Reducing the Cost of Electricity Monitoring

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Background

Our experiences in the C-Aware project led us to consider how we might reduce the cost of monitoring electricity use – particularly fine-grained monitoring. We found that available solutions were costly, assumed large usage, and/or were vertically integrated into "complete solutions" – some meters run a web server and many have LCD displays.

For example, the main monitoring in the Gates Building at the University of Cambridge is based on meters that are accurate and robust enough to be used for charging. They also cost on the order of £200 each. However, they are "open" in the sense that the protocol for communicating with them is well specified, so that we were able to build our own monitoring system around them, and to provide measurement logs publicly on the web so that others can build their own visualisation tools.

There are a number of ways in which energy information might be used to influence energy use. One is to provide information that can help influence occupant behavior – indeed this was the motivation for the C-Aware project. A second is to provide information that can be used by building managers in configuring, replacing and controlling energy consuming devices.

The first of these requires fine-grained information. As an occupant in a large building, my behaviour is likely to influence a only small part of the building's energy consumption. Relating my behaviour to energy information aggregated across the building is not as helpful as relating it to information about my room or corridor. The second requires that we measure "that which is important to measure". We are unlikely to understand what that is, other than measuring the big circuits and providing finer granularity where we discover anomalies.

There is a tradeoff between "measuring everything" and an incremental approach that follows the anomalies. That tradeoff must be informed by the cost of measuring.

What does it cost to monitor a circuit?

There are various ways of monitoring the energy use of an individual circuit. The most practical way is to have the live conductor of the circuit pass through a current transformer, which, with a load resistor, provides a convenient voltage proportional to the current of the monitored circuit. The instantaneous power is the product of the instantaneous current – represented by the proportional voltage – and the instantaneous voltage across the circuit.

For accurate readings, one needs to measure the instantaneous live voltage. If accuracy is not important, the voltage can be assumed to have a nominal value (e.g. 240V) and be assumed to be in-phase with the current. In this case, only the current (represented by the proportional voltage) needs to be monitored, although the power factor, which is a measure of how far current is out of phase with respect to voltage, cannot be determined.

Transformers used for current monitoring can either be fixed-core or split-core. Split-core transformer can be opened up and clipped around a conductor while the conductor is live. Fixed core transformers require the monitored conductor to be disconnected and threaded through. As a very rough rule of thumb, split-core transformers are about a factor of ten more expensive than fixed-core. For circuits of 30A or less, split-core transformers cost about £15; large capacity varieties up to 200A are about £40. (There are two sorts of capacity – the maximum current and the physical size of the conductor, which are clearly related, but it is the physical size of the conductor which influences the price.)

Given the ease of installation with split core transformers, £10 is a reasonable target cost for the additional components and infrastructure needed to monitor a circuit.

Reducing Cost

The obvious way of reducing the cost per circuit is to share as much infrastructure as possible across multiple circuits. This means monitoring at the point of distribution rather than use. This also makes deployment easier – one installation located beside a distribution panel or consumer unit – rather than at each appliance. (However, such a scheme only provides information for each circuit, not for each appliance on each circuit.)

Infrastructure that can be shared includes configuration and control of the monitoring, and communication by which information can be made accessible to measurement storage services – in other words, a low-end computer.

But at an even lower level, it is cheaper to build a device that monitors 16 circuits than 16 devices that monitor one circuit each.

Integrating all control and access services into a monitoring device, rather than having an off-the-shelf computer per monitor will further reduce costs. The emergence of low cost standalone machines like the Raspberry Pi mitigate this somewhat.

The C-Aware Mon32 Electricity Monitor

The C-Aware project originally developed a simple USB based current monitor that monitored the current in a single circuit. This monitor was designed to be used with a commodity split core transformer and had a component cost of around £10. The device sampled the current measurement with a high sample rate and produced a cumulative RMS current measurement. Cumulative current has units of ampere-seconds, so with an assumption of in-phase voltage of 240V, cumulative energy (in joules) can be obtained simply by multiplying the cumulative current by 240. Conversion to kilo watt hours is left as an exercise to the reader.

We found that our deployments using this device ended up mounting multiple devices connected via USB hubs to a controlling low-end computer that continuously polled the devices. (See Figure 1.) This was fine for experimental use.

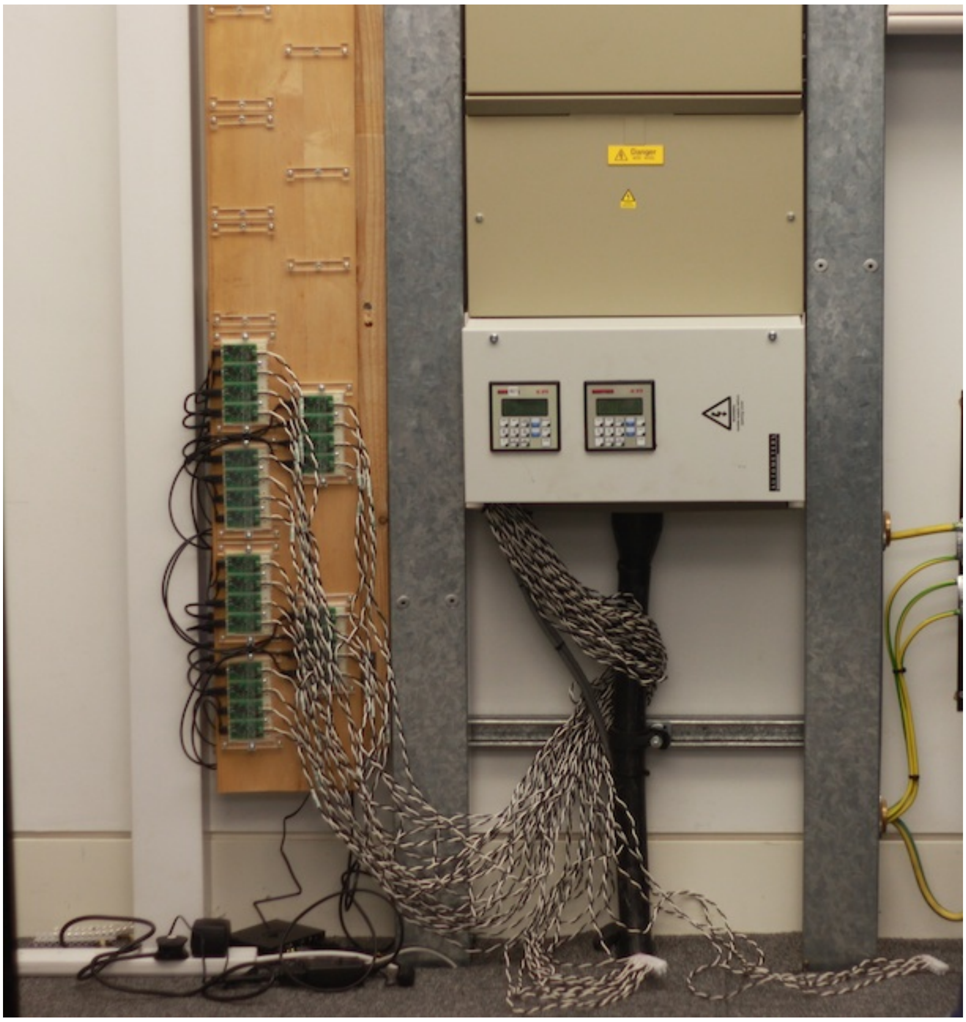

Figure 1. Monitoring multiple circuits (old-style). This shows 24 separate single circuit monitors mounted in groups of four on the left. The black and

white wires connect to the current transformers which are inside the distribution board . The black USBC cables on the left of the circuit monitors connect to USB hubs mounted on the other side of the wooden panel. The two meters mounted on the white panel are highly accurate multifunction meters with displays, but measure only 1 three-phase circuit each.

When asked to provide fine-grained monitoring for use outside the project, it was clear that a design that reflected this experience would be more economic and easier to deploy. The Mon32 device is the outcome of this.

Mon32 can monitor 32 circuits, although in its most accurate configuration should be limited to 30. It is a USB device and is USB powered. Circuits are each monitored in excess of 2000 samples per second.

It also has an input for a single isolated stepped-down mains voltage signal, so that if desired, the board can monitor the mains voltage and phase relationships. (In three phase deployments, the other voltage phases are inferred.) It is not clear how useful this feature will be, but as the cost is in the off-board transformer (a low voltage AC power adaptor which is readily available) rather than on the Mon32 board itself, it was included.

Mon32 is approximately 100x100 mm and shown in Figure 2. Its component costs are approximately £40 or £5 per circuit when used with 8 circuits, or £1.33 per circuit when used with 30 circuits.

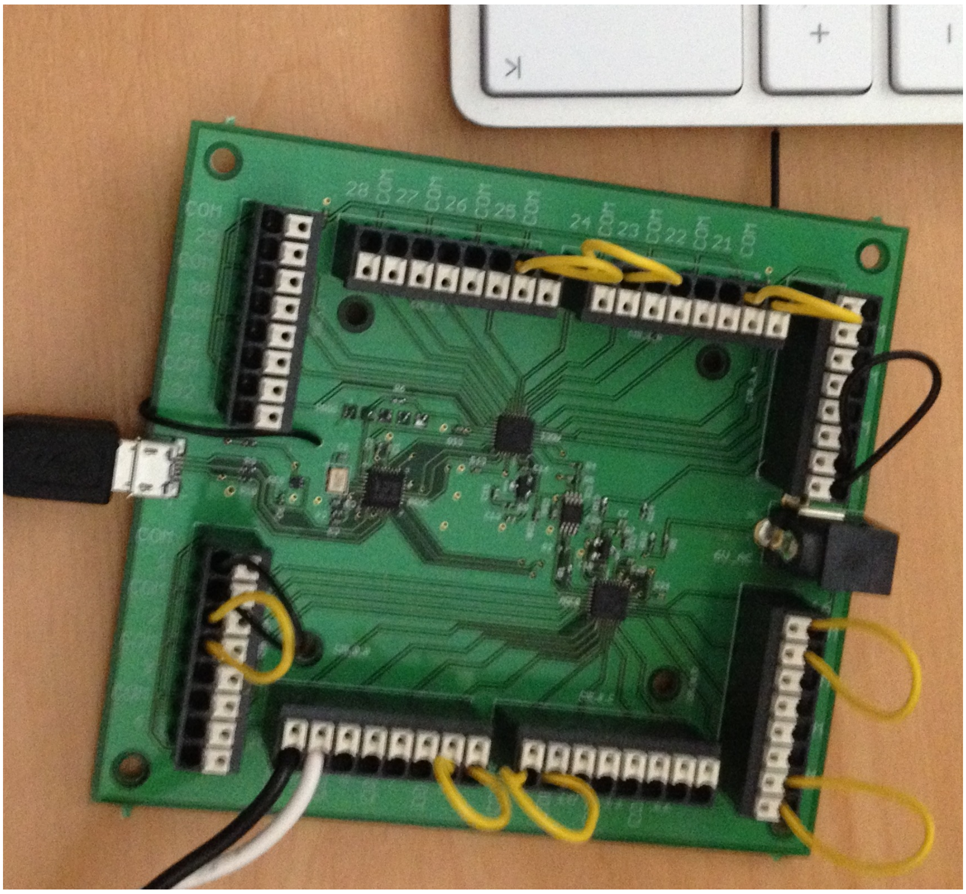

Figure 2. Mon 32 Board. USB connector to left, connector for optional isolated step-down transformer on right. A few circuits have their signal shorted to common (yellow wires). The pair of black and white wires connect to a current transformer.

The core of the device is an ARM Cortex-M0 (an NXP LPC11U35) processor and two 16-channel A/D converters. The processor continually samples the circuits and mains voltage. Host software can configure the monitor to set transformer size and phase for each circuit as well as some internal tracking parameters.

In the most accurate configuration, circuits 1 and 17 are each shorted to their common side so that the common voltages are processed in exactly the same way as the signal voltages. Unused circuits should have their signal shorted to common. Connection to the current transformers is made through tool-free insertion. Disconnection is push-to-release – a ballpoint pen is the best tool for this.

The processor also provides USB device functionality. Mon32 firmware provides a conformant USB serial device interface (which is more than can be said for most USB serial devices…) and when plugged into a Linux host simply appears as a serial device using the standard serial driver – no specific host driver is required – and the device can be accessed as a raw tty device. Example programs that run on Linux using the device are available.

Our default configuration is to use a Raspberry Pi running Linux as the host with Ethernet connectivity. Typical power supplies used to power Raspberry Pis provide sufficient power to drive Mon32 as well.

Estimated costs of this configuration are a Raspberry Pi (£25), a USB power supply (£4), mounting hardware (£10) and Mon32 (£50) or roughly £100. As long as more than 12 circuits are monitored, this meets our target of £10 per circuit (above transformer costs).

A device to monitor 16 circuits would probably not be much more than £20 in component costs, which are dominated by the connectors for the transformers and two analog-to-digital converters – only one of which would be needed in a 16 circuit version.

The hardware was developed using the Eagle PCB design system under an academic license. The devices have a USB Vendor ID that corresponds to the University of Cambridge. Firmware is developed under the LCPXpresso development system.

Manufacture is by the University of Cambridge and devices are not for sale, but can be loaned to research partners.

Future Development

Our current plan is to deploy these monitors and gain more experience in fine-grained monitoring and in our open data strategy – in particular encouraging students to develop visualisations and other applications that make use of the data.

A 15-circuit version with an integrated host may follow. This would obviate the need for the Raspberry Pi and reduce overall power consumption.

We might also consider a rack power distribution system with fixed core transformers. This would have a power inlet and a number of power outlets, independently monitored, and an Ethernet connection.