Inspiring Energy Conservation Through Open Source Power Monitoring and In-Home Display

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Abstract—Many homeowners and occupants are interested in energy conservation for economical and/or ecological reasons. A number of commercial energy conservation solutions exist on the market today. However, these products contain closed systems and do not provide easy access to much of the raw data needed for more sophisticated analysis. An open source solution would be a great benefit for homeowners and occupants, allowing access to (and custom analysis of) raw power readings. We present a complete open source solution that monitors power, stores raw power readings, and makes provision for an in-home display, that informs stakeholders about energy consumption through a real-time ambient feedback effectively becoming an eco-feedback device.

Index Terms—Power Monitoring, In-Home Display, Residential, Open Source, Arduino, RS-485, Modbus, Electric Imp, Energy Conservation

I. INTRODUCTION

Currently the world is focused on reducing electricity consumption; our increase in consumption is neither economically nor environmentally sustainable. Additionally, there is a growing consensus and realization that environmental sustainability and economical sustainability are inextricably linked. As the cost of power rises, we must find technological solutions that help reduce energy consumption and optimize energy conservation. For homeowners and occupants, one way to achieve this goal is to monitor their power consumption through an effective display mechanism.

We propose a complete open source hardware and software solution that monitors power, stores power readings, and provides for an in-home display called an Arduino Power Meter Reader (APMR). The APMR can help homeowners and occupants track their energy consumption by storing a history of how power was consumed. As well, it can inform occupants about energy consumption through a real-time ambient eco-feedback device (or in-home display or IHD). We believe that residential energy conservation should be motivated at a *grassroots level* with occupants – an initiative that power utilities can support without dictating policy and causing concern amongst the general public.

Our paper discusses the background and motivation of the APMR (Section 2) followed by the creation of a prototype system (Section 3). Section 4 then provides a discussion on how we tested and verified the system performance and the associated results. We finish with a high level discussion (Section 5) along with an outline of future work (Section 6).

II. BACKGROUND

During certain periods of the day, the demand for power is starting to exceed amount that utility companies can supply. This is common during the early evening when families return home. When demand exceeds supply, power grid blackouts occur [1]. A blackout leaves essential services such as hospitals in the dark, unable to provided critical services. Residential homes consume about 34% of the total power consumption in the USA and are projected to increase to 39% by 2030 [2] – they must play a part in the conservation solution.

To alleviate the issue of blackouts, power utilities around the world are or will be bringing in *time of day usage charges*. These charges try to discourage power consumption during *peak periods* of usage and defer that consumption to *non-peak* hours (a.k.a. peak shaving) by charging more per kWh. Peak shaving encourages the deferral of nonessential power consumption (e.g. washing and drying cloths) to times of lower demand on the power grid. Peak shaving can also encourage set points on thermostats to be relaxed – not be so low in the case of cooling and not so high in the case of heating.

Many studies [3]–[7] have shown that informed homeowners and occupants can and do reduce consumption (between 5% to 15%) when they are aware of their consumption behaviour. There are a number of commercial products, such as TED (http://www.theenergydetective.com), that homeowners can purchase make more informed decision, but often they do not provide for an open solution. The products can require the consumer to use proprietary websites to access their data which causes privacy concerns. Other products required the homeowner's computer to be on, collecting data, which is not an energy efficient solution. More notable is that consumers are buying into closed systems, which does not allow for cherry-picking different parts of products to get the best solution. For example, Product A might have the best power monitoring solution on the market but does not provide adequate data analysis, where Product B is the opposite (inadequate power monitoring, best data analysis). The best solution would be to use the power monitor from Product A and the data analysis from Product B – homeowners are left unsatisfied.

III. Prototype Creation

There are a number of open source hardware and software development platforms available to build prototype systems. We chose Adruino for power monitoring, Linux and MySQL for our database server, and Electric Imp for the in-home display. Our choices where based on 5 principles: (1) that the hardware and software platforms be open source and available to the public; (2) that there are no additional licencing fees or on going costs associated with using the platform for the hardware and software creator, vendor, or supplier; (3) that the cost of the hardware be relatively cheap; (4) that the hardware be readily available for purchase; and (5) software be easily accessible for download. This section discusses our prototype design in detail. Figure 1 shows a block diagram of the overall system.
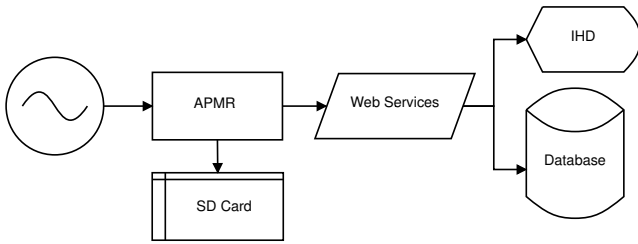

Fig. 1.   Overall prototype system block diagram.

A. Power Monitoring

The Arduino open source prototyping platform (http://arduino.cc/) presents a great opportunity for electronic professionals and hobbyists to develop projects with relative easy. Our prototype takes advantage of this by using Arduino hardware.

Hardware The Arduino Mega 2560 board was used with a third generation Arduino Ethernet Shield and two custom built shields; shields are simply add-on boards that are stack up on to the main board. Other Arduino main boards (e.g. Arduino Uno) could not be used due to their flash memory limitations. The two custom shields that were built were the Real-Time Clock (RTC) Shield (see Figure 2(a) schematic) and the RS-485 Shield (see Figure 2(b) schematic).

The RTC Shield is used for exact timing purposes, recording readings every minute on the zero-second. The RS-485 Shield is used to communication to a power meter (in our case the Schneider Electric PowerLogic ION6200) enabled with RS-485/Modbus communication. Both custom shields use inexpensive electronics and further savings can be realized by combining the two shields into one or by not using the RTC Shield.

Firmware The firmware of our prototype was designed with a number of features that make it recoverable, scalable, and robust. These features are:

1) readings are recorded locally using an SD card,
2) SD card logs files are downloaded using a web browser,
3) configurations are saved on EEPROM and changeable via a web browser,
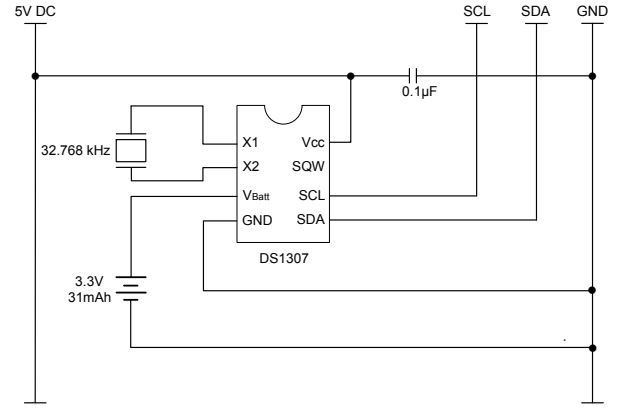
(a) RTC Shield
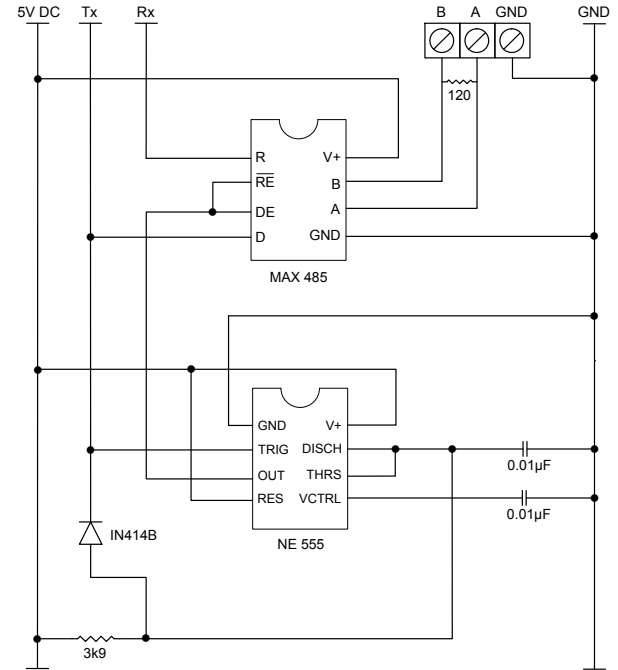
(b) RS-485 Shield

Fig. 2.   Schematics for our custom shields.

4) readings are sent to a remote website/database server,
5) ability to sense when the network is down, and then send all unsent readings when network becomes available.

Figure 3 provides a flowchart of the firmware design of the APMR which incorporates these features.

B. Database Server

All real power and energy readings are stored on a database server for further analysis, and for deciding what consumption rates to correspond to the three (green, yellow, and red) different ambient colours emitted from the IHD. As well, the database server must filter outlier data and transmit pricing signals when peak charges for power apply.

Levels of Consumption There are 3 levels of consumption: level 1 (green), low power demand; level 2 (yellow), normal power demand; level 3 (red), high power demand. *Green* would signal a real power (P) demand $P \leq \tilde{x}$ (median) of historical demand. *Yellow* signals a real power demand
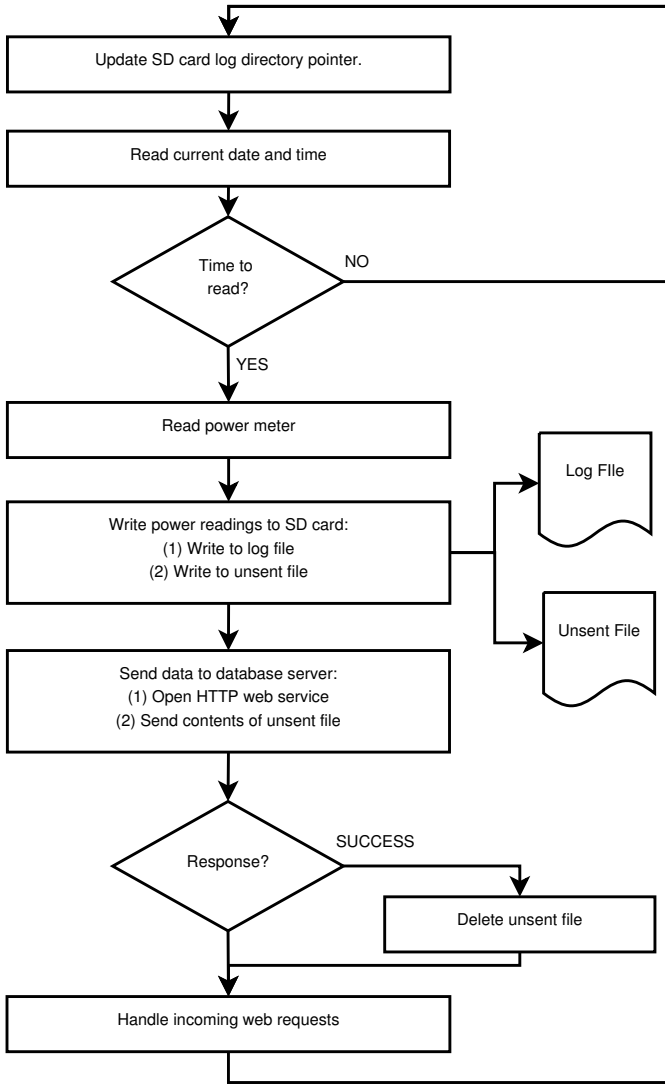
Fig. 3. Firmware design flowchart.

type of appliances that are in the home (e.g. heat pump), and how the home is being used (e.g. home-based business, stay-at-home parent, etc.) [9], [10]. Using median IQRs has the added advantage of being able to adapt over time as home use changes [11]. Using static breakpoints does not allow for these advantages and may create an adoption barrier. For example, a large house that used static breakpoints set for a small house may only ever see a red status no matter how much they tried to conserve energy.

Pricing Signal We needed to implement a way to notify occupants when the utility would charge more per kWh, usually during peak periods. In our experiment we set the peak period to be between 17h00 and 19h00. Our implementation of the pricing signal logic could allow for any number of peak periods, but we chose only 1 peak period. Our database server sent a pricing signal (1 = peak period, 0 = off-peak period) with every real power reading update (more details are provided in the next section).

C. In-Home Display

For our IHD we needed a compact yet powerful hardware platform. The Electric Imp (http://electricimp.com/) met our requirements. The IHD communicates the real power demand (P) in near real-time (depending on the APMR read rate) to the home occupants via different coloured LEDs. Such an ambient display would not rely on occupants needing to understand what a kWh is, an issue discussed by others [12]. Occupants could understand how they are consuming power relative to how they have consumed in the past. Our IHD used ambient colours to indicate energy consumption performance and blinking to indicate peak periods.

Hardware The IHD was built using the Electric Imp along with an April development board. Figure 4 shows our IHD prototype. We simply soldered the 3 LEDs (one for each colour) with the appropriate resistor value to the April board and mounted the April board into a translucent housing. We bound the LEDs together with heat shrink and mounted them on top of the SD card holder. Drilling a hole on the side of the housing, we mounted a 2.1mm barrel jack to power the IHD by way of an external AC/DC wall transformer.

Firmware Figure 5 depicts the *Imp Plan* used to program and interface the IHD hardware with the Internet. Each time the IHD is powered up or restarts, a request is made to receive the *aggregate power values for the colour LEDs*. These aggregate values are the median IQR values discussed in the *Levels of Consumption* section. Two values are returned that act as breakpoints. These breakpoints are compared against the current real power reading to determine which LED is lit.

The database server sends a *refresh* consisting of the most current real power reading and a pricing signal each time it receives power readings from the APMR. The refresh rate is equal to the APMR periodic read rate set on the APMR. Even though the power reading and pricing signal are sent at the same time from the same place, we chose to implement the 2 values using separate HTTP input sources (see Figure 5). We gave consideration to the fact that in the future the pricing

between the median and the 3rd quantile (75th percentile). *Red* would signal a real power demand above the 3rd quantile. To allow for a more stable median, outliers are filtered using *interquartile ranges* (IQR) [8].

More specifically, any data that is more than 1.5 IQRs above the 3rd quantile (Q_3) is considered an outlier. Power readings will never go below zero so we do not consider values below the 1st quartile (Q_1). The IQR equation is as follows:

$$1.5IQR = 1.5(Q_3 - Q_1) , \qquad (1)$$
$$lbound \geq Q_1 - 1.5IQR , \qquad (2)$$
$$ubound \leq Q_3 + 1.5IQR , \qquad (3)$$

where outlier data is considered to be data numerically lower than *lbound* or numerically higher than *ubound*.

The decision to use median IQRs as breakpoints for colour status change, comes from the idea that home consumption is very different from one home to another. The amount of consumption a home sees relies heavily on the home size, the
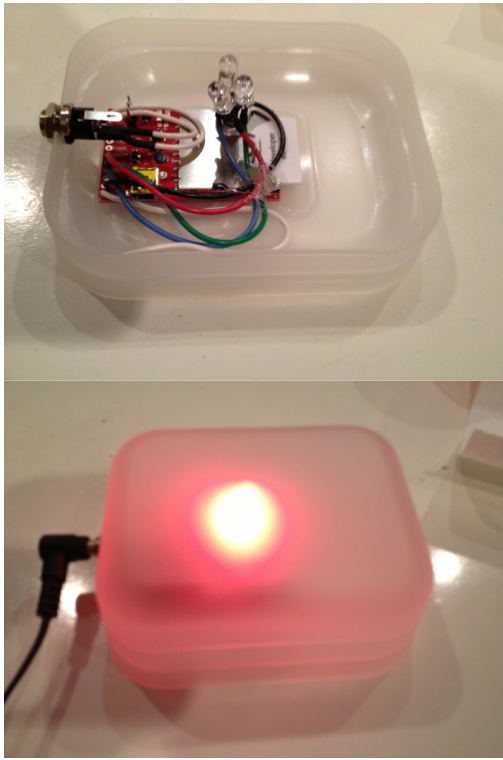
Fig. 4. Prototype in-home display: (above) the inside, and (below) running with red lit to show high power demand.
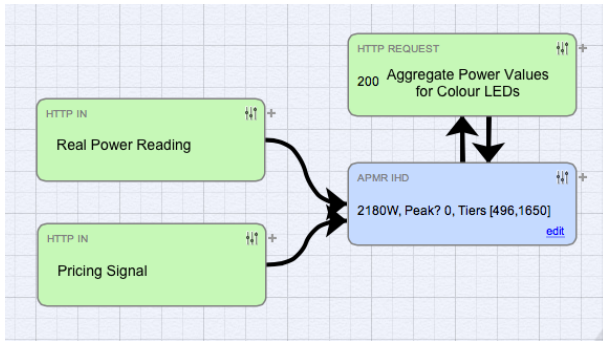

Fig. 5. In-home display Electric Imp plan diagram.

signal might come directly from the power utility company. When the pricing signal indicates a peak period the IHD will blink the correctly lit LED every 2 seconds to indicate this to the occupants. During off-peak periods, the lit LED does not blink, remaining a solid colour.

D. Prototype Costs

Table I summarizes the total cost of creating the APMR and IHD prototypes. Given economies of scale, the price would be considerably less if these prototypes became commercialized. Even at this value, assuming an electricity price of $0.12 cents/kWh, the materials in the prototype would pay for themselves in just over two years if on average the system identified one 100W incandescent light bulb of electricity savings per hour.

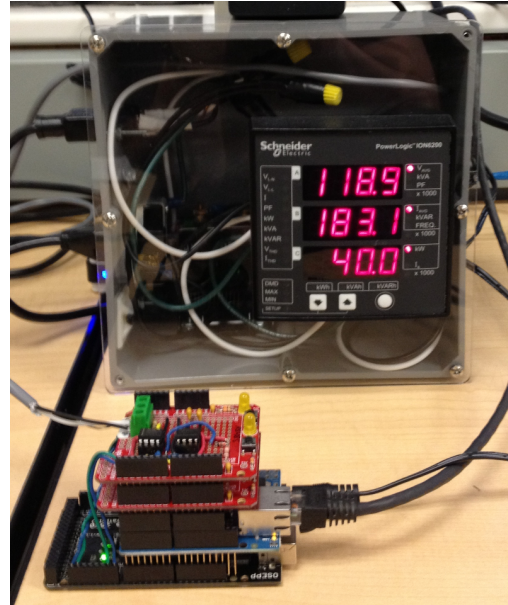| Item Description	Cost
APMR RTC Shield	21
APMR RS-485 Shield	20
APMR Prototype (remaining costs)	121
APMR-IHD Prototype	74
Total Cost	**$236**

Fig. 6. Experimental setup: APMR (front) is communicating with a Schneider Electric PowerLogic ION6200 power meter (back).

IV. EXPERIMENTAL SETUP AND RESULTS

Figure 6 shows our prototype (APMR 2.0), power meter, and other equipment used for our experiment. Our prototype communicated to a Schneider Electric PowerLogic ION6200 power meter which was monitoring the load of a computer workstation and LCD monitor. The APMR was set to read power in 1 minute intervals. Over a 2 week period both the APMR and IHD operated without fault. Prior to the current project, the APMR version 1.0 ran for 8 months reading 2 ION6200 meters once per minute without fault. Our testing confirms the stability of the APMR and IHD choices in an open source hardware platform, and our custom hardware and firmware.

A. Electrical Characteristics

A Kill-A-Watt power monitor from P3 International (http://www.p3international.com/) was used to measure the different electrical characteristics of the APMR and IHD when powered on. Both the APMR and the IHD were powered with a 12V–850mA 10W switching wall transformer/adaptor (rated to have a current leakage of 0.25mA max). The APMR ran at 100mA or 4W with a power factor of 0.38 when powered, consuming 0.11 kWh over a 24-hour period. The IHD ran

at 50mA or 1W with a power factor of 0.25 when powered, consuming 0.04 kWh over a 24-hour period.

V. DISCUSSION

We found that using a power reading rate of 1 minute was too infrequent when sending updates to the IHD. If a large appliance was to turn off between the 1 minute rate then the IHD was not responsive enough. We expected the IHD to change immediately from red to yellow or green when the large appliance ceased operation. This left us wondering if there was another large appliance powered on that caused the IHD to remain lit as red. Other researchers have concluded the need for immediate feedback as well [13].

We did observe problems with using only ambient feedback. When the IHD transitioned from yellow to red, the appliance responsible was discernible because major appliance usage caused high levels of consumption. The consumption events included the use of HVAC, stove/oven, and clothes dryer. In the case of the clothes dryer, the IHD lit red only when the heating element was on. If the clothes dryer was operating in a cool down state (no heating element) the IHD changed from red to yellow, which caused some confusion at first.

When the IHD changed from green to yellow, appliance usage was hard to discern. After careful investigation, we determined that the colour change was caused by the fridge and/or basement freezer compressor powering on–not something easily observable. When occupants turned lights on or off it was more easily discernible as to why the IHD changed colour. This shows the need for a eco-feedback device that can list the appliances that are powered on in real-time. The same or an additional IHD is needed to display the appliances that are running to further inform occupants of how power is being consumed. One way to do this, is to use load disaggregation algorithms [14]–[16] , which would give a list of likely appliances being used. Only the APMR would be needed to accomplish this – no additional power monitors would need to be used – saving the homeowner time and money.

Finally, we have identified the need for the median IQRs to be modified to suit the conservation goals of the occupants. Occupants could choose goals that are less aggressive, normal, or more aggressive (similar to the heating/cooling logic found in advanced HVAC thermostats). These conservation goals may change at different points throughout the year. For example, HVAC in the winter means more energy consumption but this cannot be avoided because of occupant comfort issues.

VI. CONCLUSION AND FUTURE WORK

We have shown how open source components can be used to create solutions that help conserve energy. Our open source prototype can be reproduced, used, and extended by anyone who is interested in conserving energy now. Most importantly, homeowners and occupants will have access to the raw consumption data to do with as they see fit.

Our future work involves adding a load disaggregation algorithm that would notify occupants as to which appliances are running and how much power each is consuming. This is an important feature that can be used to help occupants decide if they would like to participate in a demand-response call from the utility. If so, what appliance, or appliances would need to be powered down to meet the amount of power reduction required of the demand-response call. Without load disaggregation, the realization of demand-response will not be seen [17].

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