of rewards used in this study was arbitrarily chosen within a reasonable range set by our sponsor. Although most student participants expressed their interests in winning the prizes, and still gave their preference to completing tasks over saving energy, we could not determine if the level of rewards was too high or too low that potentially biased the results.

- The use of first two weeks' computer usage in each academic year as baseline data may have introduced bias. Since the workload is unevenly distributed across each semester, which is likely higher in the following weeks; the actual energy efficiency may be higher than our statistics.

For future work, it would be desirable to conduct similar experiments in more diverse environments, where users may (a) be able to gain more control of the ICT equipment they use (e.g. install or remove software, turning off unused hardware components such as WiFi and Bluetooth modules); (b) carry out similar tasks therefore comparable with each other; (c) have other social backgrounds than students. An immediate example is to experiment with people in office environments, who have more stable and consistent work hours (typically 9am to 5pm, 5 days a week for almost the entire year). Given the large population of frequent computer users at work places, the aggregated energy savings are expected to exceed what could be achieved from university students.

Depending on the potential population of participants, it may be beneficial to extend the energy efficiency competition to a longer period, and offer more frequent prizes, e.g. weekly winner(s) rather than 3 winners for the entire 4 to 5 weeks of competition. It is expected that frequent prize giving and announcements could raise the awareness of users and work as a repeating incentive to keep users engaged. More users may be attracted to saving energy, and the collective savings may therefore increase and exceed the investments of rewards. In addition, penalties for energy wastage could be issued as a different form of incentive for saving energy, although this should be carefully designed to not to drive users away. Our study focused more on the systems engineering perspective; it is therefore desirable to get psychologists, sociologists and Human-Computer Interaction (HCI) experts involved in the design and/or the analysis of future studies, which could lead to further improvements.

It has been pointed out that over-use of financial motivation may actually reduce users' long-term intrinsic motivation to save energy [42]. Similar "pay for results" approach was used and proven effective in other studies, but the feedback from participants suggested that they are unlikely to participate in the future without the same rewards if not better [86]. A possible solution to reduce the negative impact of the use of pure financial rewards in this case is to reduce material rewards and add computer game-like *virtual rewards* such as scores, medals of achievements that are publicly visible to all users, in order to stimulate peer pressures and recognitions that motivate users to sustain their energy saving behaviours/habits.

It was clear that no one complained that the information we provided was too much. It is therefore desirable to improve the power feedback applet and provide more information utilising the latest technology, e.g. per application power profile based on Apple's new power impact metric in *Mac OS X Mavericks* [26], preferably with lower overhead.

Our proposed system level energy saving interventions, actions and high level 'green' policies were only drawn from the dataset after the experiment had been completed. Therefore the students, academic staff and system administrators did not have a chance to work together and evaluate our proposal. A number of natural extensions of this work would be (1) to also investigate the compatibility between our user-end approach and previous work that used less user- involved system level energy saving technologies and techniques. We would like to see which could be used together to maximise energy savings, both when desktop computers are in use and when they are idle. (2) to evaluate the practicability and effectiveness of our proposed 'green' policies, which requires better interactions with the the enterprise owner, e.g. the university, to enforce them. If the 'green' policies are sufficiently well designed and easy to follow, e.g. always put computers to sleep mode (suspend-to-RAM) when leaving the desk for more than 3 minutes, users may even adopt them elsewhere and make even more savings outside the initially targeted scope.

Last but not least, the energy monitor and feedback software we used in this study still have rough edges. Other than the possible future performance improvements described in Section 3.8, we still intend to test its integration with Ganglia as described in Section 3.6, and increase the coverage of monitoring to more complex ICT systems at a larger scale.

Appendix A

CPU Power Profiling

A.1. Methodology

We observed the power consumption of 2 high-end, rack-mount servers and 2 typical home/office desktop computers, at constant room temperature of 22°C, with regard to: machine baseline (idle) power consumption and CPU power consumption of different workload.

For fine-tuned synthetic CPU workload, we created a load generator[1] that adds workload to each CPU core with granularity of 1%, from 0% to 100%.

For power measurements, we used a rack power distribution unit (PDU)[2] that supports per-outlet power monitoring, samples every 0.066 seconds and reports the average readings every 3 seconds with less than 1% error.

Machine Model	CPU	Memory	Benchmark	Idle Pwr	Peak Pwr
Dell PowerEdge 1950	Intel Xeon 5110 (2 cores)	512MB×4 + 2GB×4	11.1892 GFlops	228W	249W
Dell PowerEdge 2950	Intel Xeon 5150 (2 cores ×2 units)	4GB×8	35.2068 GFlops	260W	355W
Shuttle SD36G50	Intel Pentium D 945 (2 cores)	1GB×2	12.1603 GFlops	98W	159W
Shuttle SG31G200	Intel Core2 Quad Q6600 (4 cores)	2GB×2	32.8073 GFlops	93W	190W

Table A.1. Machine specifications

A.2. Machine Specifications

A.3. Observations

The plots indicate that the hardware manufactures are doing reasonably well in reducing baseline power of computers. i.e. newer computers with higher performance consume same or less baseline power than comparable older models. Overall, we see that DVFS is in only place for low-end CPUs, and offers satisfying fine-grained voltage-frequency control towards proportional power dynamics to CPU utilisation, ignoring the base line power usage at 0% utilisation. On the other hand, DVFS is either not implemented or disabled by default for high-end CPUs due to the requirements of high performance, high availability and low latency. Each core of the tested high-end CPUs has limited power saving feature by switching between *low* (L) and *high* (H) states, depending on the workload. i.e. for the duo-core Dell Server 1950, its CPU power steps can be interpreted as L-L (∼228W), L-H (∼238W), and H-H (∼249W). For the quad-core Dell Server 2950 (two duo-core CPUs), its CPU power steps can be interpreted as L-L-L-L (sin271W), L-L-L-H (∼282W), L-L-H-H (∼299W), L-H-H-H (∼311W), and H-H-H-H (∼322.5W). In contrast, 11 power steps were observed for each low-end CPU in Shuttle desktop computers, indicating each CPU core switches between 3 and 6 power states to provide just enough computing power.

[1]based on a simple CPU load generating program written by *Masanori ITOH* (masanori.itoh@gmail.com) in 2007.

[2]Raritan Dominion PX-5367
http://www.raritan.com/products/power-distribution/intelligent-rack-pdus

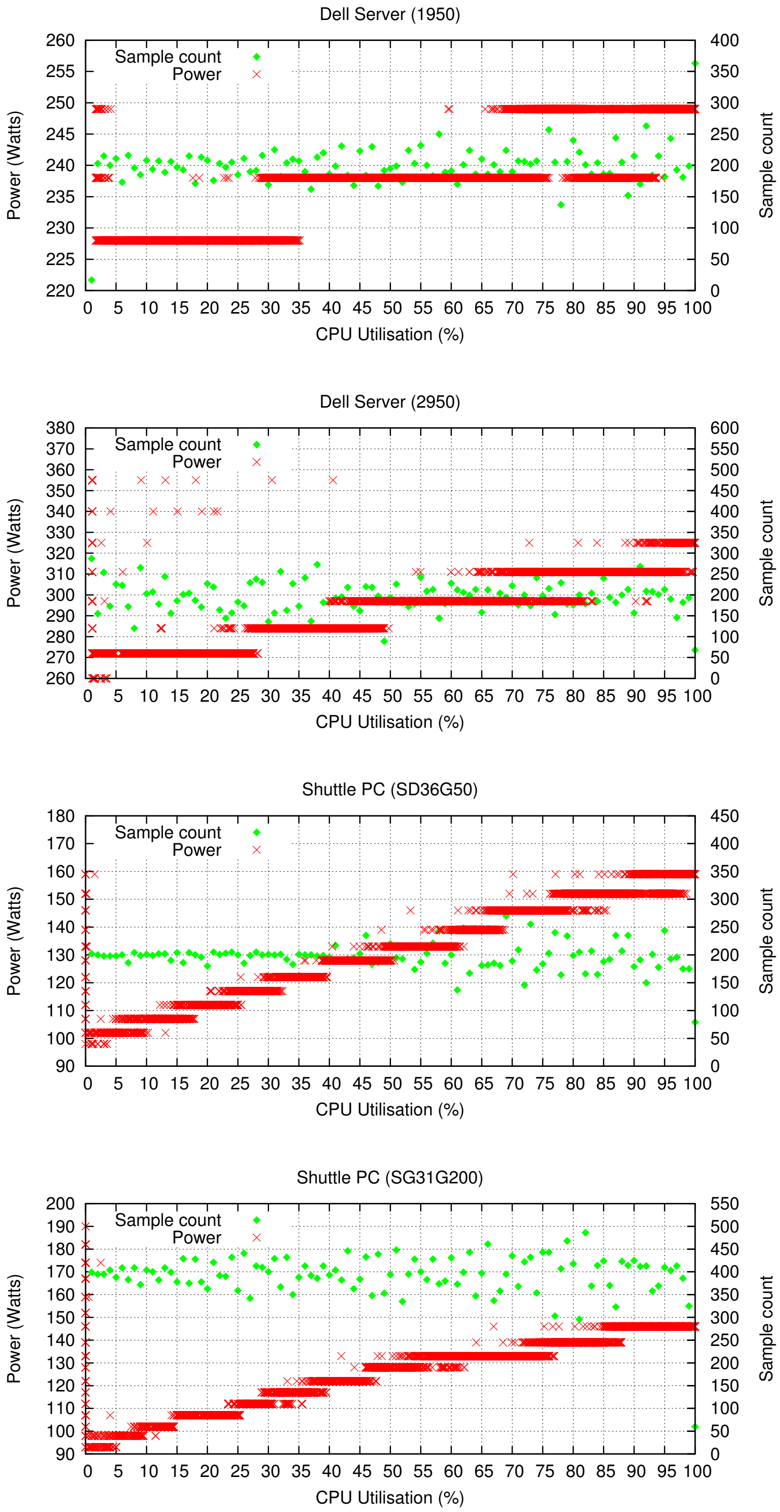

Figure A.1. CPU power profiling of Dell PowerEdge 1950 (Intel Xeon 5110), Dell PowerEdge 2950 (Intel Xeon 5150), Shuttle PC SD36G50 (Intel Pentium D 945) and Shuttle PC SG31G200 (Intel Core2 Quad Q6600).

Appendix B

Current Cost Envi CC128 Smart Power Meter

B.1. Specifications

See below for key specifications taken from the official product web page [1].

Product Size	9.3cm x 12cm (base) x 15.5 cm
Viewable Screen	7.3cm x 9cm
Retail Package Size	35cm x 17cm x 5.5cm
Internal Power Requirement	Mains block adapter (nominal 1.0 watt)
Physical Format	Table-top
Energy Monitored	Electricity (gas, LPG, oil option in development)
Receiver	433MHz SRD band
Communication Platform	C2 architecture
Sensor Coding Recognition	10 channel (each three input potential)
Recognition Method	User Initiated - seeks 4,096 possibilities
Number of Permitted Sensors	Ten (x3 input)
Display	Liquid Crystal segmented display
Main services	Energy, Current Cost
Subordinate Services	Clock time (24hr), room temperature (0-29C)

- 24 hour rolling consumption (bar graph) display (social division into 3 x 8hr periods)
- PC connection for streaming data for seven years historical data.

[1] http://www.currentcost.com/product-cc128-specifications.html

- Offers an overall accuracy of >97% depending on the type of appliances in use

B.2. XML Sample Output v0.11 and Parser

According to the official documentation[2], CC128 output ASCII text over its serial port at 57600 baud, 1 start, 8-bit data, 1 stop, no parity, no handshake. The Current Cost USB cable is effectively a serial-USB converter for easy access. CC128 outputs real-time measurements and aggregated historical data over 2-hour, 1-day and 1-month periods. In this study, only real-time measurements were used. Other data were discarded.

B.2.1. Sample Output of Real-Time Measurements. As given on the official documentation web page:

```xml
<msg>                          <!-- start of message -->
   <src>CC128-v0.11</src>      <!-- source and software version -->
   <dsb>00089</dsb>            <!-- days since birth, ie days run -->
   <time>13:02:39</time>       <!-- 24 hour clock time as displayed -->
   <tmpr>18.7</tmpr>           <!-- temperature as displayed -->
   <sensor>1</sensor>          <!-- Appliance Number as displayed -->
   <id>01234</id>              <!-- radio ID received from the sensor -->
   <type>1</type>              <!-- sensor Type, "1" = electricity -->
   <ch1>                       <!-- sensor channel -->
      <watts>00345</watts>     <!-- data and units -->
   </ch1>
   <ch2>
      <watts>02151</watts>
   </ch2>
   <ch3>
      <watts>00000</watts>
   </ch3>
</msg>                         <!-- end of message -->
```

[2]http://www.currentcost.com/cc128/xml.htm

B.2.2. A Simple Parser Written in Python. In Linux environment, once CC128 is connected to the computer via USB, its real-time power measurements can be extracted using the code below:

```
import serial
import xml.dom.minidom

# serial port on a Linux computer is identified as /dev/ttyUSB0
# this value needs changing if running in other OS
ser = serial.Serial( port='/dev/ttyUSB0', baudrate=57600, bytesize=8,
                   parity='N', stopbits=1, timeout=2, xonxoff=0, rtscts=0 )

try:
    while 1:
        line = ser.readline().strip() # raw ASCII texts from CC128
        if line !="":   # not a blank line
            try:
                doc = xml.dom.minidom.parseString(line)
                # get real-time total power
                watts = doc.getElementsByTagName("watts")[0].firstChild.data
                # get real-time ambient temperature (optional)
                temp  = doc.getElementsByTagName("tmpr")[0].firstChild.data
                # other XML values may be extracted as necessary
                # ...
                # actions with data
                # ...
            except Exception:
                pass   # expect corrupted data. ignore.

except KeyboardInterrupt:
    print '\nQuiting CC128 USB reader...'
```

Appendix C

Collecting Data From Apple SMC

The source code of Apple System Management Control (SMC) Tool is available from: `https://github.com/hholtmann/smcFanControl/tree/master/smc-command`.
It has been updated since the version used for this study in 2011. The raw readings acquired from internal sensors are now *decoded* and output by default, which makes the use of this tool much easier.

C.1. Apple SMC Sensors and Data Structures

Each Macintosh computer may have different versions of Apple System Management Control (SMC) software available depending on the model and firmware updates. They also have slightly different sets of sensors built-in. For instance, laptops have motion sensors while desktops do not.

The Apple SMC Tool used for this study lists all SMC sensors and polls their raw readings. The names of the SMC sensors are 3 to 4 characters; and the reported raw data consist of 16 bits, in Apple's proprietary format. Sensors names follow some naming conventions that are easy to relate to their functions. Some commonly used sensors are listed as the following:

```
# Ambient Light sensors, start with AL
ALV0 - Left
```

```
ALV1 - Right

# Battery System Info byte, starts with BSI
BSIn - 0=Charging
       1=AC present
       2=AC presence changed
       3=OS Stop Charge
       4=OS Calibration Req
       5=BatteryQueryInProgress
       6=batOK
       7=adcInProgress

# Fan sensors, start with 'F'
FNum - number of fans in the system
F0Ac - Fan0 actual speed
F0Mn - Fan0 minimum speed
F0Mx - Fan0 maximum speed
F0Sf - Fan0 safe speed
F0Tg - Fan0 target speed
FS!  - See if fans are in automatic or forced mode

# Motion sensors, start with 'M'
MO_X - X axis
MO_Y - Y axis
MO_Z - Z axis

# Temperature sensors, start with 'T'
# The actual meanings of many sensors require more
# testing and guessing due to lack of documentation.
TB0T - Enclosure bottom temperature
TC0P - CPU temperature
TM0P - Memory temperature
TN0P - Northbridge temperature
Th0H - Harddisk temperature
Ts0P - Slot (PCI express?) temperature
Th1H - Heatsink temperature
```

Power sensors of a number of Mac computers were polled to determine naming patterns and their actual meanings. The second column of returned data in '[ ]'is data format, and the last column in '( )' are the 16 bits values in Hex decimal representation.

```
# system information returned by executing the following command in Mac OS Terminal
$ system_profiler SPHardwareDataType

###

Model Name:            MacBook
Model Identifier:      MacBook1,1
SMC Version (system):  1.4f12

PC0C  [fp88]  (bytes 0c 10)
PC0C  [fp88]  (bytes 0e 88)
PD0R  [fp88]  (bytes 1e c7)
PD0R  [fp88]  (bytes 1c 90)
PN0R  [fp88]  (bytes 01 e6)
PN0R  [fp88]  (bytes 01 c9)
PP0R  [fp88]  (bytes 00 99)
PP0R  [fp88]  (bytes 00 93)


###

Model Name:            MacBook
Model Identifier:      MacBook3,1
SMC Version (system):  1.24f3

PC0C  [fp88]  (bytes 14 f0)
PC0C  [fp88]  (bytes 16 5a)
PD0R  [fp88]  (bytes 28 ec)
PD0R  [fp88]  (bytes 28 d9)
PG0C  [fp88]  (bytes 00 e1)
PG0C  [fp88]  (bytes 00 89)
PHPC  [fp88]  (bytes 17 a3)
PN0R  [fp88]  (bytes 02 21)
PN0R  [fp88]  (bytes 02 33)
PP0R  [fp88]  (bytes 00 c0)
PP0R  [fp88]  (bytes 00 be)
PTHC  [fp88]  (bytes 1e 12)

###

Model Name:            MacBook Air
Model Identifier:      MacBookAir2,1
```

```
SMC Version (system):  1.34f8

PcOR [sp78] (bytes 0d 39)
PcOR [sp78] (bytes 0f 7b)
PB0R [sp78] (bytes 00 d9)
PB0R [sp78] (bytes 00 da)
PC0c [ui16] 192 (bytes 40 c0)
PC0C [sp78] (bytes 05 ed)
PC0c [ui16] 0 (bytes 4c 00)
PC0C [sp78] (bytes 05 cd)
PD0R [sp78] (bytes 17 4d)
PD0R [sp78] (bytes 18 87)
PN0C [sp78] (bytes 01 a5)
PN0C [sp78] (bytes 01 a6)
PT0C [sp78] (bytes 0e 80)
PT0C [sp78] (bytes 0e 80)

###

Model Name:            MacBook Pro
Model Identifier:      MacBookPro5,2
SMC Version (system):  1.42f4

PC0C [fp88] (bytes 0c d5)
PC1C [fp88] (bytes 0d e4)
PC2C [fp88] (bytes 00 8e)
PC0C [fp88] (bytes 0c bc)
PD0R [fp88] (bytes 1a f3)
PD0R [fp88] (bytes 1a 91)
PG0C [fp88] (bytes 00 00)
PG1C [fp88] (bytes 00 00)
PG0C [fp88] (bytes 00 00)
PHPC [fp88] (bytes 12 d2)
PN0R [fp88] (bytes 03 7f)
PN1R [fp88] (bytes 00 e1)
PN0R [fp88] (bytes 03 7f)
PP0R [fp88] (bytes 01 ae)
PP0R [fp88] (bytes 01 ae)
PTHC [fp88] (bytes 32 7c)

###

Model Name:            MacBook Pro
```

```
Model Identifier:      MacBookPro5,5
SMC Version (system):  1.47f2

PC0C  [fp88]  (bytes 0b 7d)
PC0R  [fp88]  (bytes 0d 24)
PC0C  [fp88]  (bytes 0b 97)
PC0R  [fp88]  (bytes 0d 41)
PD0R  [fp88]  (bytes 19 97)
PD0R  [fp88]  (bytes 19 d1)
PHPC  [fp88]  (bytes 11 10)
PN0C  [fp88]  (bytes 03 3b)
PN1C  [fp88]  (bytes 00 76)
PN0C  [fp88]  (bytes 03 41)
PP0R  [fp88]  (bytes 01 84)
PP0R  [fp88]  (bytes 01 84)
PTHC  [fp88]  (bytes 20 fb)
PTHI  [fp88]  (bytes 20 fb)

###

Model Name:            iMac
Model Identifier:      iMac10,1
SMC Version (system):  1.52f9

PC0C  [sp96]  (bytes 03 40)
PC0R  [sp96]  (bytes ff ff)
PC0C  [sp96]  (bytes 03 44)
PC0R  [sp96]  (bytes ff ff)
PDSR  [sp96]  (bytes 16 70)
PDTR  [sp96]  (bytes 16 13)
PG0R  [sp96]  (bytes ff ff)
PG0R  [sp96]  (bytes ff ff)
PN0R  [sp96]  (bytes 01 a8)
PN1R  [sp96]  (bytes 00 00)
PN0R  [sp96]  (bytes 01 a8)
PNTR  [sp96]  (bytes 01 a8)
PZ0E  [sp96]  (bytes 1a 40)
PZ0G  [sp96]  (bytes 03 44)
PZ0E  [sp96]  (bytes 1a 40)
PZ0G  [sp96]  (bytes 03 44)

###
```

```
Model Name:            iMac
Model Identifier:      iMac11,2
SMC Version (system):  1.64f5

PC0C  [sp96]  (bytes 03 1b)
PC5R  [sp96]  (bytes 00 00)
PC8R  [sp96]  (bytes 00 32)
PC0C  [sp96]  (bytes 03 21)
PCTR  [sp96]  (bytes 06 5d)
PCVR  [sp96]  (bytes 03 12)
PDSR  [sp96]  (bytes 0f 90)
PDTR  [sp96]  (bytes 0f ae)
PG0R  [sp96]  (bytes 02 94)
PG0R  [sp96]  (bytes 02 95)
```

Most crucial information extracted from the sample data is as the following:

```
# assumed meanings of Apple data formats for 16 bit raw binary data
fp88 - Floating Point (16=8+8)
    - 8 bits on each side of decimal point

ui16 - Unsigned Integer (16=16)
    - using all 16 bits

sp78 - Signed (floating) Point (16=1+7+8)
    - 1 bit for sign
    - 7 bits and 8 bits on left and right of decimal point
    - precision up to 1/2^8

sp96 - Signed (floating) Point (16=1+9+6)
    - 1 bit for sign
    - 9 bits and 6 bits on left and right of decimal point
    - precision up to 1/2^6


# power sensors and data format used in this study with iMac 10,1
PDTR [sp96] - Machine total power
PC0C [sp96] - CPU power
PN0R [sp96] - Northbridge power
```

C.2. Decoding SMC Raw Data in Python

Raw power readings in sp96 format were passed to a simple Python function to decode as listed below. The function takes 16 bits of data in Hex decimal representation as an argument, and outputs the its decimal value with upto 3 decimal points precision.

```
def decode(sp96): # return float value as string
    d = {"0":"0000","1":"0001","2":"0010","3":"0011",\
        "4":"0100","5":"0101","6":"0110","7":"0111",\
        "8":"1000","9":"1001","a":"1010","b":"1011",\
        "c":"1100","d":"1101","e":"1110","f":"1111"}
    # convert hex string to 16 bits binary
    binary = d[sp96[0]]+d[sp96[1]]+d[sp96[2]]+d[sp96[3]]
    # now we crack Apple's secret number :)
    value = int(binary[1:10],2) + int(binary[10:],2)/64.0
    return "%.3f" % value
```

Appendix D

Sample System Process Data Collected from iMac

The following command was executed by the power monitor daemon. The specified columns (in quotes below) to output in order is: user name (from UID), symbolic process state, elapsed running time, accumulated CPU time, percentage CPU usage, percentage memory usage, virtual size in Kbytes, resident set size, control terminal name, process ID, command without arguments. Refer to `ps` man page for more details and instructions.

```
$ ps axo "user stat etime time pcpu pmem vsize rss tt pid comm"
```

A snippet of the un-anonymised output:

```
root Ss 10:08 0:00.26 0.0 0.0 2446428 596 ?? 7231 /usr/sbin/rpc.lockd
root Ss 10:08 0:00.00 0.0 0.0 2477916 468 ?? 7232 /usr/sbin/rpc.statd
daemon Ss 10:08 0:00.01 0.0 0.0 2446360 460 ?? 7234 /usr/sbin/portmap
root S 10:08 0:00.24 0.0 0.0 2446420 304 ?? 7236 /usr/sbin/rpc.lockd
yi Ss 10:15 0:00.39 0.0 0.0 2456336 912 ?? 7200 /sbin/launchd
yi S 10:12 0:00.68 0.0 0.5 2773368 21352 ?? 7216 /System/Library/CoreServices/Dock.app
yi S 07:05 0:01.58 0.0 0.8 11223464 35068 ?? 7439 /Applications/Smultron.app
root Ss 06:32 0:00.33 0.0 0.0 2444700 1000 ?? 7455 /usr/libexec/taskgated
yi S 05:09 0:13.01 0.1 1.7 2833332 72688 ?? 8018 /Applications/Safari.app
yi S 00:57 0:00.00 0.0 0.0 2436092 844 ?? 7219 /home/yi/a.out
```

Any occurrence of user ID (i.e. `yi`) is hashed with a secret key before data collection:

```
root Ss 10:08 0:00.26 0.0 0.0 2446428 596 ?? 7231 /usr/sbin/rpc.lockd
root Ss 10:08 0:00.00 0.0 0.0 2477916 468 ?? 7232 /usr/sbin/rpc.statd
daemon Ss 10:08 0:00.01 0.0 0.0 2446360 460 ?? 7234 /usr/sbin/portmap
root S 10:08 0:00.24 0.0 0.0 2446420 304 ?? 7236 /usr/sbin/rpc.lockd
f9240d68ee124639e7496463ea3cab5e Ss 10:15 0:00.39 0.0 0.0 2456336 912 ?? 7200 /sbin/launchd
f9240d68ee124639e7496463ea3cab5e S 10:12 0:00.68 0.0 0.5 2773368 21352 ?? 7216
    /System/Library/CoreServices/Dock.app
f9240d68ee124639e7496463ea3cab5e S 07:05 0:01.58 0.0 0.8 11223464 35068 ?? 7439
    /Applications/Smultron.app
root Ss 06:32 0:00.33 0.0 0.0 2444700 1000 ?? 7455 /usr/libexec/taskgated
f9240d68ee124639e7496463ea3cab5e S 05:09 0:13.01 0.1 1.7 2833332 72688 ?? 8018
    /Applications/Safari.app
f9240d68ee124639e7496463ea3cab5e S 00:57 0:00.00 0.0 0.0 2436092 844 ?? 7219
    /home/f9240d68ee124639e7496463ea3cab5e/a.out
```

Appendix E

Participant Information Sheet

PARTICIPANT INFORMATION SHEET

Project Title

Building Energy-Awareness into ICT Systems

What is this study about?

We invite you to participate in a research project about the effect of real-time energy-usage feedback in daily computer use. This experiment aims at observing the behaviours of lab computer users with respect to energy consumption. Results from the experiment will help us understand the effectiveness of providing real-time energy usage in promoting energy-saving behaviour.

Do I have to take part?

This information sheet has been written to help you decide if you would like to take part. It is up to you and you alone whether or not to take part.

Will my participation be anonymous and confidential?

Absolutely. Any personal identifier in the data we collect will be anonymised using a secure (key-based), non-reversible scheme BEFORE it leaves the computer you use. Hence, even if some of the data is accidentally disclosed, it is not possible to infer your identity from it (visit https://hopback/info/ to see some sample data that we collect). When the data is used in demonstrations or publications, you will not be identified in any form unless you wish to be credited and give us written permission to be explicitly identified. Data of your computer and energy usage are only used for research purposes, and will NOT be shared with the school admin team or the university IT services.

Storage of data collected

Data collected will be handled only by researchers with appropriate approval, and will be stored securely on a dedicated server that is only accessible by the same researchers. Future use and archiving of this data for scholarly purposes will be carried out as agreed in the 'Participant Consent Form'.

What would I be required to do?

Please give us permission to collect your anonymised data by completing and returning a Participant Consent Form (also available online at https://hopback/info/) to Yi Yu (JCB1.02) or the school office (JCB0.01). Then please use the iMacs in the lab as usual. At a certain time you will be given some energy-saving advices, but you are not obliged to carry them out. After then, you will be invited to complete some questionnaires voluntarily.

Are there any potential risks?

Our observation is non-intrusive, passive and anonymous. There is no potential risk to you.

Questions

Please feel free to ask any questions in relation to this project before completing a Participant Consent Form. Contact details are available on top of the Participant Consent Form.

Consent and approval

This research proposal has been scrutinised and been granted Ethical Approval through the University ethical approval process (ref. No. CS7712).

What should I do if I have concerns about this study?

A full outline of the procedures governed by the University Teaching and Research Ethical Committee is available at http://www.st-andrews.ac.uk/utrec/complaints/

Appendix F

Participant Consent Form

PARTICIPANT CONSENT FORM

Project Title : Building Energy-Awareness into ICT Systems

Researcher's Name	Supervisor's Name
Yi Yu yi@cs.st-andrews.ac.uk 01334 461627	Prof. Saleem Bhatti saleem@cs.st-andrews.ac.uk 01334 461640

The University of St Andrews attaches high priority to the ethical conduct of research. We therefore ask you to consider the following points before signing this form. Your signature confirms that you are happy to participate in the study.

Consent

The purpose of this form is to ensure that you are willing to take part in this study and to let you understand what it entails. Signing this form does not commit you to anything you do not wish to do and you are free to withdraw at any stage.

Material gathered during this research will be treated as confidential and securely stored on a dedicated server with limited access by the researcher and supervisor. Please answer each statement concerning the collection and use of the research data.

I am 18 years old or over.	☐ Yes	☐ No*
* I will be 18 years old by________________ (we can only use your data if you are 18 or over)		
I have read and understood the information sheet.	☐ Yes	☐ No
I have been given the opportunity to ask questions about the study.	☐ Yes	☐ No
I have had my questions answered satisfactorily.	☐ Yes	☐ No
I understand that I can withdraw from the study at any time without having to give an explanation.	☐ Yes	☐ No
I understand that I will not be identified in any circumstances unless I give written consent.	☐ Yes	☐ No
I understand that my data will be kept confidential and anonymous and that only the researcher and supervisor will have access.	☐ Yes	☐ No
I agree to my data (in line with conditions outlined above) being archived and used for further research projects / by other bona fide researchers.	☐ Yes	☐ No
I have been made fully aware of the potential risks associated with this research and am satisfied with the information provided.	☐ Yes	☐ No
I agree to take part in the study	☐ Yes	☐ No

Participation in this research is completely voluntary and your consent is required before you can participate in this research. If you decide at a later date that data should be destroyed we will honour your request in writing.

Print name____________________________________Signature____

CS log-in ID____________________________________Date____

Appendix G

Y1 Surveys

Energy Awareness Background Survey

Thank you for participating in this research!

We will try to make this as easy and interesting as possible.

Your responses to this background survey is essential to

our research, so please be frank and tell us what you

really think rather than what you should have done :-)

There are 15 questions to be answered, which

should take approximately 5 minutes.

Questions without red star (*) are optional.

There are 23 questions in this survey

Question group 1 of 1

1 [1]Gender

Please choose **only one** of the following:

- Male
- Female

2 [2]Do you pay for your energy usage separately at your residence? *

Please choose **only one** of the following:

- Yes
- No

3 [3]Are you aware of your energy usage in your residence? *

Please choose **only one** of the following:

- Yes
- No

4 [4]Have you been given any guidance on how to save energy in your residence? e.g. TV programmes, leaflets. *

Please choose **only one** of the following:

- Yes
- No

5 [5]Do you practice any energy saving techniques in your residence? *

Please choose **only one** of the following:

- Yes
- No

6 [5a]What motivates you to save energy at home? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((5.NAOK == "Y"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep costs down						
To protect the environment						
I don't want to be wasteful						
I have been told to do so (e.g. residence policies/rules, etc.)						
To impress or set a good example for others						
Other (please briefly describe in 5c if any)						

7 [5b]Could the following reasons motivate you to save energy at home? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((5.NAOK == "N"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
Not to be wasteful	○	○	○	○	○	○
Enforcement (e.g. residence policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 5c if any)	○	○	○	○	○	○

8 [5c]Please briefly describe one other reason that motivates you to save energy at home.

Only answer this question if the following conditions are met:
° ((5a_SQ006.NAOK != "A1")) or ((5b_SQ006.NAOK != "A1"))

Please write your answer here:

9 [6]Do you think that energy management is important to the School of Computer Science? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

10 [7]Who do you think should be actively involved in energy management activities in the school? *

Please choose **all** that apply:

- ☐ The university management staff
- ☐ The school administrators
- ☐ The school technical staff
- ☐ The school academic/research staff
- ☐ The school janitors/cleaning staff
- ☐ Students
- ☐ Don't know
- ☐ Other:

11 [8]Are you aware of the energy usage of the School of the Computer Science? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

12 [9]Have you been given any guidance on saving energy at school? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

13 [9a]The guidance was delivered via *

Only answer this question if the following conditions are met:
° ((9.NAOK == "Y"))

Please choose **all** that apply:

- ☐ Leaflet/handout
- ☐ Posters
- ☐ Radio/TV programmes
- ☐ Talks during freshers' week and/or induction (but not lectures)
- ☐ Other:

14 [10]Do you practice energy saving techniques at school? *

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

15 [10a]What motivates you to save energy at school? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((10.NAOK == "Y"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep energy costs down	◯	◯	◯	◯	◯	◯
To protect the environment	◯	◯	◯	◯	◯	◯
I don't want to be wasteful	◯	◯	◯	◯	◯	◯
I have been told to do so (e.g. school/university policies/rules, etc.)	◯	◯	◯	◯	◯	◯
To impress or set a good example for others	◯	◯	◯	◯	◯	◯
Other (please briefly describe in 10c if any)	◯	◯	◯	◯	◯	◯

16 [10b]Could the following reasons motivate you to save energy at school? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((10.NAOK == "N"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep energy costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
Not to be wasteful	○	○	○	○	○	○
Enforcement (e.g. school/university policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 10c if any)	○	○	○	○	○	○

17 [10c]Please briefly describe one other reason that motivates you to save energy at school.

Only answer this question if the following conditions are met:
° ((10a_SQ006.NAOK != "A1")) or ((10b_SQ006.NAOK != "A1"))

Please write your answer here:

18 [11]How would the following facilitate your participation in saving energy at school? *

Please choose the appropriate response for each item:

	I don't think about this	Not useful at all	Minimum useful	I'd be prepared to use this	Would be useful	Very useful
More information on how to save energy	○	○	○	○	○	○
Information on personal energy usage	○	○	○	○	○	○
Information on other people's energy usage	○	○	○	○	○	○
Information on the school's energy usage as a whole	○	○	○	○	○	○
Other (please briefly describe in 11a if any)	○	○	○	○	○	○

19 [11a]

Please briefly describe any other information that would facilitate your participation in saving energy at school.

Only answer this question if the following conditions are met:
° ((11_SQ005.NAOK != "A1"))

Please write your answer here:

20 [12]What is your general attitude toward energy saving? *

Please choose **only one** of the following:

- ◯ Very Positive - I actively save energy and believe I can make a difference
- ◯ Aware and positive, but it is not part of my current work day practice
- ◯ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- ◯ I'm aware, but not motivated to save energy
- ◯ I'm not aware of what I can do to save energy
- ◯ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

21 [13]How aware are you of the environmental impact of energy use? *

Please choose **only one** of the following:

- ◯ I am very aware and often do my own research
- ◯ I am aware of some of the environmental issues
- ◯ I am aware of the current debate, but am not yet convinced
- ◯ I am hardly aware of the environmental issues
- ◯ I am not aware of the environmental impact at all
- ◯ I am not aware of it and I don't want to know

22 [14]How motivated are you to save energy? *

Please choose **only one** of the following:

- ◯ I am motivated and try to follow all the advices I know all the time
- ◯ I am motivated and try to follow all the advices I know most of the time
- ◯ I am motivated but I don't always remember to save energy
- ◯ I am motivated but I don't know how to save energy
- ◯ I am not motivated but I want to find out how to save energy
- ◯ I am not motivated and I don't want to know how to save energy

23 [15]Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Saving Tips Feedback Survey

Hi, thanks for doing this survey!

It should take you approcimately 5 minutes to finish.

If you do not see any question on 1 or more pages of this survey, it means the questions in this group do not apply to you. Please just hit "Next" to move onto the next page.

There are 49 questions in this survey

Background

1 [1]Have you read the energy-saving tips in the iMac lab? *

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Feedback per energy-saving tip 1/7

Tip 1:

Dim Screen whenever possible
Maximum brightness is not always required

2 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

3 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

4 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

5 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

6 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- Almost all the time (almost every time you used the computers, you used this tip)
- Often (most of the time that you used the computers, you used this tip)
- Sometimes (You used this tip about as often as you did not use it)
- Rarely (most of the times you used the computer, you did *not* use this tip)
- Only when you were reminded (by seeing the notes on the desk)
- Not at all

7 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- [ ] It was not understandable to me.
- [ ] It did not seem sensible to me.
- [ ] It was too hard/complicated to carry out.
- [ ] I did not think it was important/significant in terms of energy-saving.
- [ ] I forgot about it.
- [ ] Other: ____________

Feedback per energy-saving tip 2/7

Tip 2:

Use ‘lightweight’ applications (low CPU & disk usage)
e.g. use vim or Smultron instead of Xcode

8 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

9 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

10 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

11 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

12 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- ○ Almost all the time (almost every time you used the computers, you used this tip)
- ○ Often (most of the time that you used the computers, you used this tip)
- ○ Sometimes (You used this tip about as often as you did not use it)
- ○ Rarely (most of the times you used the computer, you did *not* use this tip)
- ○ Only when you were reminded (by seeing the notes on the desk)
- ○ Not at all

13 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- ☐ It was not understandable to me.
- ☐ It did not seem sensible to me.
- ☐ It was too hard/complicated to carry out.
- ☐ I did not think it was important/significant in terms of energy-saving.
- ☐ I forgot about it.
- ☐ Other: ________

Feedback per energy-saving tip 3/7

Tip 3:

Think about your use of audio and video

e.g. Flash video uses a lot of CPU resources, use

iTunes or VLC for audio

14 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

15 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

16 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

17 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

18 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Almost all the time (almost every time you used the computers, you used this tip)
- ◯ Often (most of the time that you used the computers, you used this tip)
- ◯ Sometimes (You used this tip about as often as you did not use it)
- ◯ Rarely (most of the times you used the computer, you did *not* use this tip)
- ◯ Only when you were reminded (by seeing the notes on the desk)
- ◯ Not at all

19 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- ☐ It was not understandable to me.
- ☐ It did not seem sensible to me.
- ☐ It was too hard/complicated to carry out.
- ☐ I did not think it was important/significant in terms of energy-saving.
- ☐ I forgot about it.
- ☐ Other: ____________

Feedback per energy-saving tip 4/7

Tip 4:

Block unwanted web contents

e.g. Flash, pop-ups, adverts etc, using Adblock &

Flahsblock add-ons for browsers such as Firefox or

Chrome

20 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

21 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

22 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

23 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

24 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Almost all the time (almost every time you used the computers, you used this tip)
- ◯ Often (most of the time that you used the computers, you used this tip)
- ◯ Sometimes (You used this tip about as often as you did not use it)
- ◯ Rarely (most of the times you used the computer, you did *not* use this tip)
- ◯ Only when you were reminded (by seeing the notes on the desk)
- ◯ Not at all

25 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- ☐ It was not understandable to me.
- ☐ It did not seem sensible to me.
- ☐ It was too hard/complicated to carry out.
- ☐ I did not think it was important/significant in terms of energy-saving.
- ☐ I forgot about it.
- ☐ Other: ____________

29 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

30 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Almost all the time (almost every time you used the computers, you used this tip)
- ◯ Often (most of the time that you used the computers, you used this tip)
- ◯ Sometimes (You used this tip about as often as you did not use it)
- ◯ Rarely (most of the times you used the computer, you did *not* use this tip)
- ◯ Only when you were reminded (by seeing the notes on the desk)
- ◯ Not at all

31 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- ☐ It was not understandable to me.
- ☐ It did not seem sensible to me.
- ☐ It was too hard/complicated to carry out.
- ☐ I did not think it was important/significant in terms of energy-saving.
- ☐ I forgot about it.
- ☐ Other: ____________

Feedback per energy-saving tip 6/7

Tip 6:

Quit unused applications

Reduce CPU usage by quitting, not just minimising, the apps you are not using.

32 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

33 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

34 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

35 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

36 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- Almost all the time (almost every time you used the computers, you used this tip)
- Often (most of the time that you used the computers, you used this tip)
- Sometimes (You used this tip about as often as you did not use it)
- Rarely (most of the times you used the computer, you did *not* use this tip)
- Only when you were reminded (by seeing the notes on the desk)
- Not at all

37 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- It was not understandable to me.
- It did not seem sensible to me.
- It was too hard/complicated to carry out.
- I did not think it was important/significant in terms of energy-saving.
- I forgot about it.
- Other:

Feedback per energy-saving tip 7/7

Tip 7:

Turn off, but do NOT sleep, the iMacs after use, especially after 6pm.

The iMacs take only ~50s from Off to Ready-for-Use (20s to boot up to the login screen, then another 30s to connect to the remote file server). The 'Sleep' feature will break the iMac's connection to school NFS server when it wakes up, hence is forbidden on any lab computers.

38 [1]Did you understand this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

39 [2]Did the tip seem sensible to you? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

40 [3]Was this tip easy to carry out? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

41 [4]Were you motivated to use this tip? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

42 [4a]How often did you practice this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "Y"))

Please choose **only one** of the following:

- ◯ Almost all the time (almost every time you used the computers, you used this tip)
- ◯ Often (most of the time that you used the computers, you used this tip)
- ◯ Sometimes (You used this tip about as often as you did not use it)
- ◯ Rarely (most of the times you used the computer, you did *not* use this tip)
- ◯ Only when you were reminded (by seeing the notes on the desk)
- ◯ Not at all

43 [4b]What demotivated you from practicing this tip? *

Only answer this question if the following conditions are met:
° ((4.NAOK == "N"))

Please choose **all** that apply:

- ☐ It was not understandable to me.
- ☐ It did not seem sensible to me.
- ☐ It was too hard/complicated to carry out.
- ☐ I did not think it was important/significant in terms of energy-saving.
- ☐ I forgot about it.
- ☐ Other: ____________

Last page of questions!

44 [1]Did you read the information about electricity generation that was sent out by email? *

Please choose **only one** of the following:

- Yes
- No

On 27/10, titled "Environmental impact of electricity generation"

45 [1a]Did you understand it? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No

46 [1b]Did it make you change your view on using the energy saving tips? *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose **only one** of the following:

- Yes
- No (please briefly describe why ->

Make a comment on your choice here:

47 [2]Did the notice of energy-saving tips beside the iMacs remind you to save energy? *

Please choose **only one** of the following:

- Yes
- No

48 [3]What is your current attitude toward energy saving? *

Please choose **only one** of the following:

- Very Positive - I actively save energy and believe I can make a difference
- Aware and positive, but it is not part of my current work day practice
- Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- I'm aware, but not motivated to save energy
- I'm not aware of what I can do to save energy
- Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

49 [4]Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Competition Feedback Survey

There are 9 questions in this survey

Group 1 of 1

1 [1]

What motivates you to save energy during the competition? Please rate each option accordingly.

*

Please choose the appropriate response for each item:

	Almost all the time (almost every time you used the computers, you thought about this)	Often (most of the time that you used the computers, you thought about this)	Sometimes (there were times you used the computer that you did not think about this)	Rarely (most of the times you used the computer without considering this)	Only when I was reminded by seeing the menu-bar energy applet	Not at all
To win the prizes	○	○	○	○	○	○
To keep the electricity costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe below if any)	○	○	○	○	○	○

2 [1a]

Please briefly describe what else motivates you to save energy during the competition.

Only answer this question if the following conditions are met:
° ((1_SQ007.NAOK == "A1" or 1_SQ007.NAOK == "A2" or 1_SQ007.NAOK == "A3" or 1_SQ007.NAOK == "A4" or 1_SQ007.NAOK == "A5"))

Please write your answer here:

3 [2]

Did you find the menu-bar energy applet helpful?

*

Please choose **only one** of the following:

- ○ Yes
- ○ No

4 [2a]

In which way(s) it was helpful to you?

*

Only answer this question if the following conditions are met:
° ((2.NAOK == "Y"))

Please choose **all** that apply:

- [ ] It helps me to explore possible ways to reduce energy consumption by showing me my real-time energy usage.
- [ ] It shows me my total energy consumption (in the current session)
- [ ] It shows me my carbon footprint (mass: grams)
- [ ] It shows me my carbon emission (volume: litres)
- [ ] It shows me my total energy cost (in the current session)
- [ ] It acts as a reminder for me to save energy
- [ ] Other:

5 [2b]

It was not helpful to you because:

*

Only answer this question if the following conditions are met:
° ((2.NAOK == "N"))

Please choose **all** that apply:

- [ ] The information it showed did not make sense to me
- [ ] The information it showed was not sufficient
- [ ] I found it annoying
- [ ] I did not notice it at all
- [ ] Other:

6 [3]

Please briefly comment on how we could improve the menu-bar energy applet to make it more helpful.

Please write your answer here:

7 [4]

Please select the energy saving tips that you have practised during the competition.

Please choose **all** that apply:

- ☐ Dim Screen whenever possible
- ☐ Use 'lightweight' applications
- ☐ Think about your use of audio and video
- ☐ Block unwanted web contents
- ☐ Avoid multiple downloads of same document
- ☐ Quit unused applications
- ☐ Turn off the iMacs after use

8 [5]

What is your current attitude toward energy saving?

*

Please choose **only one** of the following:

- ◯ Very Positive - I actively save energy and believe I can make a difference
- ◯ Aware and positive, but it is not part of my current work day practice
- ◯ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- ◯ I'm aware, but not motivated to save energy
- ◯ I'm not aware of what I can do to save energy
- ◯ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

9 [6]

Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Study Final Survey

There are 9 questions in this survey

final survey

1 [1]It has been over a week since the energy efficiency competition ended. Are you still motivated to save energy during your use of lab computers? *

Please choose **only one** of the following:

- Yes
- No

2 [1a]What motivates you to save energy? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose the appropriate response for each item:

	Almost all the time (almost every time you used the computers, you thought about this)	Often (most of the time that you used the computers, you thought about this)	Sometimes (there were times you used the computer that you did not think about this)	Rarely (most of the times you used the computer without considering this)	Only when I was reminded by seeing the menu-bar energy applet	Not at all
To keep the electricity costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 1b if any)	○	○	○	○	○	○

3 [1b]Please briefly describe what was the 'other' reason.

Only answer this question if the following conditions are met:
° ((1a_SQ006.NAOK == "A1" or 1a_SQ006.NAOK == "A2" or 1a_SQ006.NAOK == "A3" or 1a_SQ006.NAOK == "A4" or 1a_SQ006.NAOK == "A5"))

Please write your answer here:

4 [2]When the menu-bar energy applet was not present, did you still think about your energy usage and/or practise energy saving techniques in the lab? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

5 [2a]Please select the energy saving tips that you still practise. *

Only answer this question if the following conditions are met:
° ((2.NAOK == "Y"))

Please choose **all** that apply:

- ☐ Dim Screen whenever possible
- ☐ Use 'lightweight' applications
- ☐ Think about your use of audio and video
- ☐ Block unwanted web contents
- ☐ Avoid multiple downloads of same document
- ☐ Quit unused applications
- ☐ Turn off the iMacs after use
- ☐ Other:

6 [2b]Would you be reminded to think about your energy usage and/or practise energy saving techniques by the menu-bar energy applet? *

Only answer this question if the following conditions are met:
° ((2.NAOK == "N"))

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

7 [3]What is your current attitude toward energy saving? *

Please choose **only one** of the following:

- ◯ Very Positive - I actively save energy and believe I can make a difference
- ◯ Aware and positive, but it is not part of my current work day practice
- ◯ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- ◯ I'm aware, but not motivated to save energy
- ◯ I'm not aware of what I can do to save energy
- ◯ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

8 [4]Any general comments regarding above questions and/or your answers?

Please write your answer here:

9 [*]Would you like to recieve some plots and statistics of your historical energy usage when they are available? (PDF ducument x1)

Please choose **only one** of the following:

- ◯ Yes
- ◯ No

Appendix H

Y2 Surveys

Energy Awareness Background Survey 2012

There are 23 questions in this survey

Question group 1 of 1

1 [1]Gender

Please choose **only one** of the following:

- Male
- Female

2 [2]Do you pay for your energy usage separately at your residence? *

Please choose **only one** of the following:

- Yes
- No

3 [3]Are you aware of your energy usage in your residence? *

Please choose **only one** of the following:

- Yes
- No

4 [4]Have you been given any guidance on how to save energy in your residence? e.g. TV programmes, leaflets. *

Please choose **only one** of the following:

- Yes
- No

5 [5]Do you practice any energy saving techniques in your residence? *

Please choose **only one** of the following:

- Yes
- No

6 [5a]What motivates you to save energy at home? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((5.NAOK == "Y"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so (e.g. residence policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 5c if any)	○	○	○	○	○	○

7 [5b]Could the following reasons motivate you to save energy at home? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((5.NAOK == "N"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
Not to be wasteful	○	○	○	○	○	○
Enforcement (e.g. residence policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 5c if any)	○	○	○	○	○	○

8 [5c]Please briefly describe one other reason that motivates you to save energy at home.

Only answer this question if the following conditions are met:
° ((5a_SQ006.NAOK != "A1")) or ((5b_SQ006.NAOK != "A1"))

Please write your answer here:

9 [6]Do you think that energy management is important to the School of Computer Science? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

10 [7]Who do you think should be actively involved in energy management activities in the school? *

Please choose **all** that apply:

- ☐ The university management staff
- ☐ The school administrators
- ☐ The school technical staff
- ☐ The school academic/research staff
- ☐ The school janitors/cleaning staff
- ☐ Students
- ☐ Don't know
- ☐ Other:

11 [8]Are you aware of the energy usage of the School of the Computer Science? *

Please choose **only one** of the following:

- Yes
- No

12 [9]Have you been given any guidance on saving energy at school? *

Please choose **only one** of the following:

- Yes
- No

13 [9a]The guidance was delivered via *

Only answer this question if the following conditions are met:
° ((9.NAOK == "Y"))

Please choose **all** that apply:

- Leaflet/handout
- Posters
- Radio/TV programmes
- Talks during freshers' week and/or induction (but not lectures)
- Other:

14 [10]Do you practice energy saving techniques at school? *

Please choose **only one** of the following:

- Yes
- No

15 [10a]What motivates you to save energy at school? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((10.NAOK == "Y"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep energy costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so (e.g. school/university policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 10c if any)	○	○	○	○	○	○

16 [10b]Could the following reasons motivate you to save energy at school? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((10.NAOK == "N"))

Please choose the appropriate response for each item:

	I've never thought about this	Not at all	Rarely	Sometimes	Often	Most of the time
To keep energy costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
Not to be wasteful	○	○	○	○	○	○
Enforcement (e.g. school/university policies/rules, etc.)	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe in 10c if any)	○	○	○	○	○	○

17 [10c]Please briefly describe one other reason that motivates you to save energy at school.

Only answer this question if the following conditions are met:
° ((10a_SQ006.NAOK != "A1")) or ((10b_SQ006.NAOK != "A1"))

Please write your answer here:

18 [11]How would the following facilitate your participation in saving energy at school? *

Please choose the appropriate response for each item:

	I don't think about this	Not useful at all	Minimum useful	I'd be prepared to use this	Would be useful	Very useful
More information on how to save energy	○	○	○	○	○	○
Information on personal energy usage	○	○	○	○	○	○
Information on other people's energy usage	○	○	○	○	○	○
Information on the school's energy usage as a whole	○	○	○	○	○	○
Other (please briefly describe in 11a if any)	○	○	○	○	○	○

19 [11a]

Please briefly describe any other information that would facilitate your participation in saving energy at school.

Only answer this question if the following conditions are met:
° ((11_SQ005.NAOK != "A1"))

Please write your answer here:

20 [12]What is your general attitude toward energy saving? *

Please choose **only one** of the following:

- Very Positive - I actively save energy and believe I can make a difference
- Aware and positive, but it is not part of my current work day practice
- Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- I'm aware, but not motivated to save energy
- I'm not aware of what I can do to save energy
- Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

21 [13]How aware are you of the environmental impact of energy use? *

Please choose **only one** of the following:

- I am very aware and often do my own research
- I am aware of some of the environmental issues
- I am aware of the current debate, but am not yet convinced
- I am hardly aware of the environmental issues
- I am not aware of the environmental impact at all
- I am not aware of it and I don't want to know

22 [14]How motivated are you to save energy? *

Please choose **only one** of the following:

- ◯ I am motivated and try to follow all the advices I know all the time
- ◯ I am motivated and try to follow all the advices I know most of the time
- ◯ I am motivated but I don't always remember to save energy
- ◯ I am motivated but I don't know how to save energy
- ◯ I am not motivated but I want to find out how to save energy
- ◯ I am not motivated and I don't want to know how to save energy

23 [15]Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Saving Tips 2012 - pre competition survey

Hello again!

Here are some energy saving tips that may help you to reduce energy consumption and win the competition.

There are 14 questions in this survey

Page 1 of 1

1 [T1]

Tip 1:
Dim Screen whenever possible.
High brightness is not always required, and lower brightness may even be better for your eyes.

*****

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

2 [T1a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T1_SQ004.NAOK == "N" or T1_SQ004.NAOK == "U"))

Please write your answer here:

3 [T2]

Tip 2:
Use 'lightweight' applications (low CPU, RAM & disk usage) whenever possible. e.g. use vim or Smultron instead of Xcode or Eclipse for coding.

*

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

4 [T2a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T2_SQ004.NAOK == "N" or T2_SQ004.NAOK == "U"))

Please write your answer here:

5 [T3]

Tip 3:
Think about your use of audio and video on the iMac. e.g. online Flash video uses a lot of CPU power hence energy. You may want to use iTunes or other media player applications for video/audio playback.

*

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

6 [T3a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T3_SQ004.NAOK == "N" or T3_SQ004.NAOK == "U"))

Please write your answer here:

7 [T4]

```
Tip 4:
 Block unwanted web contents.
 You can use Adblock and Flahsblock add-ons for browsers
such as Firefox or Chrome to stop Flash, pop-ups, adverts
etc. from loading to reduce network, CPU, RAM and disk usage,
therefore to save energy.

*
```

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

8 [T4a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T4_SQ004.NAOK == "N" or T4_SQ004.NAOK == "U"))

Please write your answer here:

9 [T5]

```
Tip 5:
 Quit unused applications.
 Reduce CPU, RAM and disk usage by quitting, not just
minimising, the apps you do not use in (a session)
any more.

*
```

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

10 [T5a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T5_SQ004.NAOK == "N" or T5_SQ004.NAOK == "U"))

Please write your answer here:

11 [T6]

Tip 6:
Turn off, but do NOT sleep, the iMacs after use, especially after 6pm. The iMacs take only ~50 seconds from Off to Ready-for-Use (20s to boot up to the login screen, then another 30s to connect to the remote file server).

The 'Sleep' feature will break the iMac's connection to school NFS server when it wakes up, hence is forbidden on any lab computers.

*****

Please choose the appropriate response for each item:

	Yes	Uncertain	No
Do you understand this tip?	○	○	○
Does the tip seem sensible to you?	○	○	○
Do you consider this tip easy to carry out?	○	○	○
Are you motivated to use this tip?	○	○	○

12 [T6a]Please briefly tell us why

Only answer this question if the following conditions are met:
° ((T6_SQ004.NAOK == "N" or T6_SQ004.NAOK == "U"))

Please write your answer here:

13 [motivation]What is your current attitude toward energy saving? *

Please choose **only one** of the following:

○ Very Positive - I actively save energy and believe I can make a difference
○ Aware and positive, but it is not part of my current work day practice
○ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
○ I'm aware, but not motivated to save energy
○ I'm not aware of what I can do to save energy
○ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

14 [comments]Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Competition Feedback 2012

There are 10 questions in this survey

Group 1 of 1

1 [1] What motivates you to save energy during the competition? Please rate each option accordingly. *

Please choose the appropriate response for each item:

	Almost all the time (almost every time you used the computers, you thought about this)	Often (most of the time that you used the computers, you thought about this)	Sometimes (there were times you used the computer that you did not think about this)	Rarely (most of the times you used the computer without considering this)	Only when I was reminded by seeing the menu-bar energy applet	Not at all
To win the prizes	○	○	○	○	○	○
To keep the electricity costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe below if any)	○	○	○	○	○	○

2 [1a]Please briefly describe what else motivates you to save energy during the competition.

Only answer this question if the following conditions are met:
° ((1_SQ007.NAOK == "A1" or 1_SQ007.NAOK == "A2" or 1_SQ007.NAOK == "A3" or 1_SQ007.NAOK == "A4" or 1_SQ007.NAOK == "A5"))

Please write your answer here:

3 [2]Did you find the menu-bar energy applet helpful? *

Please choose **only one** of the following:

- Yes
- No

4 [2a]In which way(s) it was helpful to you? *

Only answer this question if the following conditions are met:
° ((2.NAOK == "Y"))

Please choose **all** that apply:

- It helps me to explore possible ways to reduce energy consumption
- It shows me my real-time energy consumption level
- It shows me my historical energy usage in plots
- It shows me my total energy consumption in each session
- It shows me my carbon footprint (mass: grams) in each session
- It shows me my carbon emission (volume: litres) in each session
- It shows me my total energy cost in each session
- It acts as a reminder for me to save energy
- Other:

5 [2b]It was not helpful to you because: *

Only answer this question if the following conditions are met:
° ((2.NAOK == "N"))

Please choose **all** that apply:

- ☐ The information it showed did not make sense to me
- ☐ The information it showed was not sufficient
- ☐ I found it annoying or distracting
- ☐ I did not notice it at all
- ☐ Other:

6 [3]Please briefly comment on how we could improve the menu-bar energy applet to make it more helpful.

Please write your answer here:

7 [work_vs_energy]Please mark on the scale below your relative importance of energy saving and completing your work *

Please choose the appropriate response for each item:

	Completing work			Same			Saving energy
Importance	○	○	○	○	○	○	○

Button towards left means you consider your work more important; towards right means saving energy is more important to you

8 [4]Please select the energy saving tips that you have practised during the competition. *

Please choose **all** that apply:

- [ ] I did not use any energy saving technique
- [ ] Dim Screen whenever possible
- [ ] Use 'lightweight' applications
- [ ] Think about the use of audio and video
- [ ] Block unwanted web contents
- [ ] Quit unused applications
- [ ] Turn off the iMacs after use
- [ ] Other:

9 [5]What is your current attitude toward energy saving? *

Please choose **only one** of the following:

- ◯ Very Positive - I actively save energy and believe I can make a difference
- ◯ Aware and positive, but it is not part of my current work day practice
- ◯ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- ◯ I'm aware, but not motivated to save energy
- ◯ I'm not aware of what I can do to save energy
- ◯ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

10 [6]Any general comments regarding above questions and/or your answers?

Please write your answer here:

Energy Study 2012 Final Survey

There are 10 questions in this survey

final survey

1 [1]It has been over 2 weeks since the energy efficiency competition ended. Are you still motivated to save energy during your use of lab computers? *

Please choose **only one** of the following:

○ Yes

○ No

2 [1a]What motivates you to save energy? Please rate each option accordingly. *

Only answer this question if the following conditions are met:
° ((1.NAOK == "Y"))

Please choose the appropriate response for each item:

	Almost all the time (almost every time you used the computers, you thought about this)	Often (most of the time that you used the computers, you thought about this)	Sometimes (there were times you used the computer that you did not think about this)	Rarely (most of the times you used the computer without considering this)	Only when I was reminded by seeing the menu-bar energy applet	Not at all
To keep the electricity costs down	○	○	○	○	○	○
To protect the environment	○	○	○	○	○	○
I don't want to be wasteful	○	○	○	○	○	○
I have been told to do so	○	○	○	○	○	○
To impress or set a good example for others	○	○	○	○	○	○
Other (please briefly describe below if any)	○	○	○	○	○	○

3 [1b]Please briefly describe what was the 'other' reason.

Only answer this question if the following conditions are met:
° ((1a_SQ006.NAOK == "A1" or 1a_SQ006.NAOK == "A2" or 1a_SQ006.NAOK == "A3" or 1a_SQ006.NAOK == "A4" or 1a_SQ006.NAOK == "A5"))

Please write your answer here:

4 [app]Did you (still) find the menu-bar energy applet helpful? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

5 [app_a]In which way(s) it was helpful to you? *

Only answer this question if the following conditions are met:
° ((app.NAOK == "Y"))

Please choose **all** that apply:

- ☐ It helps me to explore possible ways to reduce energy consumption
- ☐ It shows me my real-time energy consumption level
- ☐ It shows me my historical energy usage in plots
- ☐ It shows me my total energy consumption in each session
- ☐ It shows me my carbon footprint (mass: grams) in each session
- ☐ It shows me my carbon emission (volume: litres) in each session
- ☐ It shows me my total energy cost in each session
- ☐ It acts as a reminder for me to save energy
- ☐ Other:

6 [app_b]It was not helpful to you because: *

Only answer this question if the following conditions are met:
° ((app.NAOK == "N"))

Please choose **all** that apply:

- ☐ The information it showed did not make sense to me
- ☐ The information it showed was not sufficient
- ☐ I found it annoying or distracting
- ☐ I did not notice it at all
- ☐ Other:

7 [2]After the competition, did you still think about your energy usage and/or practise energy saving techniques in the lab? *

Please choose **only one** of the following:

- ○ Yes
- ○ No

8 [2a]Please select the energy saving tips that you still practise after the energy efficiency competition. *

Only answer this question if the following conditions are met:
° ((2.NAOK == "Y"))

Please choose **all** that apply:

- ☐ Dim Screen whenever possible
- ☐ Use 'lightweight' applications
- ☐ Think about the use of audio and video
- ☐ Block unwanted web contents
- ☐ Quit unused applications
- ☐ Turn off the iMacs after use
- ☐ Other:

9 [3]What is your current attitude toward energy saving? *

Please choose **only one** of the following:

- ◯ Very Positive - I actively save energy and believe I can make a difference
- ◯ Aware and positive, but it is not part of my current work day practice
- ◯ Partly energy aware - I occasionally take some actions when I remember, and try to share information with colleagues
- ◯ I'm aware, but not motivated to save energy
- ◯ I'm not aware of what I can do to save energy
- ◯ Negative - I'm not aware of what I can do to save energy, and I'm not motivated to find out

10 [4]Any general comments regarding above questions and/or your answers?

Please write your answer here:

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