The Cost of Virtue: Reward As Well As Feedback Are Required to Reduce User ICT Power Consumption

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ABSTRACT

We show that students in a school lab environment will change their behaviour to be more energy efficient, when appropriate incentives are in place, and when measurement-based, real-time feedback about their energy usage is provided. Rewards incentivise 'non-green' users to be 'green' as well as encouraging those users who already claim to be 'green'. 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. In our measurements, weekly mean group energy use as a whole reduced by up to 16%; and weekly individual user energy consumption reduced by up to 56% *during active use*. The findings are drawn from our longitudinal study that involved 83 Computer Science students; lasted 48 weeks across 2 academic years; monitored a total of 26778 hours of active computer use; collected approximately 2TB of raw data.

Categories and Subject Descriptors

J.m [**Computer Applications**]: Miscellaneous

Keywords

user behaviour; energy usage; energy efficiency; energy monitoring; energy feedback; green ICT

1. INTRODUCTION

ICT systems consume significant and increasing amount of energy on the planet, with estimated total CO_2 comparable to the aviation industry [18]. As the use of ICT grows, it is increasingly important to improve energy efficiency in the use of ICT systems.

Forrester Research [21] and Gartner [11] 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 [12] 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.

However, the aggregated energy waste due to inefficient *usage* is still high. For instance, it is estimated that US\$2.8 billion was wasted in 2009 in the US by $\sim$108 million office PCs left on when not in use [1]. While technical solutions for managing such desktop systems continue to mature, *modest energy savings from the user would scale up and yield significant impact*. How can we motivate users to improve energy efficiency in their use of ICT systems? What changes in their use of ICT systems are they willing to make?

1.1 Motivation and Approach

We take the position that: (i) there is the potential to reduce users' energy wastage; and (ii) 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.

People using portable devices (e.g. smart phones, tablets, laptops) conserve battery power to achieve longer use by adjusting the ways they operate their devices. Common power saving techniques include setting device screen to auto turn off sooner when idle; dimming the screen brightness when possible; keeping WiFi, Bluetooth and/or other wireless communication interfaces off when not in use; using some kind of task manager to auto kill inactive background processes on smart phones (although this technique is proven unnecessary in modern mobile operating systems). In contrast, people using desktop computers, do not have concerns for battery life, and might not be incentivised to employ energy efficient behaviour. Unlike portable devices, desktop computers may not have even the most basic power usage indicators to help users self-assess their power usage.

Our objective was to find out, without changing users' objectives or their tools (lab computers):

- if ICT users can change their behaviour in using computers and improve energy efficiency;
- what level of effort they are willing to make to improve energy efficiency;
- how feedback on energy usage and incentives (rewards) help them to improve their energy efficiency.

1.2 Contribution and Structure of This Paper

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%

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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 in use [2].

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'.

We first present some related work in Section 2 covering well-known power management techniques in the industry, previous research on using feedback to reduce power wastage in household environments, and some relevant behavioural studies. We then describe our experiment design in Section 3. In Section 4 and 5 we present our observations and discuss their implications. Limitations of our work are discussed in Section 6. We conclude with a summary and indications for future work in Section 7.

2. RELATED WORK

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.

2.1 User Behaviour

Demand Side Reduction, or Demand Side Management (DSM), is a technique primarily used in the electric power industry to reduce consumers' demand for energy. Various methods, including financial incentives and education to encourage consumers, are used to reduce energy usage during peak hours and shift the power demanding jobs to off-peak periods such as night time [4]. It demonstrates reduction in energy usage by changing user behaviour, rather than focusing solely on improving the energy efficiency of hardware.

Kollmuss et. al. [14] showed that people are concerned about the environment, but this does not always translate into protective actions. There are social, cognitive and behavioural factors explaining why many people have not yet adopted changes to help reduce energy consumption.

Fogg's behaviour model [9] suggests three crucial factors that are required to change human behaviours: *sufficient motivation*, *sufficient ability* and an *effective trigger*. In most cases, people rarely have completely no motivation or ability towards a reasonable target behaviour. Effective persuasive techniques will help to boost their motivation and/or ability, followed by the right trigger to realise the desired behaviour.

The UK Cabinet Office Behavioural Insights Team [5] 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 [16] – this is the reason why people do not always pay now to get more saving in the future.
Social norms. Behavioural studies show that people are greatly 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.

So, in our study, 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.

2.2 Power Usage Feedback

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 [20]. Also, psychologists, power providers and the UK government also conducted experiments and determined direct power feedback was useful for energy savings in household environments [3, 7]. They used small desktop displays to show real-time and/or historical energy usage, as well as the estimated electricity costs in households. The results showed that most people paid attention to such information, and achieved 5-15% power savings by reducing their energy wastage in the use of air conditioning systems, lighting, etc. [6].

It has been observed in both domestic and office environments, that users have strong impact on energy demand and usage [15, 17]. 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 [17]. However, raw data without annotations provide little information to non-expert users, but finely annotated data may pose privacy concerns [17] and lead to resistance towards energy saving by feedback.

Yun et al. [22] 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 used the 6 points identified by Yun et al. [22]. 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. However, the study by Yun et al. [22] was concerned with the whole office and lab environment, and did not consider the sue of the computer systems in detail as we have.

3. A 2-YEAR MEASUREMENT STUDY

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 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 1 to refer to different periods of the 2-year study.

Table 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

Guided by Fogg's design process of creating persuasive technologies [10], we adapted both Fogg's behaviour model for persuasive design [9] and Geller's behaviour-change model [13]. 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 which stages the participants considered themselves at.

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, 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 3 in Appendix D shows a detailed experiment timeline over two years.

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. Measurements used the iMac's built-in power sensors along with some standard software (such as *ps*), with some of our own software for orchestration, management and collection (Appendix B). 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.

A control group was not used because: 1) there is no group interaction or collaboration, and so individual users may behave differently; 2) the focus is 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. (Appendix A details about the participant group.)

During the study, participants' identities were automatically anonymised, from both their survey submissions and automatically collected workstation measurements, using a one-way hash algorithm to protect their privacy, and guarantee the uniqueness of individual user's data.

3.1 Power Usage Feedback for Users

We used 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 1. 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.

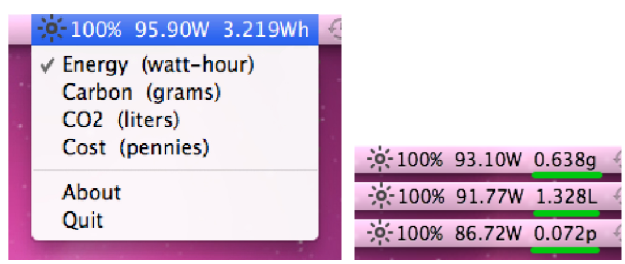

Figure 1: The menu bar power applet used in Y1. Users were able to select the display unit of total session energy consumption from 4 options.

In Y2, we improved the power applet with new features including colour-coded graphical indicators – see Figure 2. We added: green/amber/red 'smiley' faces for low/moderate/high power consumption levels with predefined thresholds based on observations in Y1; live plots of real-time and historical power usage; rate of cost and carbon emissions, in addition to power usage.

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.

3.2 Power and System Usage Monitoring

Using iMac's built-in power sensors and standard Unix utilities, we were able to implement a single, lightweight program that collects, anonymises, and uploads both computer power measurements and participants' computer usage (more details in Appendix B). The collected data are described in Section 4.1.

3.3 Surveys

Four surveys were conducted during the experiment. 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.

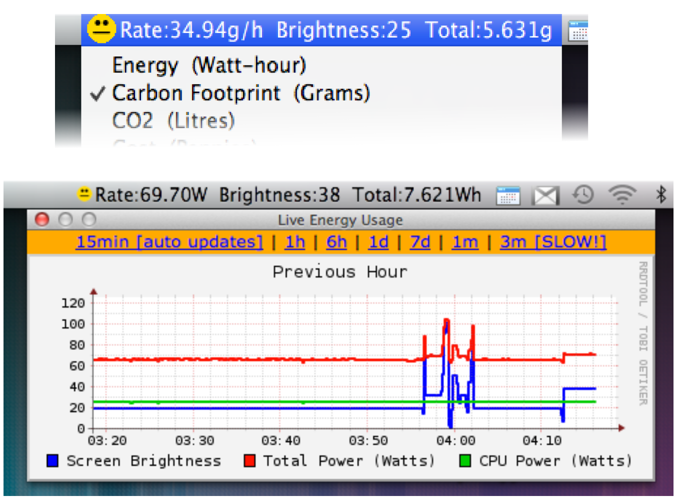

Figure 2: The improved power applet used in Y2, with a colour indicator, rate of power consumption in selected unit, and the option of viewing live plots of historical power usage.

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. 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 3.

4.1 Collected Data

Our monitoring tool captured one snapshot of computer power measurements and process status every 1s during active user sessions, and every 10s while the computer was idling. Table 2 shows the metadata of these collected data.

Table 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

4.2 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 3, 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, or at Stage 1.

Overall, the attitudes of users were stable, but on an individual basis, some self-assessments moved between Stage 2 and 3+. Figure 3 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

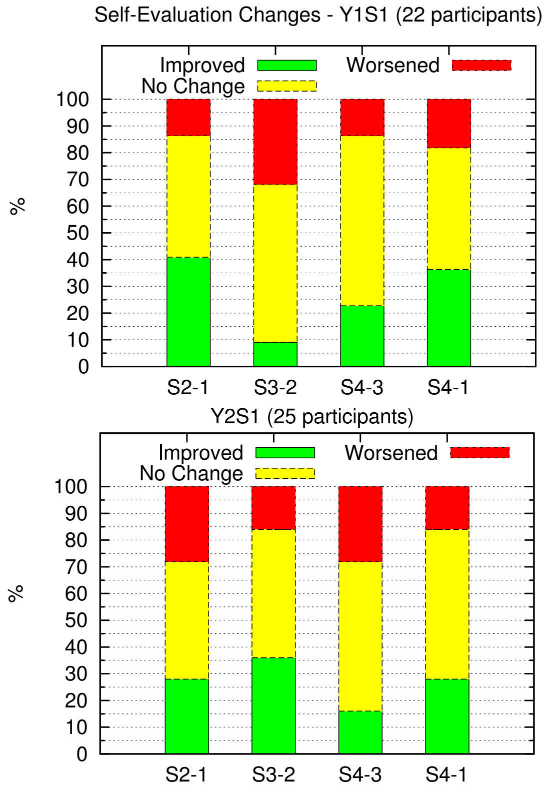

Figure 3: Attitude changes between surveys. Data presented are from those who completed all four surveys during our experiment. 'Sn-m' on the X axis stands for comparison of response to survey n compared to survey m.

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 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.

4.4 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 (see Appendix C). 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.

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*.

4.5 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.

1. Reduce screen brightness.
2. Use 'lightweight' applications (with reduced CPU and disk usage).
3. Reduce the use of streaming audio and video, 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 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 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 low popularity. Tips 3, 4 and 6 gained reasonably high and balanced votes

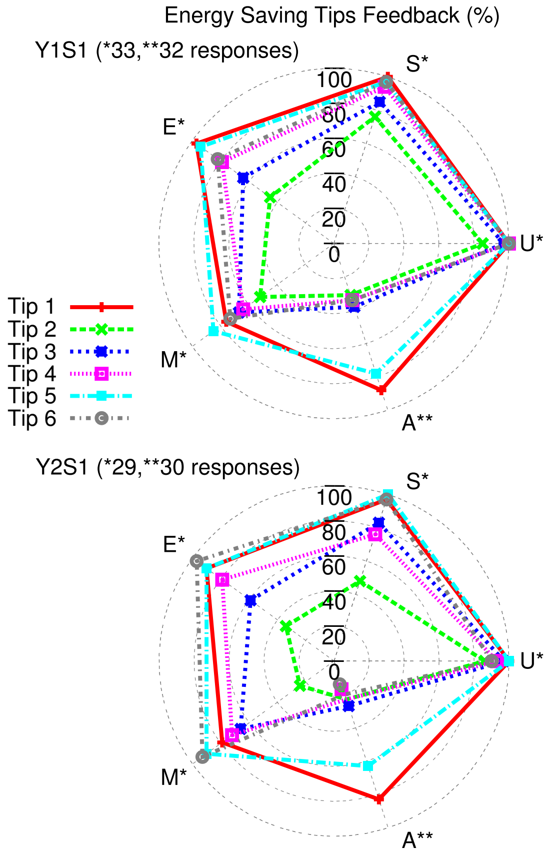

Figure 4: Feedback on energy-saving tips for Y1S1 and Y2S1. U: understandable; S: sensible; E: easy to carry out; M: motivated to use; A: actively practised during competition.

in U, S, E and M, but did not get practised much during the competition (see Section 5.1). Note that Tip 6 is periphery to our study, as our key aim was to find what actions and behaviour change users would accept *whilst using the computers*.

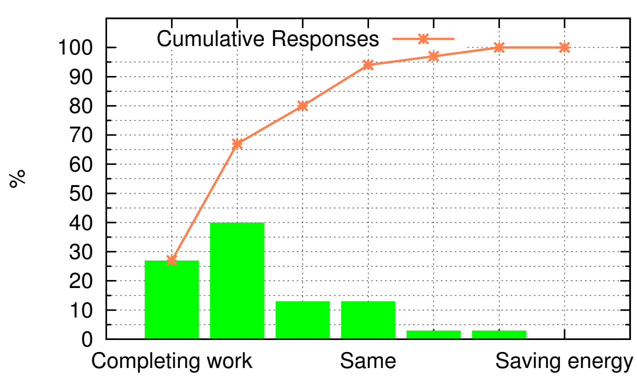

Figure 5: Distribution of users' personal preferences of completing their work vs saving energy in Y2S1. (33 responses)

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. As Figure 5 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 6 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.

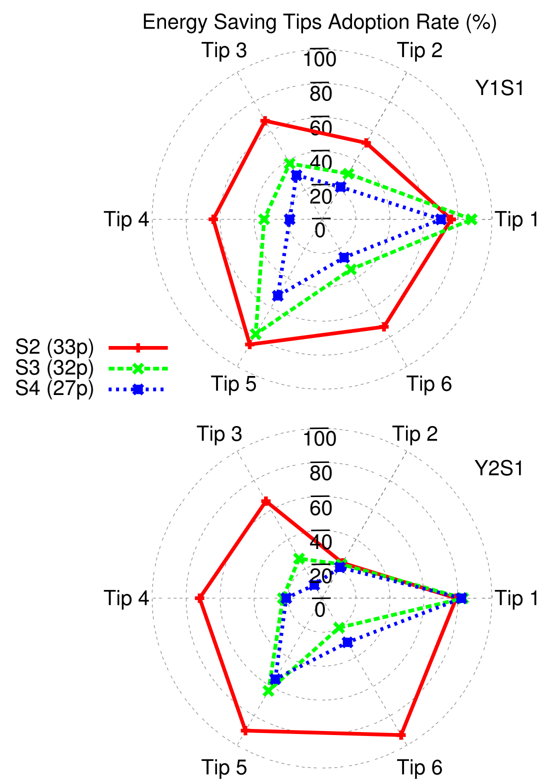

Figure 6: Adoption rates of energy saving tips by users who were motivated to save energy, recoded in surveys S2, S3 and S4. The overall rates decreased over time due to personal preferences, practicability and school/system restrictions. Tip 1 and 5 retained high adoption rates because they were the easiest to carry out.

4.6 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). Users suggested that a reward programme would make a significant difference.

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, due to an energy-saving campaign at the beginning of the semester organised by the University and not part of our study).

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

4.7 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 consumptions 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 5.5.)

Trends of power consumptions 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:

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

Potentially, we might expect 4 types of patterns: (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 7).

From Figure 7, 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 8).

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.

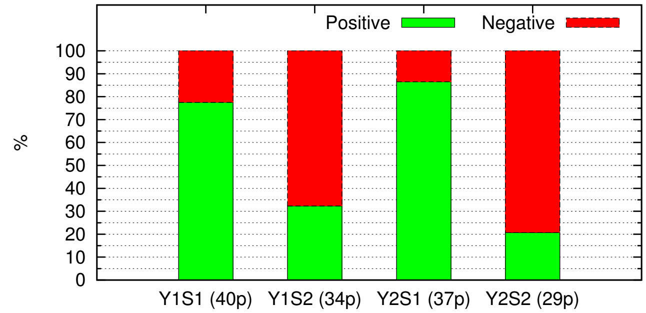

Figure 7: Proportions of positive (decreasing power consumption) and negative (increasing power consumption) trends in users' power usage. In both years, Semester 1 did have a competition (incentives) but Semester 2 did not.

5. ANALYSIS AND DISCUSSION

5.1 Choosing Effective Energy Saving Tips

During the competition (Figure 4), 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 5).

Tip 6 (Turn off computer after use.) This was periphery 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. [2]. Some users did not want to cause inconvenience for other lab users out of goodwill, although we

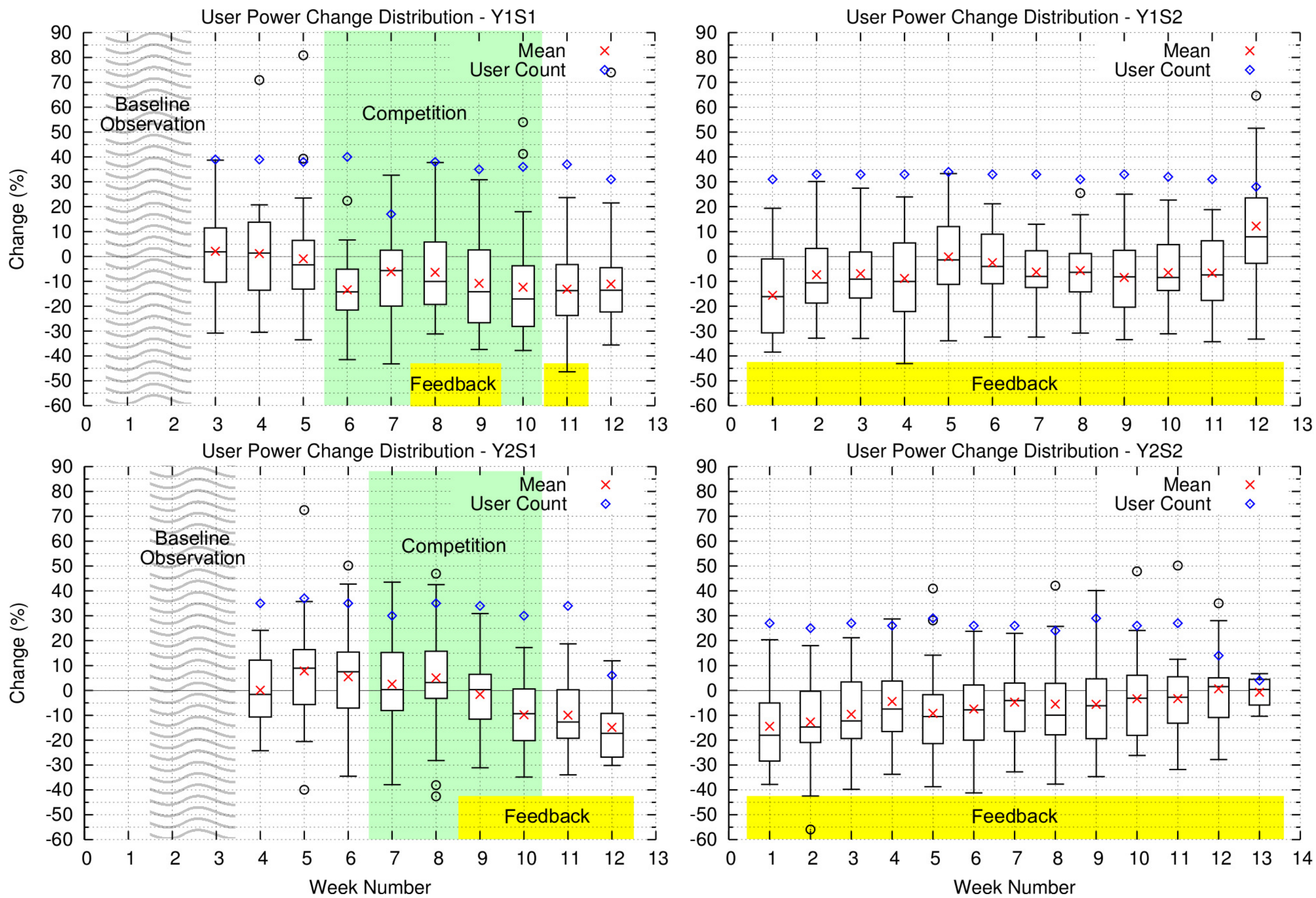

Figure 8: Distributions of users' power changes per week per semester using boxplot. A user's power change in a given week is calculated using the equation and description in Section 4.7 (the mean values taken over the duration of individual user sessions). The 'Change (%)" on the vertical axes are with 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.

made it clear that the iMac in the lab only takes about 50 seconds from being powered-down to read-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[1] 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.

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

5.2 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 decline 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.

However, from Figure 5, we also see that users prioritise completing their work. How can we move users' priority from completing work towards saving energy? Offering bigger prizes may attract more attention on saving energy. However, is it worth trading off work efficiency of students (or employees in an organisation) for energy savings? A balance must be found so that the value of the compromise made does not exceed the gains of saved energy.

5.3 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 8). 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 consumptions 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 8, 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.

5.4 Rewards & Feedback Together are Better

As discussed in Section 5.2 and 5.3, although helpful, none of rewards or feedback alone yields sustainable energy saving behaviour. However, consistent decreasing and low power power consumptions 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.

5.5 Inflated Self-Assessments

In Section 4.2, 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 abilities and/or 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 [8]. 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.

5.6 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 248.177 KWh was achieved by our users *during the use of iMacs*, excluding any saving by powering off the computers when not in use. If all first and second year students had participated in our experiment (we had volunteers and some of the class chose not to participate), the saving would have been approximately double this amount.

We can translate this saving to a global scale in the spirit of a Fermi estimate. Bloomberg[2] reported that Apple iMacs sales in 2012 were expected to reach 3.8 million, according to the research firm DisplaySearch[3]. 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[4] 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 [19], which means the energy saving from the iMacs worldwide is enough to power approximately 2581 homes in the UK for a year. In is equivalent to approximately GBP 14.6 million[5] (USD 24.1 million[6])). Note that this is only for new iMacs sold in 2012, and does not include any other iMacs, or other desktop computers: the potential total global savings are significant.

6. 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 usefully indicative.

Due to considerations of personal privacy and constraints 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

[2]http://goo.gl/zc7Z4D
[3]http://www.displaysearch.com
[4]Independent regulator and competition authority for the UK communications industries: http://goo.gl/6JUxsY
[5]Based on British Gas standard electricity price at 13.38 pence per KWh in 2013. http://www.britishgas.co.uk/
[6]At exchange rate of GBP 1 = USD 1.65

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 Appendix B for more details). Given that the iMac consumes $\sim$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. 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 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 what the the users 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. [2]) 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.

7. CONCLUSIONS AND FUTURE WORK

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 users do prioritise the tasks they have to perform over energy savings.

As future work, we would like 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); (b) carry out similar tasks therefore comparable with each other; (c) have other social backgrounds than students. It was clear that no one complained that the information we provided was too much. It is therefore desirable to improve our power monitor and provide more information, e.g. per application power profiles, preferably with lower overhead. A natural extension of this work is also to investigate the compatibility between our approach and previous work that investigates system-level interventions, to see which could be used together to gain energy savings, both when desktop computers are in use and when they are not in use.

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APPENDIX

A. PARTICIPANTS

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 do not pay directly for their electricity usage at school.
5. They were responsive to material rewards (free food, gifts, coupons, etc.).

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

B. DATA COLLECTION

Our data collection was performed by a python script that incorporated the following information and then uploaded to a collection sink.

In line with our ethics approval, user Unix IDs were anonymised with HMAC keyed-hashing, as we were required to anonymise all data collection.

System usage information was collected using:

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

Our ethics approval required that command-line arguments to programs and processes were not recorded to preserve users' privacy.

Various other system information, including screen brightness and power consumption, was collected using the Apple System Management Control (SMC) Tool v0.01. The decoding and parsing methodology for which is available upon email request to the authors.

The SMC allowed us to collect two types of data. The first type is the raw power measurements and screen brightness. The raw power measurements include total computer power, CPU power and North Bridge (data IO) power. These were read from the built-in power sensors in each iMac. The screen brightness was measured through an operating system API, ranging from level 0 (lowest brightness setting, but not off) to 100 (highest brightness setting).

All the information above was captured as a sample (a snapshot of system/power usage). Every 30 samples were compressed and cached locally in an archive. The power monitor uploaded all cached samples at a random interval between 32 and 100 seconds to: 1) avoid network congestion; 2) avoid data loss; 3) achieve near-real-time data collection. User historical usage was displayed via power applet or the Web front end on demand. Real-time power feedback was always displayed in the menu bar via applet using local measurements. As future work, we intend to implement a round-robin local storage for displaying historical usage

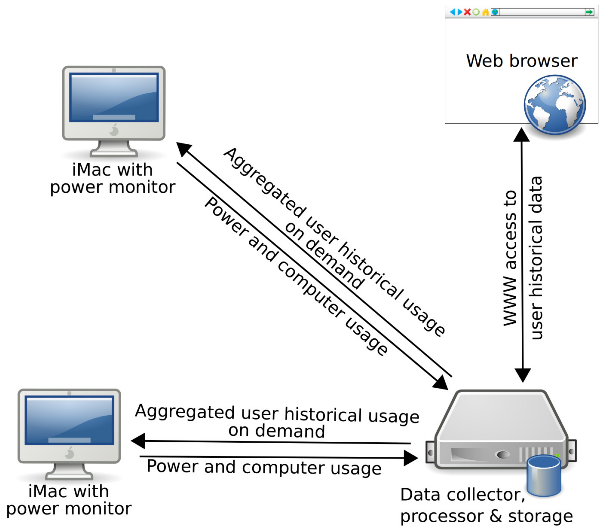

Figure 9: A sketch of power monitor-feedback model.

without contacting the collection server to enable off-line viewing, reduce network traffic and server load.

During an active user session, the power monitor took a sample every second, and consumed a mean of 0.77 Watts of power. When the machine was not in use, a sample was taken every 10 seconds to lower the power overhead to ∼0.08 Watts. If not for our experiment, the power monitor would only need to execute during active user sessions to provide feedback, and would not be operational otherwise.

B.1 Screen Power

Screen power was not available from the built-in power sensors, so we measured the total power of an idle iMac at every possible screen brightness setting (level 0 to 100), subtracting the iMac's total idle power when the screen is turned off (22 Watts), and obtained a mapping table from screen brightness level to its power consumption for our reference – see Figure 10.

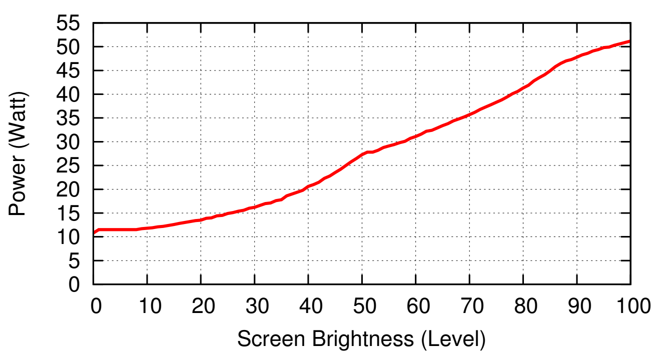

Figure 10: Screen brightness level to power consumption mapping by measurements.

C. HOW MOTIVATED TO SAVE ENERGY

Figure 11 shows participants' self-assessments in S1 on how motivated they were to save energy. Similar and overall positive results were observed in both years.

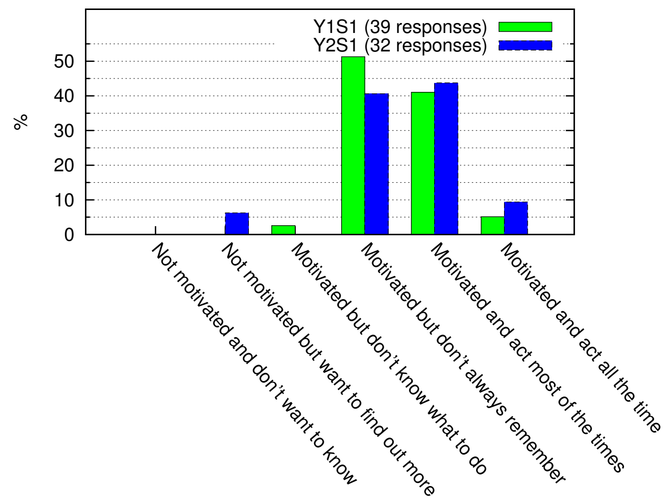

Figure 11: Participants' self-assessments on how motivated they were to save energy at the beginning of our experiment.

D. EXPERIMENT PLAN

As described in Section 3, below is the detailed, week-by-week breakdown of when the various activities ran.

Table 3: 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 8).

	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									✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	