Economical Real-Time Monitoring of Power Consumption

Colin Copeland

December 13, 2006

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1 Introduction

Energy is a crucial national and international concern. It's tied closely to environmental problems, much of it is imported, and unequal global consumption raises questions of international resource equity and sustainability (Smoot 1995). The total United States energy consumption in 1992 was 82.4 quads of energy, more than any year in the past and accounts for one-fourth of global energy use, despite having less than 5% of the total world population. Coal, the most significant energy source for electricity, has a vast reserve base exceeding 425 billion metric tons across 32 states, far exceeding both natural gas and crude oil, whose reserves are fairly limited (Tillman, Warshauer, and Prinzing 1995). One estimate (Ashworth and Little 2001) on natural gas world reserves believes about 5,100 trillion cubic feet (TCF) of natural gas remains, while the United States currently consumes 22 TCF annually. Further, fossil fuel usage is tied very closely to environmental concerns. The combustion of coal produces nitrogen and sulfur oxides that are the key causes of acid rain and nitrogen oxide can lead to an increased production of ozone in the troposphere and stratospheric ozone depletion (Smoot 1995). The burning of natural gas, like other fossil fuels, produces carbon dioxide, but almost no other waste other than water vapor (Tillman, Warshauer, and Prinzing

Residential Energy Sources

Percentage of Total Energy Sources

47% — Natural gas
30% — Electricity
15% — Oil
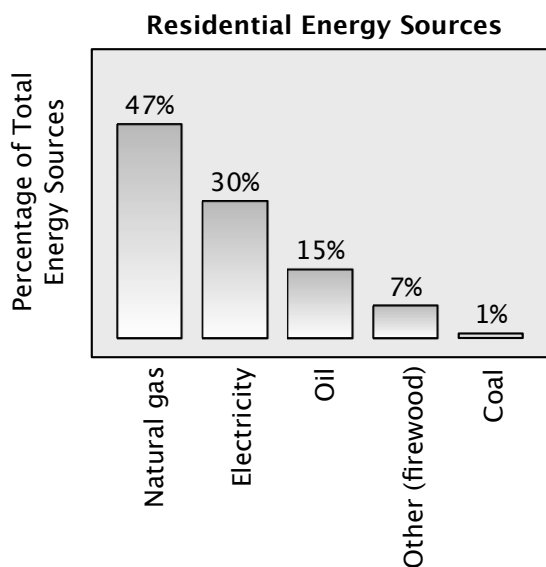7% — Other (firewood)
1% — Coal

Figure 1: Residential Energy Sources (Komor and Moyad 1995)

1995). Regrettably, the most serious environmental effects of actions made today will occur in the future. Long lasting changes in consumer behavior are needed.

As shown in Appendix A, the industrial sector leads in energy consumption, consuming almost twice as much as the residential and commercial sectors combined. Public utility companies can spend time with large industrial consumers to help reduce energy consumption. However, there are many, many consumers, so this method would not be cost effective for utility companies to spend time with every single small consumer. Therefore, some consumers must be approached in a different way.

In an interview with Gregg Duke of Richmond Power and Light (RPL), I inquired about their metering equipment and their communication with consumers about reducing energy. Richmond Power and Light offers on sight monitoring services to residential, commercial, and industrial consumers. Using Data Acquisition Units (DAQ), they have the ability to monitor every circuit to isolate energy consumption, which can then be compared to the over all bills. RPL believes consumers are very interested in their usage, as the DAQ units constantly remain in the field.

> We tend to think the residential customers don't have a lot of sophistication that you generally associate with an industrial customer, but there's still a lot of sophistication in a residential audit. You go to a residence and there's a lot more education to it then there is data analysis.

Generally, residences contact RPL about saving money. For example, a common concern is with heating bills. The first step taken is to educate the customer —inform them about programmable thermostats, more efficient appliances, or encourage them to look into alternative types of heating systems, like geothermal heating and they investigate other large energy users, like dehumidifiers and air conditioners. Further, in relation to utilities spending time with larger customers, they've setup test systems to allow industrial consumers to closely monitor consumption. For example, a wireless web server continuously monitors Hill's Pet Nutrition Inc. around the clock, allowing workers to log on track their consumption at any time. Monitoring usage statistics and collecting

continuous data over time allows the information to be quantified for the consumer, "a picture is worth a thousand words, and that's no joke here... If you educate them, they will change."

Figure 1 shows that natural gas and electricity are significant energy sources for residential energy consumption. Monitoring gas use would require severing gas lines, which is possible, but not the easiest method. Electricity is an easier resource to monitor, because monitoring equipment can be installed without interrupting the service. How can we help people change their behavior and conserve?

2   Feedback, Behavior, and The Consumer

Energy use is generally invisible to the consumer (Darby 2006). Domestic energy use, being limited to monthly utility bills, is directed towards the cost of each utility, and leads consumers to think solely in terms of dollars per month. People may hold vague ideas about their energy consumption, but it usually doesn't concern their day-to-day behavior and activity. Although single everyday actions use small amounts of energy on a national scale (aggregated across millions of people and billions of occasions) they must be taken into consideration (Stern 1981).

For that reason, there must be a focus on behavior. Consumer behavior is influenced by feedback and Darby outlines various types of feedback, including: direct, indirect, and inadvertent (Darby 2006).

Direct feedback is available on demand; the consumer learns by looking or paying. Self-meter-reading, direct display, and interactive feedback via a PC are all examples of direct feedback. All involve having direct access at any time to information. This can be as simple as walking outside to read utility meters. Further, a computer can be used to present feedback information, possibly displaying consumption statistics over time or allowing the homeowner to interact with the data (view specific time periods, change the rate feedback, generate graphs, etc).

Indirect feedback is learning by reading and reflecting. Rather than seeing how certain activities directly effect energy consumption with frequent feedback, the feedback is presented indirectly, in that the data is processed by the utility and sent out to customers on a larger time scale. Utility bills are examples of indirect feedback; they can be very detailed with historical information, etc, but are less frequent. Therefore the consumer reads and reflects on what they did, rather than seeing their actions directly effect the feedback, i.e. looking at a meter and seeing how a space heater consumes electricity.

Finally, inadvertent feedback is learning by association. For example: small scale micro-generation. In contrast to energy consumption, micro-generation allow homes to generate energy through the use of photovoltaic (PV) arrays, wind turbines, etc. Generation on a small scale forces consumers to watch their energy habits closely. Weather can directly effect energy production — cloud cover and calm days greatly decrease energy production. Home owners learn to pay attention to weather changes, changing their behavior accordingly. This form of inadvertent feedback leads consumers to not only monitor their battery banks on a day-to-day basis, but to be aware of the weather as well. They're the fully informed and aware consumers.

Beyond the various forms of feedback, an integral aspect lies in with how it effects the consumer. van Houwelingen and van Raaij outline the functions of feedback. Information through feedback is used as a basis for improvement. For example, consumers may not be aware of changes they can make to conserve energy. However, they can learn to understand the results of their actions through different types of feedback and reduce their uncertainty. van Houwelngen and van Raaij believe this influences habit formation. Subsequently, as habits are being set and reinforced, people are behaving in an "energy conscious way" and this behavior causes people to adapt new attitudes
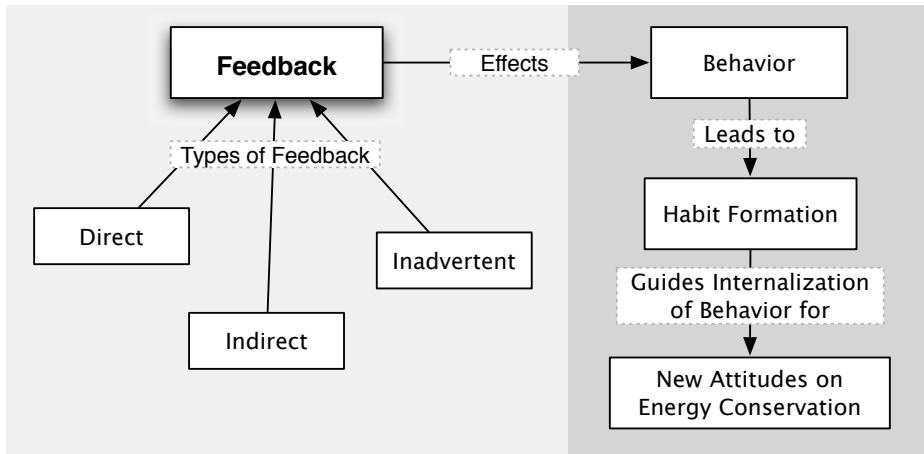
Figure 2: Feedback and Behavior

on energy conservation (van Houwelingen and van Raaij 1989). Figure 2 shows Darby's various forms of feedback and illustrates van Houwelngen and van Raaig's functions of behavior.

Further, the method by which feedback in conveyed is very important —display, frequency, and presentation improve it's quality. Energy use feedback with better message presentation can lead to energy savings of 10% to 20% through direct energy-saving actions (Stern 1981). Therefore, combining data frequency with better presentation can lead to substantial savings. "Feedback adds no information beyond what is already on people's utility meters, but it provides the information soon after any behavior change, and in a vivid and easily understandable manner" (Stern 1981).

While the quantity of information provided to the consumers is important, the main goal is a presentation to capture their attention. In order to sustain consumer attention, the information should be persuasive enough to penetrate into their day-to-day activities.

> Behaviorally, investment is a one-time action, whereas management and curtailment require changing behavior patterns and continuously maintaining the changed behavior. We would thus expect that management and curtailment would require more frequent feedback to make visible the energy effects of changed behavior. (Kempton, Darley, and Stern 1992)

Purchasing energy efficient appliances (e.g., hot water heater, refrigerator, etc), thermostats that automatically reduce heating/cooling use at night, low flow water utilities, etc, are all one time investments that can significantly reduce energy use. However, there is very little behavioral change in consumers. According to (Darby 2006) and (van Houwelingen and van Raaij 1989), curtailment is achieved by consumers learning through feedback and developing habits to reduce consumption,

The below studies analyze various forms of feedback, including public feedback, feedback frequency, and goal setting with feedback.

2.1 Public Posted Feedback

Displaying information for public viewing can bring about a reduction in certain behaviors. A study (van Houten and Nau 1981) performed in Dartmouth, Nova Scotia, compared the effectiveness of publicly posted feedback with increased police surveillance on highways. The test focused on a four-lane divided highway where the speed limit decreased from 80 km/h to 50 km/h entering an

urban area. A large sign, placed adjacent to the speed limit sign, displayed the percentage of drivers traveling under the speed limit the previous week ("Drivers Not Speeding Last Week") and the highest percentage achieved to ("Best Record").

The study showed that public posting achieved greater percentage reductions relative to the baseline averages than the police radar surveillance and ticketing, concluding that public posting was at least 10 times more efficient in controlling speeding (van Houten and Nau 1981). The researchers believe that "strict enforcement is not effective in reducing speeding behavior" (van Houten and Nau 1981), and suggests the driver slows down only when the police vehicle is visible to him.

This form of indirect feedback is unique, in that it's approach is a public posting. The posting displays speeding information relating to drivers as a group, while the feedback is reflected upon individually by each driver. Drivers reflect on not only their personal speeding behavior, but see where they stand in relation to the average driver. Therefore, the drivers ideology plays a significant role in their behavior (i.e. considering their effect on the group as a whole and slowing down or reflecting on the posting solely as an individual and feeling speeding is OK because the average is low).

In conclusion, public posted feedback brought about a significant reduction in the number of speeding drivers. The average was decreased, even though not everybody probably participated in the reduction.

2.2   Simple Meter Reading

The study was performed on 40 homeowners in identical three-bedroom town houses in New Jersey. During the summer months, after recording baseline values, homeowners were told they were in an energy study and were informed of energy saving techniques (focused primarily on air conditioning, which consisted of 70% of the electricity used by the homes (Seligman and Darley 1977)). The households were then randomly assigned to a control or feedback group.

For the feedback group, a research assistant read the electric meters on a daily basis to calculate the consumption. They also maintained a predicted performance value, which was calculated using the last 24-hour consumption value and hourly temperature readings. Therefore, using a regression equation, the researchers could predict daily electric consumption from average temperature readings (Seligman and Darley 1977). Every day at 5:00 PM, each households consumption value, along with their prediction, was inserted into a 5 x 3 inch plastic number display that was set up in the kitchen window. Homeowners could then see how well they performed the previous day in comparison to their predicted performance. The predicted value is, in effect, the target or goal each homeowner can strive to achieve.

In the end, the feedback group consumed 10.5% less electricity than the control group – suggesting direct feedback significantly assisted in consumption reduction. In comparison to the previous study, feedback focused on the homeowners individually, rather than combining and displaying the information to their neighbors. The plastic number display could very well have been turned around to face their neighbors, allowing the surrounding households to see each homeowners consumption reduction as well. The results might have been much different. A combination of both methods could possible have achieved the greatest reduction.

On a separate note, the researchers opted not to use an automatic monitoring system:

> A totally automated system to give feedback is by no means beyond the range of engineering technology: Electrical components are available from which such a system could be constructed, but we did not attempt to build it for the present study. Cost

and time-consuming problems are involved in producing several devices that would be reliable and cheap. (Seligman and Darley 1977)

The participating households agreed to allow a researcher to enter their yard and read the electric meter. Would more frequent or detailed feedback, which would have been impossible with the method they used, have changed the average consumption reduction?

While direct feedback significantly effected consumption, many questions still remained unanswered. For example, no post-experimental data was collected. How long will the effects of feedback persist after the study? Maybe the information presented in feedback could have changed. Would displaying the feedback in dollars and cents been more effective?

2.3 Setting Goals with Natural Gas Consumption

A natural gas conservation study (van Houwelingen and van Raaij 1989) focused on a large number of identical rental homes in Nieuwegein, Netherlands. Most Dutch homes are heated with natural gas. A subset of the total of the 325 participating families agreed to strive for a savings of 10%, while the houses that did not agree to the conservation goal were assigned to a separate control group. Fifty select households received electronic devices to monitor natural gas use, called "Indicators", which displayed the daily amount of natural gas in comparison with the conservation goal. The rest of the testing group was divided into two groups: one received monthly external feedback about their gas use and the other monitored their own gas use by looking at their utility meters.

The study hypothesized the following:

1. Goal-setting and the use of the Indicator (plus information about energy conservation) will reduce the use of natural gas for home heating.

2. The reduction of gas use in the Indicator condition will be larger than in the monthly external feedback and self-monitoring conditions.

3. The reduction of gas use in the experimental conditions will be larger than in the control conditions (if there is a reduction in the control conditions at all).

4. The reduction of energy use use in the Indicator condition (and in the other experimental conditions) will last after the experimental period of one year; i.e., there will be a significant difference between the experimental and the control groups in long-term effects.

Experimental groups are shown in relation to their presentation frequency and quality in Figure 3. The self monitoring group with limited presentation quality (reading consumed therms on standard meters outside of the household) had the option of checking their meters as frequently as desired (direct feedback), but ended up tailing the other two groups with an average reduction of 5.1%. The informed group, with feedback on a monthly basis (indirect feedback, less frequent), received detailed reports of their consumption patterns in the mail and achieved an average reduction of 7.7%. Finally, the greatest average reduction of 12% was achieved by the Indicator group, who had feedback presented on digital displays in their living rooms (direct feedback).

To test the fourth hypothesis, all testing conditions were removed from participating households and the energy used during the year following the experiment was recorded for each group. The results show that energy use in the groups (including the Indicator group) during the experimental period did not hold during the post-experimental period. This suggests that the feedback had an effect only during the period it was given and that no long term habit formation or internalization occurred.

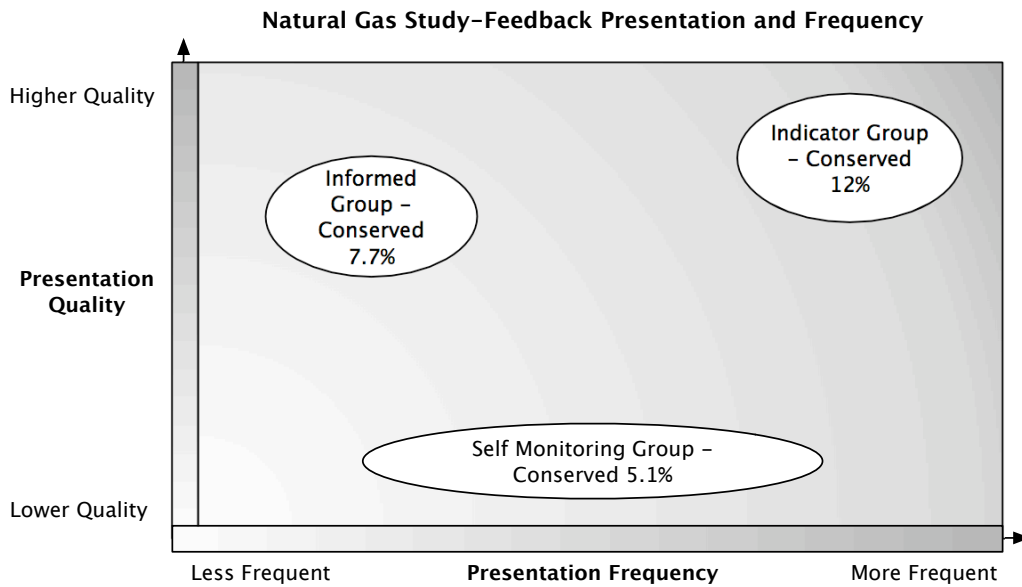**Natural Gas Study–Feedback Presentation and Frequency**

Figure 3: Feedback comparisons for participating groups in natural gas study (van Houwelingen and van Raaij 1989)

In conclusion, energy monitoring feedback presented to participants with a goal-setting ideology has a positive effect on energy conservation. Participants reported a growing awareness of their energy use and over half said they would like to have the Indicator installed permanently (van Houwelingen and van Raaij 1989). "The Indicator has a positive impact on consumer knowledge of household energy use and helps residents reduce their gas use" (van Houwelingen and van Raaij 1989). However, the post-experimental period implies the effects of energy monitoring feedback only lasts when present and residents may require a reminder in their home in order to save energy.

3 Proposal

Changing energy use behavior has a promising potential for energy conservation. Feedback plays a very important role in increasing consumer awareness. Timely feedback is helpful in guiding people to effective conservation behavior. Feedback presentation quality is important. The more unequivocally the feedback gives information, the more effect it has on the consumer. Feedback perspective is important to consumer ideology. Obviously, ones principals can greatly effect their commitment to conservation. Incorporating feedback inputs to encompass more than a single person and presenting a combined view to everyone involved, allows one to see not only how they're performing historically, but also to compare their efforts to that of their neighbors.

Instrumenting feedback can be a costly process, but it proves to be more cost effective than other alternatives. Houten compared the cost effectiveness of police surveillance and the public posting procedure (van Houten and Nau 1981). On the other hand, Seligman and Darley used man-hours instead of an automated system to implement their feedback presentation, stating "cost and time-consuming problems are involved in producing several devices that would be reliable and cheap" (Seligman and Darley 1977). van Houwelingen and van Raaij not only used man-hours to send detailed monthly reports to homeowners but also demonstrated the use of Indicators for gas consumption.

Providing consumers with a permanent daily check can give greater insight into consumption for continuous services, like electricity, gas, water, etc. A cheap, cost-effective automated system can provide frequent feedback and implementing a well executed message presentation system to convey consumption information will help with energy conservation.

4 Earlham Energy Awareness Project

The Earlham Energy Awareness Project (EEAP) is an incentive program to increase energy awareness of students living in campus housing. By promoting conservation efforts on campus, EEAP hopes to create a student body conscious of their consumption in hope of decreasing the environmental footprint of the college. EEAP collects the houses utility bills (electricity, gas, and water) every month. The quantity consumed for each utility is compared to a baseline consumption value (a three year rolling average for that month). If a house uses less energy than the baseline value, the difference is recorded. The three year rolling average is a target value for each house —this goal is the same method used for the homeowners predicted value in the Simple Meter Reading study.

The difference for each utility is displayed online on the EEAP website, so that students can monitor their conservation efforts. Detailed listings by utility and historical consumption information is available online as well. The website aims to achieve a high level of feedback quality and message presentation. Further, EEAP provides an interface for students to compare their conservation efforts to each other. This allows students to compete for a higher ranking in percentage reduction. Displaying this information publicly and allowing it to be easily compared, relates back to the public posting in the feedback and speeding study.

To motivate student conservation, EEAP will reward the students by returning a percentage of their conservation efforts in money —66% of their savings. The remaining 33% is returned to the college. This allows both the college and students to benefit from the project. At the end of each semester, the savings will be totaled and distributed to the house residents. Therefore, EEAP hopes to motivate students by rewarding them money for achieving a consumption level thats less than their target value (the three year rolling average).

The method of feedback presented to the students relates closely to the feedback given to the "Informed Group" in the the natural gas conservation study. Feedback frequency is a key item missing in EEAP, which has the capability to display more information in an accessible way. What if the students had direct, frequent feedback, like the "Indicator Group"? Students living in campus housing cannot purchase energy efficient hot water heaters, install proper insulation, etc. However, they can learn to reduce energy use with the utilities they have. As supported in the studies above, an automated power monitoring system can dramatically increase consumer awareness, more effectively than through indirect feedback. If students had access to live, frequent data, then they could focus on decreasing energy consumption. Hopefully, attitudes favorable to conservation will develop and help to sustain the motivation to the students.

5 EEAPnode Solution

5.1 Develop Baseline System

First, I plan to develop a preliminary baseline system using a single board computer (SBC) connected to a power monitoring device called a WattNode. Continental Control Systems offers the WattNode, which is a true RMS AC watt-hour meter with TTL level pulse output proportional to kilowatt-hour consumed. Installation of the WattNode requires a direct connection to the circuit
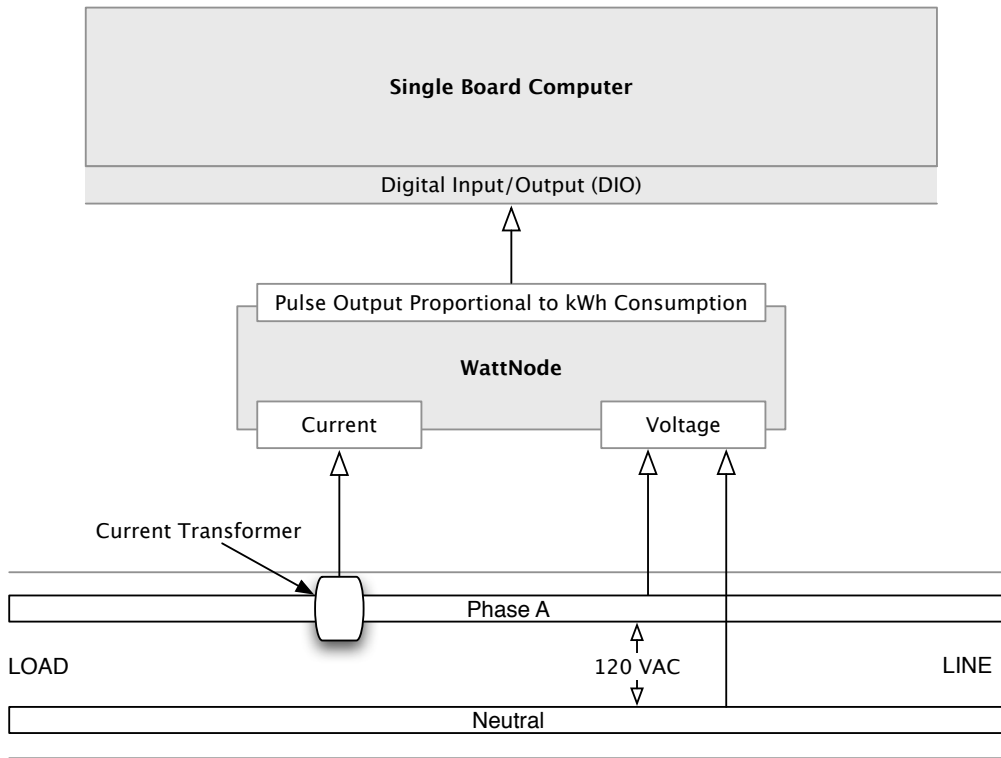
Figure 4: Baseline System

for voltage and current transformers (CT) to measure current. Continental Control Systems offers split core (opening) current transformers, which have a removable section, so that they can be installed without disconnecting the circuit being measured.

Technologic Systems offers compact single board computers (SBC). I chose to use the TS-5500, which is a standard x86-based PC compatible computer with an AMD Elan520 processor running at 133MHz. It boots a distribution of Linux off of a compact flash (CF) card for a simple development environment. The TS-5500 is equipped with TTL level digital input/output (DIO) lines.

Connecting the WattNode TTL level output to the TS-5500 (as shown in Figure 4, I've written C-code to monitor the DIO ports on the board. My program uses kernel timers to poll the DIO ports at discrete intervals, checking to see if it registers a pulse. After making sure not to count the same pulse twice, the pulse count in incremented. My code is attached in the appendix.

5.2 Build Sensor

The SBC and WattNode combination is expensive. Further, the SBC isn't being fully utilized. The WattNode uses hardware to monitor power consumption in real time and provides output in the form of pulses proportional the power consumed. It is basically converting an analog signal to a digital signal, which the TS-5500 can read on it's DIO ports. The same functionality could be performed in software on the TS-5500, as shown in Figure 5. Alternating current (AC) in the U.S. is generated at 60 Hz, or 60 cycles per second. The TS-5500 is equipped with multiple 12-bit analog-to-digital (A/D) ports, capable of performing 20,000 samples per second. Therefore, monitoring AC on the SBC is possible in software, allowing the SBC to be fully utilized and saving money by not using the WattNode.
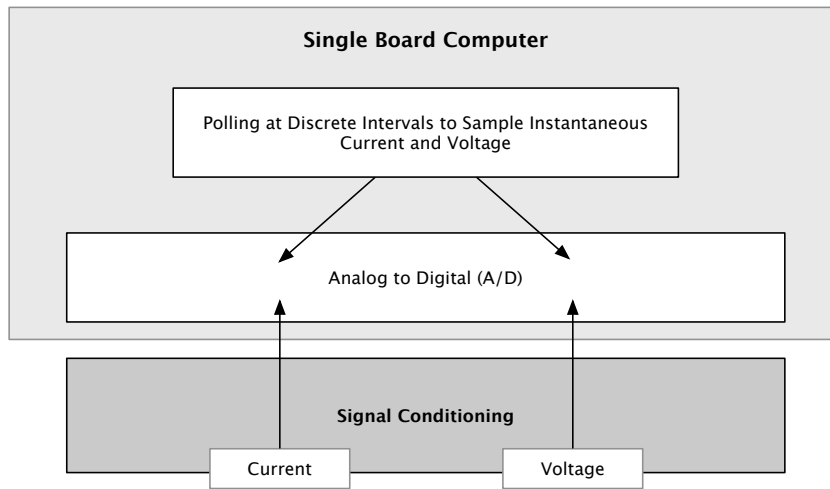
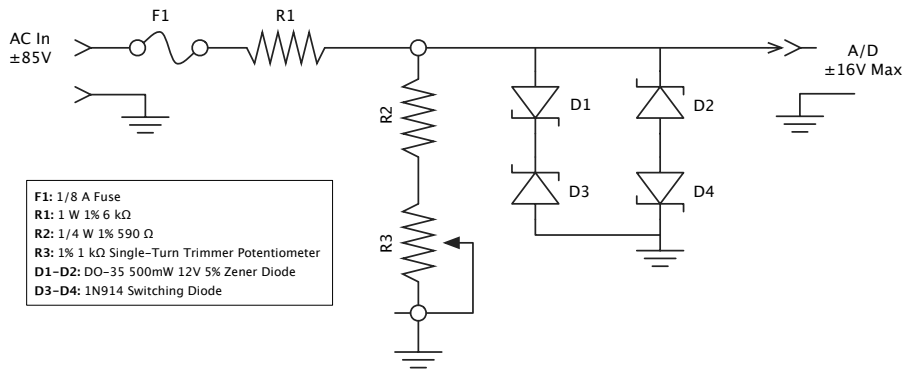Figure 5: Replace functionality of WattNode with software running on the SBC

F1: 1/8 A Fuse
R1: 1 W 1% 6 kΩ
R2: 1/4 W 1% 590 Ω
R3: 1% 1 kΩ Single–Turn Trimmer Potentiometer
D1–D2: DO–35 500mW 12V 5% Zener Diode
D3–D4: 1N914 Switching Diode

Figure 6: Voltage divider and signal conditioning circuit

5.3   Signal Conditioning and Calculating Power

To measure current and voltage on the board, I need to do signal conditioning. The voltage measurement must take into account that the input voltage is 120VAC. The TS-5500 has analog input ranges up to -10V to +10V, with each channel being over-voltage tolerant from -16V to +16V (Technolgic Systems 2003). In order to measure voltage and current safely, a circuit must be designed to condition signals enough to safely connect them to the board. I've built a voltage divider to step the voltage down to the TS-5500 levels, pictured in Figure 6. The current measurement can be assisted by the current transformer. The solid core current transformers offered by Continental Control Systems, produce 0.333 VAC output at rated current (Continental Control Systems), which means that a 30A rated current transformer will produce 0.3VAC when placed on a line with a load of 30 amps.

   In software, the SBC polls the A/D at discrete intervals to take instantaneous readings of current and voltage. In order to record the maximum number of readings per cycle, the SBC must dedicate all of it's time and processing power to my program. To ensure this, I wrote a module that runs in kernel space, allowing my program to disable interrupts before running in a tight loop to take its readings. This guarantees my program will remain active and not be swapped off so the SBC can
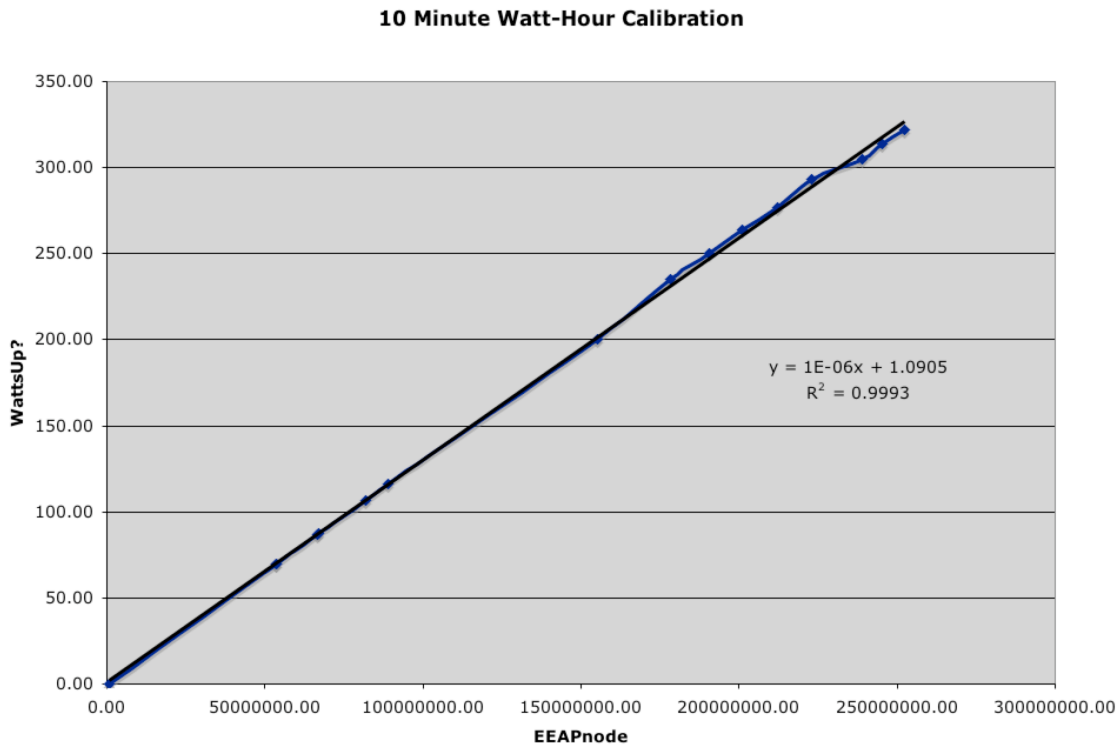
Figure 7: EEAPnode watt-hour calibration using WattsUp? Pro

handle other tasks. My module can then relinquish it's priority and allow the SBC to perform other tasks. Average power can then be calculated by dividing over the period (the number of recorded readings). This information is written into the proc filesystem, which is readable from user space.

5.4 Data Acquisition

In order to make the information presentable, it must be acquired from the SBC. Using kernel timers, a user program reads the proc file created by the power monitoring kernel module multiple times a second. It packages the information into a protocol data unit (PDU) and pushes the packet through a TCP socket. At the other end of the pipe, a server receives the packet and stores it in a postgres database.

5.5 Calibration

I calibrated against the WattsUp? Pro, a true RMS watt meter and electricity monitor. It includes an option to display the cumulative watt hours used since it was plugged in. Using a space heater and light board consisting of 5 light sockets, each powering a 100W incandescent light bulb, I ran a series of 10 minute tests under various constant loads. I recorded the various watt-hours, plotted them against my values, and plotted linear regression line, as shown in Figure 7. I used the linear equation to calibrate my readings.
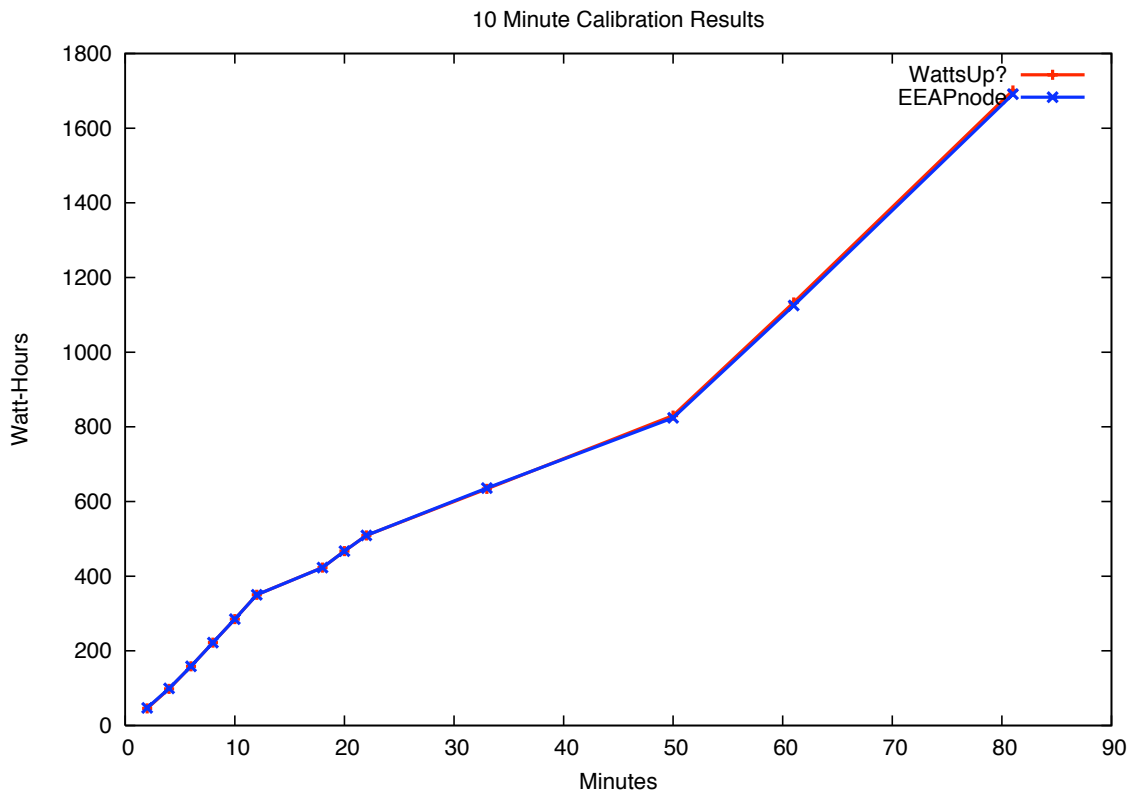
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Figure 8: Results of EEAPnode against WattsUp?

5.6 Results

To test my results, I created a simple interface to display the total cumulative watt-hours recorded in the database. I ran an 80 minute test, recording both the EEAPnode and WattsUp? reported watt-hours. The results are shown in Figure 8. The graph shows both meters inline early on, but begin to digress after about an hour. This is probably due to my calibration time being limited to a short 10 minute interval. Ideally, running a series of tests spanning longer periods of time would produce more accurate readings. I believe doing this would train the EEAPnode to be more accurate.

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